October 2017

Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Updates Under Consideration for Natural Gas and Petroleum Systems Uncertainty Estimates

In a previous version of this memo released in June 2017, and during stakeholder webinars and workshops held in April, June, and August 2017, EPA presented preliminary considerations and sought stakeholder feedback on updating the uncertainty estimates for natural gas and petroleum systems in the 2018 Inventory of U.S. Greenhouse Gas Emissions and Sinks (GHGI). This version of the memo is updated to reflect stakeholder feedback and other updates. Updates include:

- Presentation of considerations for estimating aggregate uncertainty for total CH_4 emissions across all sources, and estimated bounds by multiple approaches (pages 8–11).
- Refinement of the calculation for quantifying uncertainty around natural gas systems transmission station fugitives (page 10, Table 5).
- Expanded question for stakeholder feedback (question 1, page 12).

The most recent uncertainty analysis for the natural gas and petroleum systems emissions estimates in the GHGI was conducted for the 1990-2009 GHGI that was released in 2011. The analysis was based on a detailed assessment of the activity data and emission factor data available at that time. Since the analysis was last conducted, several of the methods and data sources used in the GHGI have changed, and industry practices and equipment have evolved. In addition, new studies and other data sources such as the EPA Greenhouse Gas Reporting Program (GHGRP) have provided more information on emissions and the underlying conditions that lead to emissions.

For the 1990-2016 GHGI (to be finalized in 2018), EPA is considering updates for the natural gas and petroleum systems uncertainty analysis to reflect new information and revised Inventory methodologies, and is seeking feedback on the updates. This memorandum provides general background on uncertainty in the GHGI, documents the previous approach to calculating uncertainty parameters, discusses a proposed updated approach for conducting the updated uncertainty analysis, and requests stakeholder feedback on the updated approach. Note that the analyses presented in this memorandum reflect estimates and methodologies used in the 2017 GHGI; therefore, resulting estimates are subject to change for the final 2018 GHGI.

<u>Overview of Uncertainty Analysis in the GHGI</u>

In conformance with the United Nations Framework Convention on Climate Change (UNFCCC) reporting requirements, EPA follows the *Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories* (IPCC Guidelines, IPCC (2006)) to develop uncertainty estimates for sources included in the national GHGI. The IPCC Guidelines note the essential role of uncertainty estimates for guiding improvements to national inventories: "An uncertainty analysis should be seen, first and foremost, as a means to help prioritize national efforts to reduce the uncertainty of inventories in the future, and guide decisions on methodological choice. For this reason, the methods used to attribute uncertainty values must be practical, scientifically defensible, robust enough to be applicable to a range of categories of emissions by source and removals by sinks, methods and national circumstances, and presented in ways comprehensible to inventory users."

The uncertainty analysis is performed by developing confidence intervals, which give the range within which the "true" value of an uncertain quantity is thought to lie for a specified level of confidence. The IPCC Guidelines suggest the use of a 95% confidence interval, which is the interval that has a 95% probability of containing the unknown "true" value.

To develop a 95% confidence interval for an emission estimate from a chosen source category (e.g., natural gas systems), it is necessary to characterize the probability density function (PDF) of the average emission and activity factors for each emission source contributing to that source category emission estimate. The PDF describes the range and relative likelihood of possible values for the average emission and activity factors corresponding to that emission source (e.g., reciprocating compressors in the natural gas transmission segment). Ideally, the PDF would be derived from source-specific information. However, in the absence of such data, it is also possible to use information developed through elicitation of expert judgment (IPCC 2006).

Once the applicable PDFs are characterized, a Monte Carlo analysis can be conducted to characterize the composite uncertainty for each emission source (e.g., national reciprocating compressor emissions in the natural gas transmission segment) as well as the overall source category (e.g., national natural gas system emissions). Although default uncertainty values are provided by IPCC and propagation of error is a valid approach, the Monte Carlo approach is more rigorous and recommended for sources that use more sophisticated estimation methodologies, where PDFs may be non-normal, and if uncertainties are large (IPCC 2006). As described in the IPCC guidelines, Monte Carlo analysis involves selecting random values for emission factors and activity data from the respective PDFs and calculating the resulting emission estimate. This procedure is repeated numerous times and the results of each simulation are used to characterize the PDF for the overall emission estimate for the source category (IPCC 2006). Figure 1 depicts the steps involved in conducting a Monte Carlo analysis. From the figure, only Steps 1 and 2 require user input (e.g., specification of PDFs for emission and activity factors); Steps 3 through 5 are conducted through use of a software package such as @RISK.

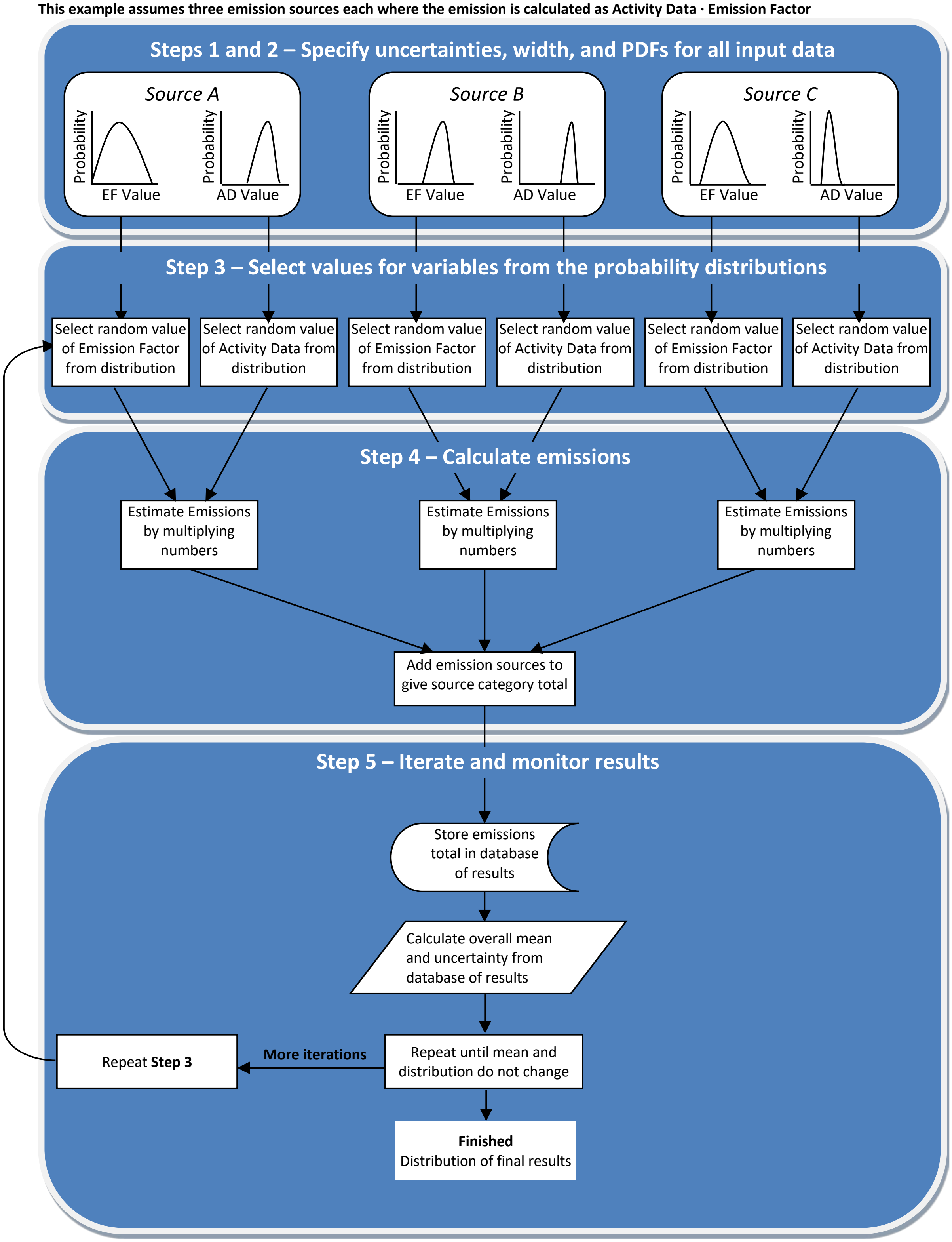
To develop uncertainty bounds around total estimated emissions at the national level, the source-specific emissions that correspond to the lower and upper confidence bounds can be summed, as the total national level estimate is the simple sum of source-specific emissions.

