February 12, 2021

INDUSTRY PARTNERSHIPS & THEIR ROLE IN REDUCING NATURAL GAS SUPPLY CHAIN GREENHOUSE GAS EMISSIONS – PHASE 2

SRIJANA RAI, JAMES LITTLEFIELD, SELINA ROMAN-WHITE, GEORGE G. ZAIMES, GREGORY COONEY, TIMOTHY J. SKONE, P.E.

DOE/NETL-2020/2607

Disclaimer

Errata

This report is a re-issue of the 2020 study (published on July 28, 2020). It revises the device count in the mitigation strategy "pipeline pump-down before maintenance" in the Marginal Abatement Cost (MAC) Analysis section of the report (**Section 7**). Please see the addendum for more details on this revision and resultant changes. This revision does not change most of our conclusions and recommendations. It only changes the total methane reduced from all the mitigation opportunities (low cost and high cost) from 6.5 Bcf CH_4/yr to 4.8 Bcf CH_4/yr.

Authors

Srijana Rai,[1] James Littlefield,[1] Selina Roman-White,[1]
George G. Zaimes,[1] Gregory Cooney,[1] Timothy J. Skone, P.E.[2]*

Reviewer

Don Remson[2]

[1]KeyLogic, Mission Execution and Strategic Analysis (MESA)
[2]National Energy Technology Laboratory (NETL)

*Corresponding contact: Timothy.Skone@netl.doe.gov, 412-386-4495

Suggested Citation:

S. Rai, J. Littlefield, S. Roman-White, G. G. Zaimes, G. Cooney, T. J. Skone, "Industry Partnerships & Their Role in Reducing Natural Gas Supply Chain Greenhouse Gas Emissions – Phase 2," National Energy Technology Laboratory, Pittsburgh, February 12, 2021.

This report was prepared by MESA for the U.S. DOE NETL. This work was completed under DOE NETL Contract Number DE-FE0025912. This work was performed under MESA Activity 203.

This page intentionally left blank.

Table of Contents

LIST OF EXHIBITS

ACRONYMS AND ABBREVIATIONS

AGR	Acid gas removal
AR5	Fifth Assessment Report
bbl	Barrel
Bcf	Billion cubic feet
BTS	Bureau of Transportation Statistics
Btu	British thermal unit
CF	Conversion factor
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
conv.	Conventional
DOE	Department of Energy
EIA	Energy Information Administration
EPA	Environmental Protection Agency
ESD	Emergency shutdown
g	Gram
GHG	Greenhouse gas
GHGRP	Greenhouse Gas Reporting Program
GWP	Global Warming Potential
H_2S	Hydrogen sulfide
HB	High bleed
HF	Hydraulic fracturing
HHV	Higher heating value
IB	Intermittent bleed
ICF	Inner City Fund
ID	Identification
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
km	Kilometer
LA	Louisiana
LB	Low bleed
LCA	Life cycle analysis
LDAR	Leak detection and repair
LNG	Liquefied natural gas
MAC	Marginal abatement cost
MACC	Marginal abatement cost curve
Mcf	Thousand cubic feet
MESA	Mission Execution and Strategic Analysis
MJ	Megajoule
MMBtu	Million British thermal units
MMcf	Million cubic feet
MR	Metering and regulating
MWh	Megawatt hour
N_2O	Nitrous oxide
N/A	Not available
NETL	National Energy Technology Laboratory
NG	Natural gas
NGCC	Natural gas combined cycle
NGL	Natural gas liquids
NO_X	Nitrogen oxides
OEL	Open ended lines
ONE Future	Our Nation's Energy Future
PRV	Pressure relief valve
scf	Standard cubic feet
T&D/TD	Transmission-distribution
Tcf	Trillion cubic feet
tonne	Metric ton
TX	Texas
U.S.	United States
yr	Year

This page intentionally left blank.

EXECUTIVE SUMMARY

This analysis is the product of collaboration between Our Nation's Energy Future (ONE Future) and the United States (U.S.) Department of Energy (DOE) National Energy Technology Laboratory (NETL). This analysis is an update to Phase 1 of the collaboration between ONE Future and NETL. Phase 1 had three objectives:

1. Calculate a greenhouse gas (GHG) emission profile representative of ONE Future's supply chain, including methane (CH_4) emission rates.
2. Compare ONE Future's emission profile to the emission profile for the U.S. natural gas supply chain.
3. Evaluate specific emission reduction opportunities.