The approach described estimates the national emissions associated with a source category as the product of the average emission factor and average activity factor for that source category. While recent studies show that the emissions from certain source categories may be highly skewed with potentially fat right-hand tails due to the existence of "super-emitters," per the Central Limit Theorem (CLT), the impact of such is expected to be minimal on the average emission factors and average activity factors used in calculating national estimated emissions (see section "Updated Uncertainty Analyses for Natural Gas and Petroleum Systems in the 2018 GHGI: Approach" below).[1]

[1] The Central Limit Theorem (CLT) states that the means of random samples drawn from a population with any type of distribution will be normally or near-normally distributed, provided that the sample on which these factors are based are unbiased (e.g., each population element, such as a facility or device, has an equal probability of being sampled) and is of sufficient size (Mendenhall, Wackerly, & Scheaffer, 1990). The distribution of sample means referred to in the CLT is different than a population distribution; the underlying population from which the random samples are drawn may be non-normal, however the means of random samples from that distribution can still be normally distributed as implied by the CLT.

Figure 1: Illustration of Monte Carlo Method (Adapted from IPCC 2006)

This example assumes three emission sources each where the emission is calculated as Activity Data · Emission Factor



<u>Background on Uncertainty for Natural Gas and Petroleum Systems</u>
EPA conducted the last complete uncertainty analyses for natural gas and petroleum systems for the 1990-2009 GHGI that was released in 2011. For that analysis, EPA obtained many of the emission factors and associated uncertainty parameters (e.g., PDF and standard deviation) from the 1996 EPA-Radian study of the natural gas industry and the 1999 EPA-Radian study of the petroleum industry. EPA adopted the same source category-level uncertainty intervals for natural gas and petroleum systems emission estimates subsequent to the 1990-2009 GHGI.

Basis of the 2011 GHGI Natural Gas Systems Uncertainty Analysis
The 2011 GHGI uncertainty analysis for natural gas systems included a detailed analysis for the twelve top-emitting sources in 2009 (ranked according to the 2011 GHGI estimates), in which all elements of each emission source estimate were defined in the uncertainty analysis. For the remaining sources, EPA employed a simpler methodology as described in further detail below. For natural gas systems, calculations are commonly more complex than simply multiplying an emission factor by an activity factor. For example, the activity data calculation for production site upset emissions from pressure relief valves (PRVs) involves three distinct elements: count of PRVs associated with all gas wells as originally estimated in the 1996 EPA-Radian study and updated by EPA in 2007; NEMS region-specific fraction of all gas wells for a given year; and the ratio of total gas wells in a given year compared to that in year 1992.

Table 1 provides the twelve top-emitting natural gas sources along with their year 1992 emissions used in the 2011 uncertainty analysis. As can be observed from the table, EPA examined individual emission sources at the NEMS region level for the production segment (due to the calculation methodology varying by region for many production sources), and at the national level for other segments.

Although the top twelve sources were identified based on the year 2009 emissions estimate, EPA conducted the actual uncertainty analysis on estimates for the year 1992, because it was the base year (i.e., year of key input data collection) of the emissions and activity data estimates for many emission sources. To define the uncertainty model parameters (steps 1 and 2 in Figure 1) of every element of the activity and emission factors for the top twelve sources, EPA combined judgments of an industry expert and a statistical expert along with data published in the 1996 EPA-Radian study. For all top twelve sources as well as the remaining sources (that were analyzed using a simplified methodology), EPA assumed a lognormal PDF as default. Then using the Monte Carlo simulation method in @RISK (steps 3 through 5 in Figure 1), EPA calculated the upper and lower estimates representing the 95% confidence interval for each of the top twelve sources listed in Table 1.

These top twelve sources contributed nearly 49% of the total 1992 methane emissions from natural gas systems. For the hundreds of non-top-twelve sources collectively representing approximately half of natural gas systems emissions, EPA evaluated uncertainty using a simplified method which involved assigning uncertainty values to each source activity and emission factor but not to the activity drivers associated with that source. This simplified method does not completely capture the uncertainty associated with all the sources but does ensure that the uncertainty of the sources that are not among the top twelve is represented; assuming activity drivers have associated uncertainty, this approach would lead to underestimating overall uncertainty. Also, using the Monte Carlo simulation method in @RISK, EPA calculated the upper and lower estimates representing the 95% confidence interval for the non-top twelve sources collectively.

To develop the uncertainty bounds for 1992, EPA compiled the upper and lower modeled estimates for the top twelve and non-top twelve sources and then translated these figures to +/- percentages of the GHGI estimate. EPA calculated the 95% confidence interval for natural gas systems emissions for 1992 at -19% and +30% of the GHGI-reported value. EPA then assumed that the 95% confidence interval for each of the other years was equivalent to these +/- percentage values.

Table 1. Top 12 Emission Sources for Natural Gas Systems in Previous (2011) Uncertainty Analysis for GHG Inventory Published in 2011 (2011 GHGI)

Source	2011 GHGI CH_4 Emissions, year 1992 (MMT CO_2e)
Liquids Unloading (production segment, North East region)	34.8
Reciprocating Compressor Fugitives (transmission segment)	18.6
Liquids Unloading (production segment, Gulf Coast region)	17.5
Reciprocating Compressor Fugitives (processing segment)	8.1
Liquids Unloading (production segment, Mid Central region)	7.9
Shallow Water Offshore Platforms (production segment)	7.4
Wet Seal Centrifugal Compressors (transmission segment)	6.2
Pneumatic Controllers (production segment, Mid Central region)	5.6
Liquids Unloading (production segment, Rocky Mountain region)	3.4
Pneumatic Controllers (production segment, Rocky Mountain region)	2.1
Unconventional Gas Well Workovers (production segment, Rocky Mountain region)	0.0
Unconventional Gas Well Workovers (production segment, South West region)	0.0
Other Emission Sources	116.8
Total Potential Emissions from Natural Gas Systems (before Gas STAR reductions)	**228.4**

Basis of the 2011 GHGI Petroleum Systems Uncertainty Analysis

The 2011 GHGI uncertainty analysis for petroleum systems included a detailed analysis for the seven top-emitting sources in 2009 (ranked according to the 2011 GHGI estimates), in which all elements of each emission source estimate were defined in the uncertainty analysis. As with natural gas systems, calculations of emission estimates for petroleum systems sources are more complex than simply multiplying an emission factor by an activity factor. They usually involve additional data elements for which PDFs need to be estimated for uncertainty analysis purposes.

Table 2 provides the seven top-emitting petroleum sources along with their year 1995 emissions used in the uncertainty analysis.

Although the top seven sources were identified based on the year 2009 emissions estimate, EPA conducted the actual uncertainty analysis using estimates for the year 1995, because it was the base year (i.e., year of key input data collection) of the emissions and activity data estimates for many emission sources. In the 2011 GHGI, the above seven sources contributed nearly 94% of the total 1995 methane emissions from petroleum systems. To define the uncertainty model parameters (steps 1 and 2 in Figure 1) of every element of the activity and emission factors for the top seven sources, EPA combined judgments of an industry expert and a statistical expert along with data published in the 1999 EPA-Radian study. For all top seven sources, EPA assumed a lognormal PDF as default (except for oil tanks, for which EPA assumed a combination of normal and triangular distributions to represent inputs). Then, using the Monte Carlo simulation method in @RISK (steps 3 through 5 in Figure 1), EPA calculated the upper and lower estimates representing the 95% confidence interval for each of the top seven sources.

Table 2. Top Seven Emission Sources for Petroleum Systems in Previous (2011) Uncertainty Analysis for GHG Inventory Published in 2011 (2011 GHGI)

Source	2011 GHGI CH_4 Emissions, year 1995 (MMT CO_2e)
Shallow Water Offshore Platforms (production segment)	16.1
High-Bleed Pneumatic Controllers (production segment)	9.0

Oil Tanks (production segment)	5.6
Low-bleed Pneumatic Controllers (production segment)	2.6
Gas Engines (production segment)	2.0
Chemical Injection Pumps (production segment)	1.3
Deep Water Offshore Platforms (production segment)	0.4
Other Emission Sources	2.6
Total Emissions from Petroleum Systems	**39.7**

For petroleum systems, the 2011 analysis assumed that uncertainty for these top seven emissions sources is an indication of uncertainty for the remaining emissions sources, and therefore extended the uncertainty of aggregate emissions estimates for the top seven emissions sources to the remaining sources. With that assumption, the overall uncertainty combining the top seven sources and remaining sources was re-estimated using the @RISK model.

To develop the uncertainty bounds for 1995, the upper and lower modeled estimates for the source category were translated to +/- percentages of the GHGI estimate. EPA calculated that for 1995, the 95% confidence interval for petroleum systems emissions is -24% and +149% of the GHGI-reported value. These +/- percentage values were assumed to represent the 95% confidence interval for all other years of the time series.

<u>**Updated Uncertainty Analyses for Natural Gas and Petroleum Systems in the 2018 GHGI**</u>

In recent years, EPA has made significant revisions to the GHGI methodology to use updated activity and emissions data in calculating estimates for recent years of the time series. For the 2016 and 2017 GHGIs, EPA used multiple recently published studies as well as GHGRP Subpart W data to revise the emission factors and activity data for many natural gas systems emission sources and petroleum systems production segment emission sources. To update its characterization of uncertainty, EPA has conducted a draft quantitative uncertainty analysis similar to that conducted for the 2011 GHGI using the IPCC-recommended Approach 2 methodology (Monte Carlo Simulation technique).

Approach to Estimating Source-specific Uncertainty

For its updated analysis, as in the 2011 GHGI analysis, EPA first identified a select number of “top” emission sources for each source category. Table 3 and Table 4 show the top emission sources that cover at least 75% of gross emissions in natural gas and petroleum systems for year 2015, respectively, based on the 2017 GHGI. The top 14 natural gas systems sources cover approximately 77% of total source category emissions for the year 2015; the top 5 petroleum systems sources cover 79% of total source category emissions for the year 2015. EPA seeks stakeholder feedback on how many top emission sources to include in the detailed uncertainty analysis for each source category (see next section).

Table 3. Top 14 Natural Gas Systems CH_4 Emission Sources in the 2017 GHGI

Emission Source (segment)	Year 2015 Gross Emissions (MMT CO_2 Eq.)	% of Source Category Emissions
G&B stations (production)	49.2	27%
Pneumatic controllers (production)	25.5	14%
Station total fugitives (transmission)	14.3	8%
Engine combustion (transmission)	6.3	3%
Engine combustion (production)	6.3	3%
Engine combustion (processing)	5.8	3%
Liquids unloading (production)	5.2	3%
G&B episodic events (production)	4.9	3%
Pipeline venting (transmission and storage)	4.6	3%
G&B pipeline leaks (production)	4.0	2%
Station venting (transmission)	3.8	2%
Shallow water offshore platforms (production)	3.1	2%
Chemical injection pump venting (production)	3.0	2%
Separator fugitives (production)	2.9	2%
Subtotal, Top Sources	***139.1***	***77%***
Natural Gas Systems Total	**181.1**	**100%**

Table 4. Top 5 Petroleum Systems CH_4 Emission Sources in the 2017 GHGI

Emission Source (segment)	Year 2015 Gross Emissions (MMT CO_2 Eq.)	% of Source Category Emissions
Pneumatic controllers (production)	18.6	48%
Shallow water offshore platforms (production)	4.2	11%
Associated gas venting and flaring (production)	3.7	9%
Engine combustion (production)	2.3	6%
Oil tanks (production)	2.0	5%
Subtotal, Top Sources	***30.8***	***79%***
Petroleum Systems Total	**39.0**	**100%**

Next, EPA developed uncertainty model parameters based on published studies, GHGRP Subpart W data, expert consultation, and/or the 2011 uncertainty analysis for each of the top emission sources. Appendix A documents the uncertainty parameters values for the top sources in natural gas and petroleum systems used in conducting the Monte Carlo analysis, including:

- Basis of the GHGI value,
- Basis of the uncertainty parameter values,
- PDF,
- Point estimate (i.e., estimate in GHGI which is modeled as the mean or most likely value), and
- Uncertainty range (e.g., standard deviation or minimum and maximum).

If the modeling input (e.g., emission factor) was based on GHGRP subpart W data, EPA's general approach was to employ bootstrapping to determine the shape and other parameters of the sampling distribution of the mean value. The bootstrapping analysis enabled the determination of the PDF (e.g., normal, lognormal, triangular, etc.) as well as applicable statistical parameters (e.g., standard deviation, maximum, minimum, etc.) needed for the Monte Carlo simulation. Most model inputs from GHGRP were determined to have a normal PDF as expected due to the Central Limit Theorem.[2] For modeling inputs based on recently published studies (i.e., Marchese et al. and

[2] GHGRP subpart W data sets contain information (e.g., methane emissions, number of pneumatic controllers, etc.) submitted by hundreds of facilities which generally include the majority of activity in each industry segment (e.g., natural gas

Zimmerle et al.), uncertainty information available in the study were directly used for the EPA's analyses.[3] For modeling inputs based on older data sets (e.g., EPA/GRI study) or "macro parameters," that are used as inputs to several emission source estimates (e.g., total active well count), EPA generally treated the input as a point estimate and referred to published estimates, the previous uncertainty analysis, and expert judgment to estimate upper and lower bounds. For input values obtained from certain data sources—for example, EIA or DrillingInfo—EPA assigned default uncertainty bounds as documented in the Appendix A tables; EPA specifically seeks feedback on these default bounds in the next section.

Approach to Estimating Aggregate Uncertainty for Total CH_4 Emissions Across All Sources

In response to stakeholder feedback, EPA considered multiple approaches to: 1) estimating uncertainty for non-top sources; and 2) combining uncertainty for top and non-top sources to determine uncertainty for total CH_4 emissions across all sources.

Estimating Uncertainty for Non-top Sources

- Simple Summation Approach: The uncertainty bounds for total CH_4 emissions from non-top sources can be set equal to the approximated uncertainty bounds for total CH_4 emissions from all top sources combined, which are computed using a simple summation approach. This approach was presented in the previous version of this memo.

- Propagation of Error Approach: Similar to the simple summation approach, the uncertainty bounds for total CH_4 emissions from non-top sources can be set equal to the approximated uncertainty bounds for total CH_4 emissions from all top sources combined, which are computed using the propagation of error formulas (IPCC Approach 1[4]). Propagation of error formulas are most suitable when errors for source-specific estimates being combined are uncorrelated and random. However, because certain source-specific parameters are used in estimating emissions from multiple top sources in both natural gas and petroleum systems, the error terms are expected to be correlated.

- Monte Carlo Approach: The uncertainty bounds for total CH_4 emissions from non-top sources can be estimated using a multi-step process that relies on Monte Carlo simulation as described below. Due to the existence of unmodeled sources, this approach is based on IPCC Approach 2, and similar to what EPA used in the 2011 GHGI petroleum systems uncertainty assessment.
    - *Step 1* - The uncertainty bounds for total CH_4 emissions from all top sources combined is determined using Monte Carlo simulation,
    - *Step 2* - The probability density function (PDF) (i.e., normal, lognormal, etc.) along with its parameters (e.g., mean, standard deviation) of the total CH_4 emissions from all top sources combined is derived by evaluating the obtained distribution in Step 1,
    - *Step 3* – The PDF for total CH_4 emissions from non-top sources can be approximated by the PDF obtained in Step 2 such that the adjusted mean corresponds to the estimated total CH_4 emissions from non-top sources and the standard deviation corresponds to the product of the ratio of the estimated total CH_4 emissions from non-top sources to-the estimated total CH_4 emissions from all top sources combined.

production). Hence, the bootstrap samples drawn from these GHGRP subpart W data sets were sufficiently large for the purposes of the CLT.