Phase 2 has two key enhancements over Phase 1:

1. The reporting year of the data is updated from 2016 to 2017.
2. The emission profiles and the specific emission reduction opportunities are regionalized for the ONE Future supply chain.

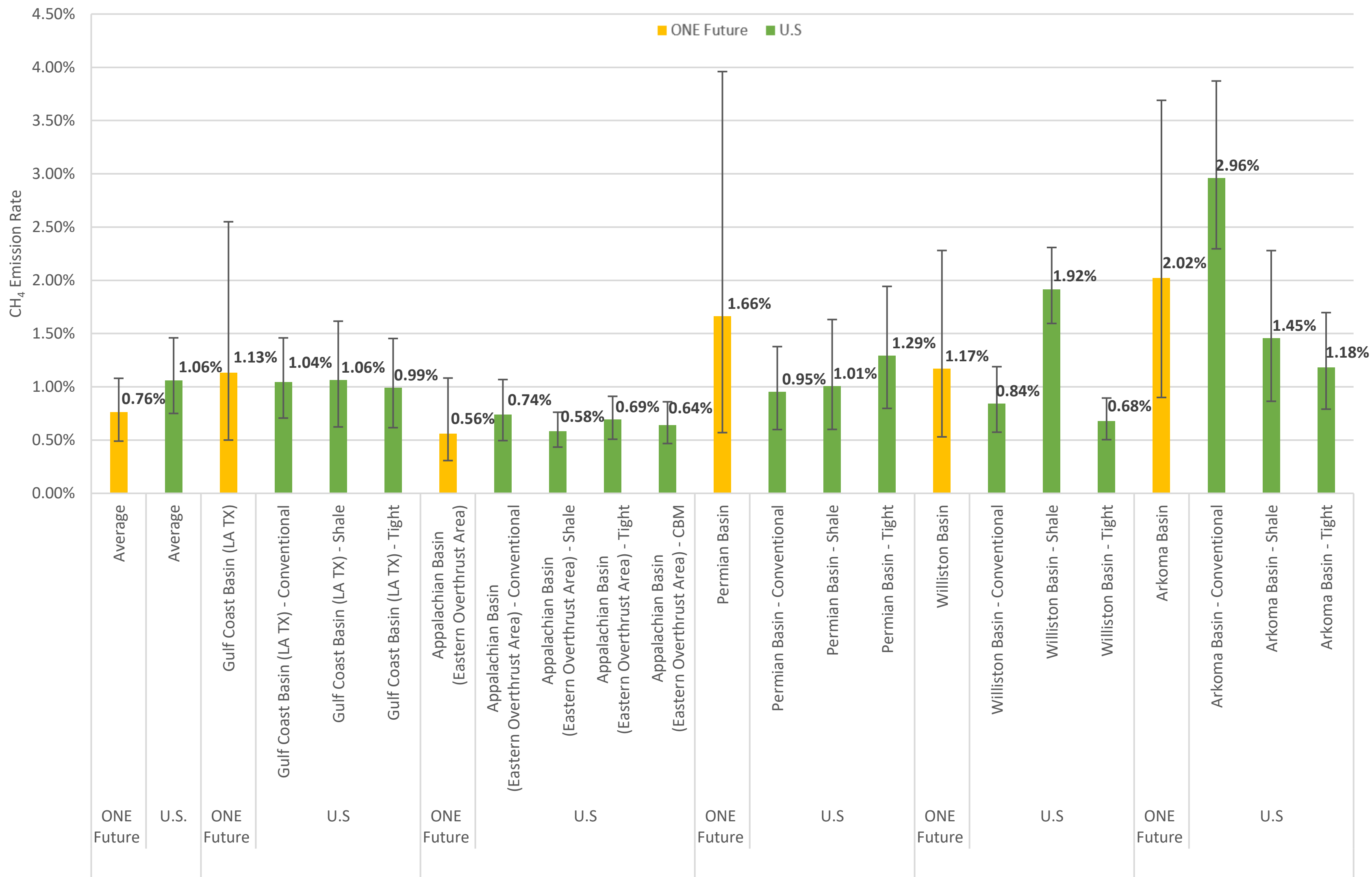
The ONE Future supply chain is based on data provided by ONE Future members for all their U.S. onshore assets. ONE Future's data are mostly representative of their participation in the Greenhouse Gas Reporting Program (GHGRP) administered by the Environmental Protection Agency (EPA) and is supplemented by ONE Future facilities that are not required to report to GHGRP. The U.S. scenario is based on NETL's life cycle analysis (LCA) of natural gas extraction and power generation, which also uses data from the GHGRP (but does not include non-GHGRP facilities). In addition to the data from these sources, NETL accounted for uncertainty due to data variability, data limitations, and variability in liquids unloading frequency and event duration.