[3] In most cases, the needed uncertainty information (e.g., standard deviation, PDF type) had to be statistically imputed using information provided in the study. For example, when a study only reported 90% confidence bounds and the shape of the PDF, the standard deviation of the distribution needed for the Monte Carlo analysis had to be back-calculated.

[4] See discussion beginning in Volume 1, Chapter 3, Section 3.2.3 of 2006 IPCC Guidelines for National Greenhouse Gas Inventories: http://www.ipcc-nggip.iges.or.jp/public/gp/english/6_Uncertainty.pdf.

- *Step 4* – The uncertainty bounds around total CH_4 emissions from non-top sources can be estimated using Monte Carlo simulation.

Combining Uncertainty for Top and Non-top Sources to Determine Uncertainty for Total CH_4 Emissions Across All Sources

- Simple Summation Approach: The uncertainty bounds for total CH_4 emissions from top and non-top sources are combined using a simple summation approach. This results in the same 95% uncertainty bounds for the top, non-top, and overall (i.e., sum of total CH_4 emissions from top and non-top sources) CH_4 emissions. Results from this approach were presented in a previous version of this memo.

- Propagation of Error Approach: The uncertainty bounds for total CH_4 emissions from top and non-top sources can be combined by applying propagation of error formulas (IPCC Approach 1). Even though this approach is easily implementable, it is predicated on the assumption that errors for total CH_4 emissions from top and non-top sources are uncorrelated and random.

- Monte Carlo Approach: The uncertainty bounds for total CH_4 emissions from top and non-top sources can be combined by using Monte Carlo simulations (IPCC Approach 2) where the PDF for total CH_4 emissions from non-top sources is estimated as noted in the Monte Carlo Approach described above.

Results

Table 5 and Table 6 below summarize calculated source category level uncertainty estimates for natural gas and petroleum systems, respectively, based on year 2015 emissions from the 2017 GHGI. Note that the reported uncertainty intervals only reflect those uncertainties that EPA has been able to quantify and do not incorporate considerations such as modeling uncertainty, data representativeness, measurement errors, misreporting or misclassification.

According to the IPCC guidelines, if inventory source category uncertainties are correlated, the use of a stochastic simulation (the Monte Carlo method) is preferable (i.e., IPCC Approach 2) for combining uncertainties provided that the PDFs and correlation structure of the source-specific uncertainties are quantified. Thus, EPA is considering using the IPCC Approach 2 for both estimating uncertainty for non-top sources and combining uncertainty for top and non-top sources for the draft 2018 GHGI.

Table 5. Summary of Natural Gas Systems Year 2015 CH_4 Uncertainty Draft Update Results[a]

Emission Source		Mean Year 2015 Emissions (MT CO_2 Eq.)	2.5% Lower Bound of Mean Year 2015 Emissions (MT CO_2 Eq.)		97.5% Upper Bound of Mean Year 2015 Emissions (MT CO_2 Eq.)	
			Value	%	Value	%
G&B Stations (Production)		49,192,568	44,648,570	-9%	53,729,999	9%
Pneumatic Controllers (Production)	High-bleed Pneumatic Controllers	2,368,036	1,120,764	-53%	3,993,889	69%
	Intermittent-bleed Pneumatic Controllers	22,380,215	12,772,278	-43%	33,786,265	51%
	Low-bleed Pneumatic Controllers	757,911	122,599	-84%	1,585,524	109%
Station Total Fugitives (Transmission)[b]	Station, Incl. Compressor Components	2,934,282	1,943,931	-34%	4,265,232	45%
	Reciprocating Compressors	8,484,047	5,290,921	-38%	13,237,091	56%
	Centrifugal Compressor (Wet Seals)	1,424,742	867,790	-39%	2,301,693	62%
	Centrifugal Compressor (Dry Seals)	1,467,867	873,408	-40%	2,370,718	62%
Engine Combustion (Production)		6,323,058	456,914	-93%	22,434,220	255%
Engine Combustion (Transmission)		6,299,036	2,088,945	-67%	8,384,561	33%
Engine Combustion (Processing)		5,806,032	1,959,080	-66%	7,438,841	28%
G&B Episodic Events (Production)		4,879,055	189,869	-96%	26,068,511	434%
Pipeline Venting (Transmission and Storage)		4,590,999	1,210,468	-74%	6,310,292	37%
G&B Pipeline Leaks (Production)		4,038,975	1,537,376	-62%	6,857,736	70%
Station Venting (Transmission)		3,849,139	735,035	-81%	7,436,119	93%
Chemical Injection Pump Venting (Production)		3,034,943	1,999,797	-34%	4,106,240	35%
Liquids Unloading With Plunger Lift (Production)		3,016,831	2,522,890	-16%	3,516,669	17%
Liquids Unloading Without Plunger Lift (Production)		2,211,607	1,689,719	-24%	2,749,717	24%
Shallow Water Offshore Platforms (Production)		3,086,499	453,544	-85%	5,728,239	86%
Separator Fugitives (Production)		2,924,891	1,758,786	-40%	4,162,242	42%
Total for Sources Modeled in Uncertainty Assessment						
Simple Summation		**139,070,729**	**84,242,680**	**-39%**	**220,463,797**	**+59%**
Propagation of Error Approach		**139,070,729**	**123,166,394**	**-11%**	**169,558,504**	**+22%**
Monte Carlo Approach		**139,070,729**	**115,487,232**	**-17%**	**167,501,749**	**+20%**
Total for Sources Not Modeled in Uncertainty Assessment						
Simple Summation		**23,354,601**	**14,147,148**	**-39%**	**37,023,204**	**+59%**
Propagation of Error Approach		**23,354,601**	**20,683,734**	**-11%**	**28,474,512**	**+22%**
Monte Carlo Approach		**23,354,601**	**19,141,032**	**-18%**	**28,226,024**	**+21%**
Source Category Total						
Simple Summation		**162,425,331**	**98,389,827**	**-39%**	**257,487,001**	**+59%**
Propagation of Error Approach		**162,425,331**	**146,298,291**	**-10%**	**193,340,018**	**+19%**
Monte Carlo Approach		**162,425,331**	**138,228,918**	**-15%**	**190,790,170**	**+17%**

a – Refer to footnote 'd' of Table A1 for explanation of how a key modeling parameter was updated since the previously presented analysis, impacting calculated bounds shown in this table for transmission station fugitive sources.

Table 6. Summary of Petroleum Systems Year 2015 CH_4 Uncertainty Draft Update Results

Emission Source		Mean Year 2015 Emissions (MT CO2 Eq.)	2.5% Lower Bound of Mean Year 2015 Emissions (MT CO2 Eq.)		97.5% Upper Bound of Mean Year 2015 Emissions (MT CO2 Eq.)	
			Value	%	Value	%
Pneumatic Controllers (Production)	High-bleed Pneumatic Controllers	2,126,086	638,737	-70%	4,181,207	97%
	Intermittent-bleed Pneumatic Controllers	15,887,354	7,755,094	-51%	26,307,172	66%
	Low-bleed Pneumatic Controllers	619,806	83,942	-86%	1,442,226	133%
Shallow Water Oil Platforms (Production)	Shallow Water Oil Platforms	4,207,887	1,053,746	-75%	11,552,844	175%
Associated Gas Flaring & Venting (Production)	Associated Gas Flaring	2,642,647	1,209,503	-54%	4,459,852	69%
	Associated Gas Venting	1,062,962	75,820	-93%	2,626,185	147%
Oil Tanks (Production)	Large Oil Tanks with Flares	202,495	84,691	-58%	340,088	68%
	Large Oil Tanks with VRU	99,012	12,738	-87%	209,784	112%
	Large Oil Tanks without Controls	1,443,504	593,070	-59%	2,511,470	74%
	Small Oil Tanks with Flares	1,726	280	-84%	4,830	180%
	Small Oil Tanks without Controls	115,514	4,828	-96%	386,500	235%
	Large Oil Tank Separators with Malfunctioning Dump Valves	149,605	21,233	-86%	533,238	256%
Gas Engine Combustion (Production)	Gas Engine Combustion	2,254,932	36,467	-98%	7,215,509	220%
Total for Sources Modeled in Uncertainty Assessment						
Simple Summation		**30,813,532**	**11,570,150**	**-62%**	**61,770,904**	**+100%**
Propagation of Error Approach		**30,813,532**	**21,469,826**	**-30%**	**44,926,168**	**+46%**
Monte Carlo Approach		**30,813,532**	**19,504,086**	**-37%**	**44,868,886**	**+46%**
Total for Sources Not Modeled in Uncertainty Assessment						
Simple Summation		**9,062,042**	**3,402,699**	**-62%**	**18,166,386**	**+100%**
Propagation of Error Approach		**9,062,042**	**6,314,124**	**-30%**	**13,212,468**	**+46%**
Monte Carlo Approach		**9,062,042**	**5,551,116**	**-39%**	**13,716,381**	**+51%**
Source Category Total						
Simple Summation		**39,875,574**	**14,972,849**	**-62%**	**79,937,290**	**+100%**
Propagation of Error Approach		**39,875,574**	**30,136,175**	**-24%**	**54,585,861**	**+37%**
Monte Carlo Approach		**39,875,574**	**27,292,147**	**-32%**	**54,063,731**	**+36%**

Requests for Stakeholder Feedback

EPA seeks stakeholder feedback on the following considerations in developing an uncertainty analysis for the 2018 GHGI:

1. The following elements of EPA's general approach to uncertainty analysis:
   a. Performing a detailed uncertainty analysis for "top" sources that cover a specified percent (e.g., 75%) of gross emissions in natural gas (Table 3) and petroleum systems (Table 4) for year 2015, and extending the uncertainty of aggregate emissions estimates for the top emissions sources to the remaining sources (as illustrated in Table 5 and Table 6).
   b. Using a Monte Carlo Approach to calculate source category total uncertainty (as illustrated in Table 5 and Table 6).
   c. Calculating uncertainty for a select year, then assuming the same relative uncertainty as the 95% confidence interval for all other years of the time series.

2. The availability of additional information and data from statistical and industry experts that are relevant to characterizing the uncertainty parameters for the sources listed in Table 3 and Table 4 and detailed in Appendix A.

3. How to compare estimated uncertainty ranges from different studies and measurement/calculation approaches, and important caveats and considerations. Appendix B of this memorandum compares the GHGI uncertainty ranges to uncertainty characterizations presented in several recently published studies. Which other studies have information on uncertainty that could be compared with the GHGI uncertainty ranges?

4. The uncertainty ranges in the GHGI reflect the uncertainty in the available emissions and activity data. Any systematic errors that may arise because of imperfections in conceptualization, models, measurement techniques, or other systems for recording or making inferences from data are not reflected in the uncertainty analysis because we lack information on them. Such errors, if they exist, could bias the results leading to either under- or over-estimates. The EPA requests additional information to characterize systematic errors in the GHGI, how and where these could be described in the GHGI, and how they could be incorporated into the uncertainty analysis.

5. Additional steps that could be taken to improve characterization of the PDFs. Most model inputs for this uncertainty assessment were determined from our analysis to have a normal PDF, as expected due to the Central Limit Theorem (CLT). As discussed earlier in this memo, the CLT states that the means of random samples drawn from a population with any type of distribution will be normally or near-normally distributed if the sample size is large enough (Mendenhall, Wackerly, & Scheaffer, 1990). The EPA seeks feedback on general approaches to consider for data sources for which sample sizes are comparatively small; the sampling methodology could be biased (e.g., may not result in a nationally representative sample); or only certain statistical parameters (e.g., mean and standard deviation) rather than the full underlying dataset were available in the source material.

6. While they do not provide overall uncertainty estimates for CH_4 emissions from natural gas systems, Brandt et al. (2016) argue that uncertainty ranges in the previous GHG Inventories might be too narrow for some source categories due to existence of extreme distributions in natural gas data

sets.[5] EPA seeks feedback on approaches that would improve characterization of extreme distributions for the GHGI uncertainty analysis.

7. As shown in tables A1 and A2, EPA has assigned default uncertainty bounds for point estimates obtained from certain data sources. EPA seeks feedback on these values:
   a. National estimates of gas production, gas consumption, and oil production (EIA): +/- 1%
   b. National estimate of transmission pipeline miles (PHMSA): +/- 1%
   c. National well count estimates (developed by EPA from DrillingInfo data): +/- 5%

8. How improved uncertainty results can be used to target improvements for the GHGI.

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[5] More specifically, they assert that "…(1) heavy-tailed distributions are a pervasive characteristic of natural gas leak size distributions; (2) natural gas leaks are more heavy-tailed than other natural and social phenomena, (3) the largest 5% of leaks are (by median expectation) responsible for over 50% of the leaked methane from a given source category; (4) the recent use of log-normal distributions to model the distribution of leaks within a source category is not supported and systematically underestimates the importance of large emitters; (5) heavier-than-log-normal distributions lead to larger uncertainty than currently included in official estimates; (6) robustly characterizing heavy-tailed distributions will require sample sizes much larger than currently used in most studies; (7) aggregating results across studies to improve accuracy and robustness is statistically challenging."

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Appendix A: Uncertainty Parameter Values for the Top Sources in Natural Gas and Petroleum Systems Used in Conducting Monte Carlo Analysis

As described above, the national emissions estimate associated with a source category is computed as the product of the average emission factor and average activity factor for that source category. Thus, the uncertainty parameters presented in Tables A1 and A2 below are associated with the distribution of these average values; not the distribution of emissions from that source (for more information, see section "Updated Uncertainty Analyses for Natural Gas and Petroleum Systems in the 2018 GHGI: Approach" above).

Table A1. Overview of Natural Gas Systems Year 2015 CH_4 Uncertainty Inputs for @RISK Modeling

Emissions Calculation Input	Input Basis [a]	Uncertainty Basis	PDF	Mean or Point Estimate or Most Likely Value	Standard Deviation [b]	Lower Bound or Minimum [c]	Upper Bound or Maximum [c]
Macro Parameters							
National active gas well count, 2015	DrillingInfo	Expert Judgment, 5%	Uniform	421,893	-	400,798	442,988
Methane content of natural gas for NE region	GTI (2001) & EIA	Statistical analysis of Allen et al. (2013) methane content data	Normal	0.865	0.008	-	-
Methane content of natural gas for MC region	GTI (2001) & EIA	Statistical analysis of Allen et al. (2013) methane content data	Normal	0.824	0.030	-	-
Methane content of natural gas for RM region	GTI (2001) & EIA	Statistical analysis of Allen et al. (2013) methane content data	Normal	0.774	0.006	-	-
Methane content of natural gas for SW region	GTI (2001) & EIA	Statistical analysis of Allen et al. (2013) methane content data	Normal	0.805	0.013	-	-
Methane content of natural gas for WC region	GTI (2001) & EIA	Statistical analysis of Allen et al. (2013) methane content data	Normal	0.919	0.014	-	-
Methane content of natural gas for GC region	GTI (2001) & EIA	Statistical analysis of Allen et al. (2013) methane content data	Normal	0.888	0.019	-	-
Default methane content of natural gas	EPA/GRI (1996)	Statistical analysis of Allen et al. (2013) methane content data	Normal	0.788	0.008	-	-
Gas Wells for NE Region (2015)	DrillingInfo	Expert Judgment, 5%	Uniform	153,380	-	145,711	161,049
Gas Wells for MC Region (2015)	DrillingInfo	Expert Judgment, 5%	Uniform	79,645	-	75,663	83,627
Gas Wells for RM Region (2015)	DrillingInfo	Expert Judgment, 5%	Uniform	75,689	-	71,905	79,473
Gas Wells for SW Region (2015)	DrillingInfo	Expert Judgment, 5%	Uniform	45,370	-	43,102	47,639
Gas Wells for WC Region (2015)	DrillingInfo	Expert Judgment, 5%	Uniform	2,417	-	2,296	2,538
Gas Wells for GC Region (2015)	DrillingInfo	Expert Judgment, 5%	Uniform	65,392	-	62,122	68,662
G&B Stations (Production)							
scfd/station	Marchese, et al. (2015)	Statistical analysis of study data	Normal	53,066	2,468		
Region Marketed Onshore Production (MMCF), 2015	EIA	EIA publication default, 1%	Uniform	7,499,108	-	7,424,117	7,574,099
National Marketed Onshore Production (BCF), 2012	EIA	EIA publication default, 1%	Uniform	23,531	-	23,295	23,766