While representative of a significant share of U.S. throughput, ONE Future's annual inventory does not represent an integrated supply chain and cannot be compared to the U.S. supply chain on the basis of the same amount of produced and delivered natural gas. To improve comparability, this analysis uses NETL's life cycle natural gas model to convert ONE Future's data into an integrated supply chain. The result represents a hypothetical unit of natural gas that is produced by ONE Future and travels through supply chain infrastructure fully operated by ONE Future. This method is different than standard inventory methods, which calculate emissions for a group of operators (or for an entire sector) but do not express emissions on a common flow of delivered product.

This analysis uses the latest data provided by ONE Future members as well as data publicly available through GHGRP for the reporting year 2017. ONE Future represents 1–13% of the U.S. natural gas supply chain, depending on the stage being represented. The average life cycle CH_4 emission rate for all of ONE Future's activity is 0.76%, with a 95% confidence interval range of

0.49–1.08%. Whereas the U.S. average scenario has an expected life cycle CH_4 emission rate of 1.06%, with a 95% confidence interval range of 0.75–1.46%. Among the regionalized scenarios for ONE Future, the expected life cycle CH_4 emission rate ranges between 0.56% and 2.02%. **Exhibit ES-1** shows the CH_4 emission rates for selected ONE Future scenarios and compares it to the corresponding U.S. scenarios.

Exhibit ES-1: CH_4 Emission Rates for ONE Future Source-Based Scenarios and Corresponding U.S. Technobasin Scenarios



A marginal abatement cost (MAC) analysis shows that ONE Future's top mitigation options are different than those for the U.S. natural gas supply chain. Low cost opportunities (less than $1.70/thousand cubic feet [Mcf] CH_4 reduced) result in 1.4 billion cubic feet (Bcf) in annual CH_4 emission reductions from ONE Future's system. Distribution mains and services are a significant contributor to ONE Future's CH_4 emissions, and these emissions are higher than average U.S. emissions from distribution mains and services. The ONE Future members include companies with leak prone cast iron pipelines in urban areas where replacement or repair is expensive (approximately $3.3 million per mile), leading to a CH_4 reduction cost of $371/Mcf CH_4 reduced.

A regionalized MAC analysis helps in identifying not just a cost-effective mitigation strategy, but also the regions where mitigation strategies will lead to the highest reduction in CH_4 emissions. For example, replacing high bleed pneumatic devices has the lowest $/Mcf CH_4 reduced value, but applying this strategy in Williston Basin will reduce 0.07 Bcf of CH_4 emissions as opposed to only 0.004 and 0.0004 Bcf in Gulf Coast Basin (LA, TX) and Permian basins, respectively.

The LCA approach used in this analysis allows direct comparisons between ONE Future and the entire natural gas sector, and the MAC analysis provides a valuable cost perspective. The regionalization of these analyses also provides enhanced resolution to this work, with focus on specific geographic units. A variety of analytical tools is necessary to prioritize CH_4 emission reduction opportunities.

1. INTRODUCTION

Our Nation's Energy Future (ONE Future) is a natural gas industry partnership dedicated to improving the efficiency of the natural gas supply chain. The National Energy Technology Laboratory (NETL) is a United States (U.S.) Department of Energy (DOE) laboratory with world-class capabilities in energy research and analysis. This analysis is a collaboration between ONE Future and NETL, with the goal of characterizing methane (CH_4) and other greenhouse gas (GHG) emissions from ONE Future's operations.