Emissions Calculation Input	Input Basis [a]	Uncertainty Basis	PDF	Mean or Point Estimate or Most Likely Value	Standard Deviation [b]	Lower Bound or Minimum [c]	Upper Bound or Maximum [c]
NE Region Marketed Onshore Production (MMCF), 2015	EIA	EIA publication default, 1%	Uniform	4,443,949	-	4,399,509	4,488,388
MC Region Marketed Onshore Production (MMCF), 2015	EIA	EIA publication default, 1%	Uniform	5,087,452	-	5,036,577	5,138,326
RM Region Marketed Onshore Production (MMCF), 2015	EIA	EIA publication default, 1%	Uniform	2,177,308	-	2,155,535	2,199,081
WC Region Marketed Onshore Production (MMCF), 2015	EIA	EIA publication default, 1%	Uniform	521,702	-	516,485	526,919
GC Region Marketed Onshore Production (MMCF), 2015	EIA	EIA publication default, 1%	Uniform	7,554,759	-	7,479,211	7,630,306
Pneumatic Controllers (Production)							
scfd/controller (low bleed)	Subpart W RY2015 & EPA/GRI (1996)	Statistical analysis of reported Subpart W data; PDF per expert judgment; statistical parameters for emission rate imputed using the reported 90% confidence bound in EPA/GRI study	Normal	23	10	-	-
scfd/controller (high bleed)	Subpart W RY2015 & EPA/GRI (1996)	Statistical analysis of reported Subpart W data; PDF per expert judgment; statistical parameters for emission rate imputed using the reported 90% confidence bound in EPA/GRI study	Normal	622	100	-	-
scfd/controller (intermittent bleed)	Subpart W RY2015 & EPA/GRI (1996)	Statistical analysis of reported Subpart W data; PDF per expert judgment; statistical parameters for emission rate imputed using the reported 90% confidence bound in EPA/GRI study	Normal	218	42	-	-
Fraction of total controllers that are low bleed	Subpart W RY2015	Statistical analysis of reported data	Normal	0.24	0.05	-	-
Fraction of total controllers that are high bleed	Subpart W RY2015	Statistical analysis of reported data	Normal	0.03	0.01	-	-
Fraction of total controllers that are intermittent bleed	Subpart W RY2015	Statistical analysis of reported data	Normal	0.73	0.05	-	-
Total controllers per well	Subpart W RY2015	Statistical analysis of reported data	Normal	1.88	0.23	-	-

Emissions Calculation Input	Input Basis [a]	Uncertainty Basis	PDF	Mean or Point Estimate or Most Likely Value	Standard Deviation [b]	Lower Bound or Minimum [c]	Upper Bound or Maximum [c]
Station Total Fugitives (Transmission)							
scfd/station	Zimmerle, et al. (2015)	PDF per expert judgment; statistical parameters imputed using the reported 95% confidence bound	Normal	9,104	1,269	-	-
Station scaling factor for national count based on subpart W count	Zimmerle, et al. (2015); Subpart W RY2012	Statistical analysis of study data[d]	Lognormal	3.52	0.5085	-	-
Engine Combustion (Transmission)							
scf/HPhr	EPA/GRI (1996)	PDF per expert judgment; statistical analysis of study data	Triangular	0.240	-	0.045	0.323
1992 MMHPhr	EPA/GRI (1996)	PDF per expert judgment; statistical parameters imputed using the reported 90% confidence bound	Normal	40,380	4,194	-	-
2015 Total National gas Consumption (tril ft^3 / yr)	EIA	EIA publication default, 1%	Uniform	27	-	27	28
1992 Total National gas Consumption (tril ft^3 / yr)	EIA	EIA publication default, 1%	Uniform	20	-	20	20
Engine Combustion (Production)							
scf/HPhr	EPA/GRI (1996)	PDF per expert judgment; statistical analysis of study data	Triangular	0.240	-	0.045	0.323
MMHPhr (for All gas wells in 1992)	EPA/GRI (1996)	PDF per expert judgment; statistical parameters imputed using the reported 90% confidence bound	Lognormal	27,460	32,531		
Total Gas Wells (2015) (excluded NE)	DrillingInfo	Expert Judgment, 5%	Uniform	268,513	-	255,087	281,939
Total Gas Wells (1992) (excluded NE)	DrillingInfo	Expert Judgment, 5%	Uniform	140,758	-	133,720	147,796
Engine Combustion (Processing)							
scf/HPhr	EPA/GRI (1996)	PDF per expert judgment; statistical analysis of study data	Triangular	0.240	-	0.045	0.323
MMHPhr/plant	Subpart W RY2015	Statistical analysis of reported data	Normal	75.3	4.9	-	-
2015 national plant count	O&GJ (2014)	O&GJ publication default, 1%	Uniform	667	-	660	674
Liquids Unloading (Production)							
Fraction of wells that vent using plungers	Subpart W RY2015	Statistical analysis of reported data	Normal	0.100	0.008	-	-
Fraction of wells that vent without using plungers	Subpart W RY2015	Statistical analysis of reported data	Normal	0.068	0.008	-	-
scfy/plunger well	Subpart W RY2015	Statistical analysis of reported data	Normal	148,589	966	-	-
scfy/non-plunger well	Subpart W RY2015	Statistical analysis of reported data	Normal	160,411	562	-	-

Emissions Calculation Input	Input Basis [a]	Uncertainty Basis	PDF	Mean or Point Estimate or Most Likely Value	Standard Deviation [b]	Lower Bound or Minimum [c]	Upper Bound or Maximum [c]
G&B Episodic Events (Production)							
Total CH4 Emissions from G&B Episodic Events (Gg/yr), 2012	Marchese, et al. (2015)	PDF per expert judgment; statistical parameters imputed using the reported 95% confidence bound reported for 2012 estimate	Lognormal	169	330	-	-
Marketed Onshore Production (MMCF), 2015	EIA	EIA publication default, 1%	Uniform	27,284	-	27,011	27,557
National Marketed Onshore Production (BCF), 2012	EIA	EIA publication default, 1%	Uniform	23,531	-	23,295	23,766
Pipeline Venting (Transmission and Storage)							
Mscfy/mile	EPA/GRI (1996)	PDF per expert judgment; statistical analysis of study data	Triangular	31.7	-	2.7	47.8
Transmission Pipeline Miles	PHMSA (2015)	PHMSA publication default, 1%	Uniform	301,748	-	298,731	304,765
G&B Pipeline Leaks (Production)							
miles/well for NE Region	EPA/GRI (1996)	PDF per expert judgment; statistical analysis of study data	Normal	0.400	0.071	-	-
miles/well for MC Region	EPA/GRI (1996)	PDF per expert judgment; statistical analysis of study data	Normal	0.620	0.110	-	-
miles/well for RM Region	EPA/GRI (1996)	PDF per expert judgment; statistical analysis of study data	Normal	1.120	0.194	-	-
miles/well for SW Region	EPA/GRI (1996)	PDF per expert judgment; statistical analysis of study data	Normal	1.120	0.195	-	-
miles/well for WC Region	EPA/GRI (1996)	PDF per expert judgment; statistical analysis of study data	Normal	1.120	0.195	-	-
miles/well for GC Region	EPA/GRI (1996)	PDF per expert judgment; statistical analysis of study data	Normal	1.120	0.198	-	-
miles (equally divided for each region)	EPA/GRI (1996)	PDF and mileage variability per expert judgment; statistical analysis of study data	Normal	14,367	3,668	-	-
CH4 emissions, Bcf	EPA/GRI (1996)	Buildup of the four pipeline materials using Monte Carlo sampling informed by the 90% confidence intervals reported in the GRI 1996 documentation.	Normal	6.6	2.1	-	-
miles	EPA/GRI (1996)	PDF per expert judgment; statistical parameters imputed using the reported 90% confidence bound reported	Normal	340,200	20,700	-	-