This report presents the findings of Phase 2 of NETL's collaboration with ONE Future. To review, Phase 1 of this collaboration had three objectives:

1. Calculate a GHG emission profile representative of ONE Future's supply chain, including CH_4 emission rates.
2. Compare ONE Future's emission profile to the emission profile for the average U.S. natural gas supply chain.
3. Evaluate specific emission reduction opportunities.

Phase 2 of this collaboration (this work) builds upon the above objectives updating NETL's life cycle analysis (LCA) of natural gas extraction and power generation model (Littlefield et al. 2019) using the most current data year available and exploring the following questions in more detail:

1. To what extent do the GHG emissions from ONE Future's members vary regionally?
2. What differentiates ONE Future members from the rest of the natural gas sector, and what have they done to reduce their emissions below a 1% supply chain CH_4 emission intensity?
3. What can ONE Future do to sustain a low GHG emission intensity?

In this work the terms "emission intensity" and "emission rate" are used to represent *mass* of methane emissions per unit *energy* of natural gas delivered and *mass* of methane emissions per unit *mass* of natural gas delivered, respectively.

This analysis was made possible by a voluntary data collection effort conducted by ONE Future companies across their U.S. assets. ONE Future's data represent the entire natural gas supply chain, beginning with natural gas production, continuing through midstream stages, and ending with delivery of natural gas to large- and small-scale consumers. The data represent ONE Future's 2017 operations. This analysis used all data provided by ONE Future (no data points were discarded).

This analysis uses NETL's natural gas life cycle model (Littlefield et al. 2019) to convert ONE Future's data into an integrated supply chain. The results represent a hypothetical unit of natural gas that is produced by ONE Future and travels through supply chain infrastructure fully operated by ONE Future. Life cycle analysis (LCA) is preferable to emission inventories for two reasons:

1. LCA can convert data from multiple supply chain stages with disparate throughputs into an integrated system. This is necessary for the ONE Future scenario because the scale of ONE Future activity varies among supply chain stages.

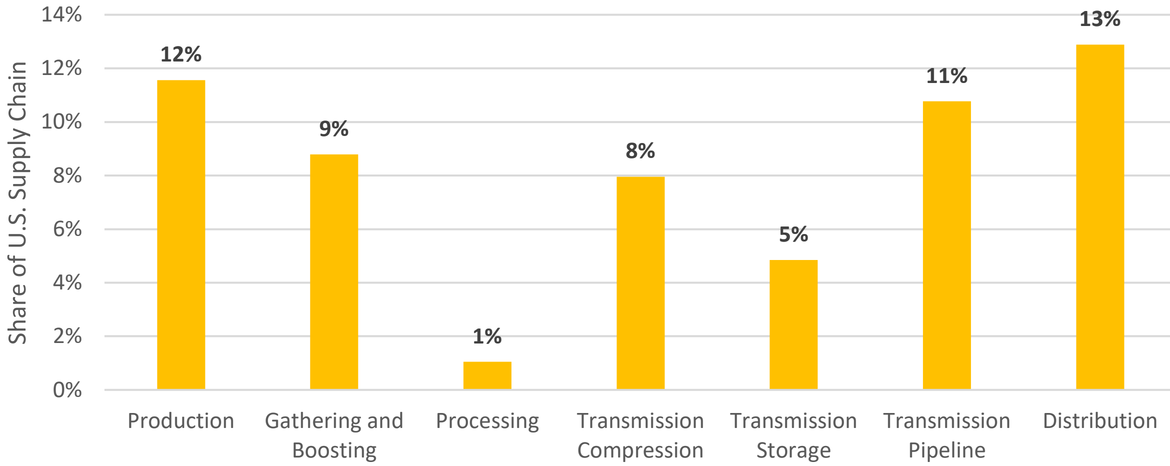
2. LCA allows comparisons of different supply chain scenarios by scaling emissions to an equivalent basis for comparison (in this analysis, 1 megajoule [MJ] of delivered natural gas). Emission inventories tabulate total emissions but do not facilitate comparisons between systems that have different quantities of delivered product.

LCA is a systematic approach for modeling emissions and other environmental burdens. NETL's life cycle natural gas model (Littlefield et al. 2019) is a compilation of unit processes that are scaled to reflect a functional unit of natural gas while accounting for study uncertainty:

- A **functional unit** is necessary to facilitate comparisons between scenarios. The functional unit for this analysis is 1 MJ of natural gas delivered to the consumer. **Section 2** discusses the purpose of functional units and other scoping and boundary concepts.
- **Unit processes** are the building blocks of life cycle models. In this analysis, each unit process accounts for the inputs and outputs of a natural gas emission source. For GHG emissions, the unit processes used in this analysis account for emissions from venting, fugitive, and combustion activities. Most of these GHG emissions are adapted directly from ONE Future's data, which follow the same reporting structure used by the Environmental Protection Agency's (EPA) Greenhouse Gas Reporting Program (GHGRP). **Section 4.1** discusses unit processes in more detail.
- **Stage connections** are necessary to model natural gas pathways from cradle through delivery. These pathways account for the portion of natural gas that travels through gathering and boosting and processing plants, the average number of transmission facilities between processing and delivery, the relationship between transmission throughput and storage capacity, and the portion of natural gas that travels through distribution. **Section 4.3** discusses stage connectivity in more detail.
- **Uncertainty** is driven by data variability and data limitations. This analysis uses a stochastic approach to sample from ONE Future's data and generates confidence intervals in average values. Uncertainty is discussed in more detail in **Section 5**.

As shown by the supply chain shares in **Exhibit 1-1**, ONE Future represents 1–13% of the U.S. natural gas supply chain. These supply chain shares represent the ratio of ONE Future throughput to U.S. throughput (except for transmission storage and transmission pipelines, where the shares are the ratios of storage capacities and pipeline miles, respectively). At a 1% share of U.S. throughput, processing is one stage where ONE Future does not have significant representation in the U.S. natural gas supply chain.

Exhibit 1-1: ONE Future's Share of Individual Supply Chain Stages (EIA 2019d), (BTS 2019)



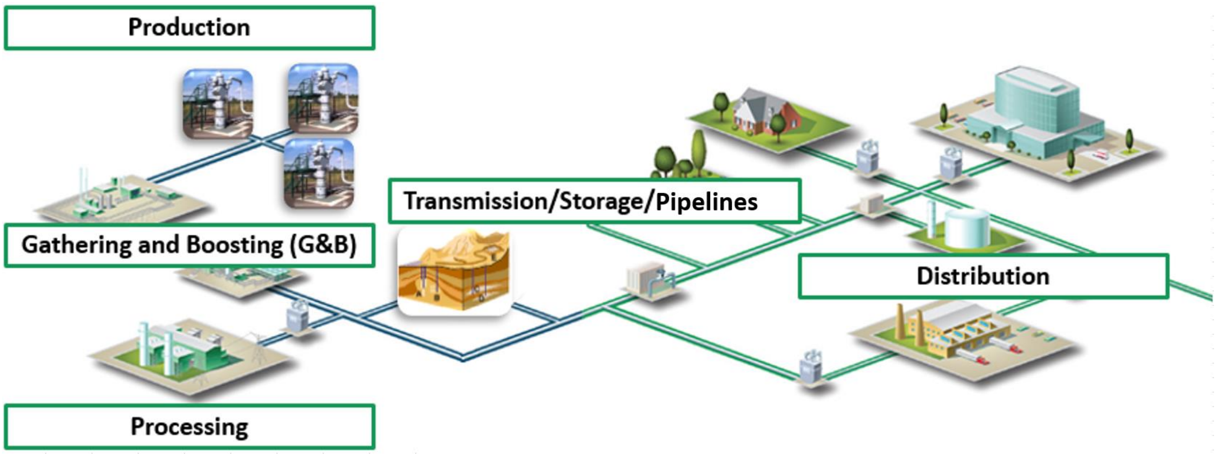
* Transmission Storage share is on a capacity basis; Transmission Pipeline share is on a mileage basis.

To complement the natural gas supply chain LCA, this analysis calculates the marginal abatement costs (MAC) for emission mitigation options and calculates the life cycle GHG emissions from the use of natural gas in power plants and subsequent delivery of electricity. By considering the costs and potential effectiveness of mitigation options within ONE Future's control, the MAC analysis facilitates prioritization of CH_4 emission reduction opportunities. By accounting for the life cycle GHG emissions from power plants, the power plant LCA shows the extent to which upstream natural gas CH_4 emissions contribute to total emissions through electricity generation and delivery.