Emissions Calculation Input	Input Basis [a]	Uncertainty Basis	PDF	Mean or Point Estimate or Most Likely Value	Standard Deviation [b]	Lower Bound or Minimum [c]	Upper Bound or Maximum [c]
Station Venting (Transmission)							
mscfy/station	EPA/GRI (1996)	PDF per expert judgment; statistical analysis of study data	Normal	4,359	1,787	-	-
Station scaling factor for national count based on subpart W count	Zimmerle, et al. (2015); Subpart W RY2012	Statistical analysis of study data[d]	Lognormal	3.52	0.5085	-	-
Chemical Injection Pump Venting (Production)							
# pumps / well	Subpart W RY2015	Statistical analysis of reported data	Normal	0.189	0.033	-	-
scfd/pump	Subpart W RY2015 & EPA/GRI (1996)	Statistical analysis of reported Subpart W data; PDF per expert judgment; statistical parameters for emission rate imputed using the reported 90% confidence bound in EPA/GRI study	Normal	216.4	6.7	-	-
Shallow Water Offshore Platforms (Production)							
scfd/platform	EPA (2015)	Statistical parameters imputed using the reported PDF and 90% confidence bound in 2000 GOADS analysis (EPA (2005))	Normal	8,899	3,873	-	-
Shallow Water Gas Platforms	BOEM (2011) & EPA (2008)	Statistical parameters imputed using the reported standard deviation in 2011 uncertainty analysis (EPA (2010a))	Normal	1,973	17	-	-
Separator Fugitives (Production)							
# separators / well	Subpart W RY2015	Statistical analysis of reported data	Normal	0.685	0.045	-	-
scfd/separator (NE & MC Region)	EPA/GRI (1996)	PDF per expert judgment; statistical analysis of study data	Normal	0.899	0.045	-	-
scfd/separator (except NE & MC Region)	EPA/GRI (1996)	PDF per expert judgment; statistical analysis of study data	Normal	122.016	24.439	-	-

"-" indicates not applicable

a - Refer to the Natural Gas Systems 2018 annex tables (*https://www.epa.gov/ghgemissions/additional-information-oil-and-gas-estimates-1990-2015-ghg-inventory-published-april*) for more detailed documentation of the estimate basis.

b - Applicable for "mean" input values (normal PDF).

c - Lower and upper bounds are applicable for "point estimate" input values (uniform PDF). Minimum and maximum values are applicable for "most likely" input values (triangular PDF).

d - Upon further review, EPA updated the estimated probability density function (PDF) for the station scaling parameter so that the mean of the PDF better corresponded to the estimated mean CH_4 emissions for the source. As a result, the bounds for the sources within this category shifted to the left. The previous station scaling parameter had a lognormal PDF with a mean of 3.52, standard deviation of 0.51, and shift parameter of 1.59. These were determined by fitting a distribution to the original data provided in the Zimmerle et al. study. The shift parameter shifts the whole distribution to the right, in this case. The revised station scaling parameter used in this updated memo still has a lognormal PDF with a mean of 3.52 and a standard deviation of 0.51. However, a value of zero was used for the shift parameter to ensure that the mean of the distribution used in the Monte Carlo analysis was equivalent to the value used in computing the CH_4 emissions for the source. This also better aligned with how the other lognormal PDFs were characterized in the remaining source categories (all with zero-value shift parameters).

Table A2. Overview of Petroleum Systems Year 2015 CH_4 Uncertainty Inputs for @RISK Modeling

Emissions Calculation Input	Input Basis [a]	Uncertainty Basis	PDF	Mean or Point Estimate or Most Likely Value	Standard Deviation [b]	Lower Bound or Minimum [c]	Upper Bound or Maximum [c]
Macro Parameters							
National active oil well count	DrillingInfo	Expert Judgment, 5%	Uniform	586,896	-	557,551	616,241
Pneumatic Controllers (Production)							
scfd/controller (high bleed)	Subpart W RY2015 & EPA/GRI (1996)	Statistical analysis of reported Subpart W data; PDF per expert judgment; statistical parameters for emission rate imputed using the reported 90% confidence bound in EPA/GRI study	Normal	621.73	100.20	-	-
Fraction of total controllers that are high bleed	Subpart W RY2015	Statistical analysis of reported data	Normal	0.03	0.01	-	-
scfd/controller (intermittent bleed)	Subpart W RY2015 & EPA/GRI (1996)	Statistical analysis of reported Subpart W data; PDF per expert judgment; statistical parameters for emission rate imputed using the reported 90% confidence bound in EPA/GRI study	Normal	218.32	41.90	-	-
Fraction of total controllers that are intermittent bleed	Subpart W RY2015	Statistical analysis of reported data	Normal	0.70	0.07	-	-
scfd/controller (low bleed)	Subpart W RY2015 & EPA/GRI (1996)	Statistical analysis of reported Subpart W data; PDF per expert judgment; statistical parameters for emission rate imputed using the reported 90% confidence bound in EPA/GRI study	Normal	22.85	9.51	-	-
Fraction of total controllers that are low bleed	Subpart W RY2015	Statistical analysis of reported data	Normal	0.26	0.07	-	-
Total controllers per well	Subpart W RY2015	Statistical analysis of reported data	Normal	1.002	0.195	-	-
Shallow Water Offshore Platforms (Production)							
scfd CH4/platform	EPA (2015)	Statistical parameters imputed using the reported PDF and 90% confidence bound in 2000 GOADS analysis (EPA (2005))	Lognormal	16,552	11,146	-	-
Total number shallow water GOM platforms	BOEM (2011) & EPA (2008)	Statistical parameters imputed using the reported standard deviation in 2011 uncertainty analysis (EPA (2010b))	Normal	1,447	10.45	-	-

Emissions Calculation Input	Input Basis [a]	Uncertainty Basis	PDF	Mean or Point Estimate or Most Likely Value	Standard Deviation [b]	Lower Bound or Minimum [c]	Upper Bound or Maximum [c]
Oil Tanks (Production)							
scf/bbl (large with flare)	Subpart W RY2015	Statistical analysis of reported data	Normal	0.35	0.10	-	-
throughput fraction (large with flare)	Subpart W RY2015	Statistical analysis of reported data	Normal	0.55	0.05	-	-
scf/bbl (large with VRU)	Subpart W RY2015	Statistical analysis of reported data	Normal	0.47	0.21	-	-
throughput fraction (large with VRU)	Subpart W RY2015	Statistical analysis of reported data	Normal	0.201	0.04	-	-
scf/bbl (large uncontrolled)	Subpart W RY2015	Statistical analysis of reported data	Normal	7.90	2.18	-	-
throughput fraction (large uncontrolled)	Subpart W RY2015	Statistical analysis of reported data	Normal	0.18	0.03	-	-
scf/bbl (small with flare)	Subpart W RY2015	Statistical analysis of reported data	Lognormal	0.088	0.050	-	-
throughput fraction (small with flare)	Subpart W RY2015	Statistical analysis of reported data	Normal	0.019	0.007	-	-
scf/bbl (small uncontrolled)	Subpart W RY2015	Statistical analysis of reported data	Lognormal	2.3	1.4	-	-
throughput fraction (small uncontrolled)	Subpart W RY2015	Statistical analysis of reported data	Normal	0.05	0.02	-	-
scf/bbl (malfunctioning dump valves)	Subpart W RY2015	Statistical analysis of reported data	Lognormal	0.15	0.15	-	-
throughput fraction (malfunctioning dump valves)	Subpart W RY2015	Statistical analysis of reported data	Normal	0.932	0.025	-	-
% National throughput managed by tanks	Subpart W RY2015	Statistical analysis of reported data	Normal	0.63	0.07	-	-
National oil production	EIA	EIA publication default, 1%	Uniform	3.44E+09	-	3.41E+09	3.48E+09
Associated Gas Venting and Flaring (Production)							
Fraction of total wells with venting or flaring	Subpart W RY2015	Statistical analysis of reported data	Normal	0.12	0.02	-	-
Fraction of wells with associated gas that flare	Subpart W RY2015	Statistical analysis of reported data	Normal	0.83	0.06	-	-
mscfy/flaring well	Subpart W RY2015	Statistical analysis of reported data	Normal	95	21	-	-
fraction of wells with associated gas that vent	Subpart W RY2015	Statistical analysis of reported data	Normal	0.17	0.06	-	-
mscfy/venting well	Subpart W RY2015	Statistical analysis of reported data	Normal	193	94	-	-

Emissions Calculation Input	Input Basis [a]	Uncertainty Basis	PDF	Mean or Point Estimate or Most Likely Value	Standard Deviation [b]	Lower Bound or Minimum [c]	Upper Bound or Maximum [c]
Gas Engine Combusion (Production)							
scf/HPhr	EPA/GRI (1996)	Statistical analysis of GRI data (NETL, 2016)	Triangular	0.24	-	0.04	0.32
compressors	EPA/Radian (1999)	PDF per expert judgment; statistical parameters imputed using the reported 90% confidence bound calculated for 1993 estimate	Normal	3,097	1,522	-	-
MMhp-hr/compressor	EPA/Radian (1999)	PDF per expert judgment; statistical parameters imputed using the reported 90% confidence bound calculated for 1993 estimate	Lognormal	6.30	4.95	-	-

"-" indicates not applicable

a - Refer to the Petroleum Systems 2017 annex tables (*https://www.epa.gov/ghgemissions/additional-information-oil-and-gas-estimates-1990-2015-ghg-inventory-published-april*) for more detailed documentation of the estimate basis.

b - Applicable for "mean" input values (normal PDF).

c - Lower and upper bounds are applicable for "point estimate" input values (uniform PDF). Minimum and maximum values are applicable for "most likely" input values (triangular PDF).

Appendix A: References for Tables A1 and A2

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Appendix B: Comparison to Recently Published Studies

Large amounts of data and information on natural gas and petroleum systems have recently become available, through the Greenhouse Gas Reporting Program (GHGRP) and external studies. In general, there are two major types of studies related to oil and gas GHG data: “bottom up” studies that focus on measurement or quantification of emissions from specific activities, processes and equipment (e.g., GHGRP data), and “top down” studies that focus on verification of estimates (e.g., aircraft and satellite studies). The first type of study can lead to direct improvements to or verification of GHGI estimates. The GHG Inventory estimates for oil and gas underwent extensive updates in recent years using data from these types of studies. The second type of study can provide general indications on potential over- and under-estimates. EPA reviews both types of studies for data that can inform GHGI updates. In this section, we compare the updated draft quantitative GHGI uncertainty estimates for CH_4 emissions from natural gas and petroleum systems, using the ranges detailed in this memorandum and developed for the 2018 GHGI, to those reported in recently published studies that include a bottom up inventory component (see Tables B1 and B2). While both top down and bottom up studies often include assessments of uncertainty, a comparison of uncertainty information from studies that use a top down approach was not developed for this memorandum, and would require further considerations.

All studies reviewed for uncertainty information used Monte Carlo simulation technique to examine uncertainty bounds for the estimates reported, which is in line with the IPCC recommended Approach 2 methodology. The uncertainty ranges in the studies listed in Tables B1, B2, and B3 differ from those of EPA. However, it is difficult to extrapolate uncertainty ranges from these studies to apply to the GHGI estimates because the GHGI source category level uncertainty analysis is not directly comparable to source- or segment-specific uncertainty analyses in these studies. Further, the methodologies and data sources used in estimating CH_4 emissions in these studies often differ significantly from the studies underlying GHGI methodologies. For example, the GRI/EPA study generally had smaller sample sizes and more rudimentary techniques for developing nationally-applicable emissions and activity factors from the collected data than the more recent bottom up studies that were used for 2015 estimates in the 2017 GHGI.

Table B1. Comparison of Quantitative Uncertainty Estimates for CH_4 Emissions from Natural Gas Systems (MMT CO_2 Eq. and Percent)

Segment	Study	Year	Emissions (MMT CO_2 Eq.)	Uncertainty Range [a] MMT CO_2 Eq. Lower Bound	MMT CO_2 Eq. Upper Bound	% Lower Bound	% Upper Bound
All Segments, National	EPA 2017 GHGI	2015	162.4	104.3	271.9	-36%	67%
Production, Barnett Shale	Lyon, et al. (2015) [b]	2013	3.6	3.37	3.87	-7%	6%
Gathering Facilities, National	Marchese, et al. (2015)	2012	42.4	37.76	47.09	-11%	11%
Gathering, Barnett Shale	Lyon, et al. (2015) [b]	2013	4.3	3.00	5.97	-30%	39%
Processing, Barnett Shale	Lyon, et al. (2015) [b]	2013	1.2	0.81	1.77	-33%	47%
Trans. & Storage, National	Zimmerle, et al. (2015)	2012	37.6	30.44	48.85	-19%	30%
Trans. & Storage, National	Lyon, et al. (2015) [b]	2013	0.4	0.28	0.55	-28%	39%
Distribution, National	Lamb, et al. (2015)	2013	9.8	NA	21.32	NA	117%
Distribution, Barnett Shale	Lyon, et al. (2015) [b]	2013	0.2	0.17	0.35	-18%	74%
Oil and Gas, All Segments, Barnett Shale	Zavala, et al. (2015) [c]	2013	12.9	10.5	16.0	-19%	24%
All Segments, National	Littlefield, et al. (2017)	2012	183.9	150.3	242.2	-24%	29%

NA = Not available

[a] The figures represent the 95 percent confidence intervals reported in each of the studies for the source.

[b] The emission estimates reported are for the 25-county Barnett shale region, not the U.S. as a whole, and encompass natural gas and petroleum emissions. Therefore, the point estimates are not comparable to those reported in other studies and are italicized to emphasize such.
[c] The Zavala et al. results represent both natural gas and petroleum activities.

Table B2. Comparison of Quantitative Uncertainty Estimates for CH_4 Emissions from Petroleum Systems (MMT CO_2 Eq. and Percent)

Segment	Study	Year	Emissions (MMT CO_2 Eq.)	Uncertainty Range [a]			
				MMT CO_2 Eq.		%	
				Lower Bound	Upper Bound	Lower Bound	Upper Bound
All Segments, National	EPA 2017 GHGI	2015	39.9	14.8	80.5	-63%	102%
Production, Barnett Shale [b]	Lyon, et al. (2015)	2013	*0.39*	*0.37*	*0.42*	-6%	6%
Oil and Gas, All Segments, Barnett Shale	Zavala, et al. (2015) [c]	2013	*12.9*	*10.5*	*16.0*	-19%	24%

[a] The figures represent the 95 percent confidence intervals reported in each of the studies for the source.
[b] The emission estimates reported are for the 25-county Barnett shale region, not the U.S. as a whole, and encompass natural gas and petroleum emissions. Therefore, the point estimates are not comparable to those reported in other studies and are italicized to emphasize such.
[c] The Zavala et al. results represent both natural gas and petroleum activities.

Table B3. Comparison of Quantitative Uncertainty Estimates for CH_4 Emissions from Specific Emission Sources from Natural Gas Systems (MMT CO_2 Eq. and Percent)

Segment & Emission Source	Study	Year	Emissions (MMT CO_2 Eq.)	Uncertainty Range [a]			
				MMT CO_2 Eq.		%	
				Lower Bound	Upper Bound	Lower Bound	Upper Bound
Production, National, Pneumatic Controllers	EPA 2017 GHGI	2015	25.5	14.0	39.3	-45%	54%
Production, National, Pneumatic Controllers	Allen, et al. (2014a)	2012	15	9.9	26.3	-34%	75%
Production, National, Chemical Injection Pump Venting	EPA 2017 GHGI	2015	3.0	2.0	4.1	-34%	35%
Production, National, Chemical Injection Pump Venting	Allen, et al. (2013)	2011	1.7	0.9	2.5	-49%	47%
Production, National, Liquids Unloading With Plunger Lifts	EPA 2017 GHGI	2015	3.0	2.5	3.5	-16%	17%
Production, National, Liquids Unloading Without Plunger Lifts	EPA 2017 GHGI	2015	2.2	1.7	2.7	-24%	24%
Production, National, Liquids Unloading With Plunger Lifts	Allen, et al. (2014b)	2012	4.8	2.8	7.3	-42%	53%
Production, National, Liquids Unloading Without Plunger Lifts	Allen, et al. (2014b)	2012	2.0	1.3	4.0	-38%	100%

[a] The figures represent the 95 percent confidence intervals reported in each of the studies for the source.