2. SCOPE AND BOUNDARIES

This study analyzes two natural gas supply chains: (1) ONE Future members and (2) all the U.S. facilities. The natural gas supply chain, as illustrated in **Exhibit 2-1**, comprises production, gathering and boosting, processing, transmission (which includes compressor stations, storage and pipelines), and distribution.

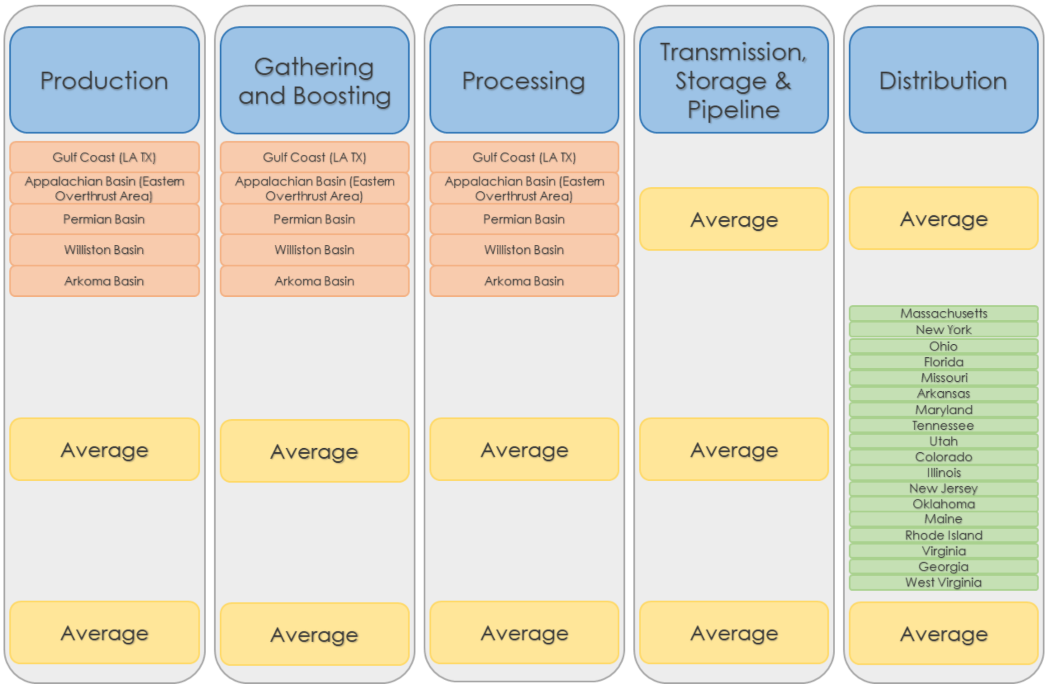
Exhibit 2-1: Supply Chain Stages that Compose the Overall Study Boundary



The ONE Future data represent 15 production basins, 8 gathering and boosting basins, 5 processing basins, and 18 U.S. states with local distribution. These data represent 10,800 unique pathways for the natural gas moving through ONE Future's assets. However, the majority of these pathways are not "geographically complete" because it is physically impossible for the gas to follow those paths. The ONE Future supply chain is divided into 24 different scenarios, 23 representing a different geographical boundary and 1 representing the average for ONE Future. **Exhibit 2-2** illustrates the pathways for these scenarios.

There are two types of scenarios, one is based on the source of the natural gas and the other is based on its destination. For source-based scenarios, the gas must travel from production through processing in the same basin, which leads to 5 basins as geographically complete scenarios. Natural gas then moves through ONE Future's average transmission compression, storage, pipeline, and distribution infrastructure. For destination-based scenarios, natural gas moves through ONE Future's average production, gathering and boosting, processing, transmission compression, storage, and pipeline, but is distributed in a specific U.S. state. This leads to 18 destination-based scenarios.

Exhibit 2-2: ONE Future Scenarios



A functional unit is necessary to facilitate comparisons among scenarios (if necessary, a functional unit can be used to compare natural gas to other energy sources). The functional unit for this analysis is 1 MJ of natural gas delivered to the consumer (calculated based on higher heating value [HHV] of natural gas). The consumer is a consumption-weighted mix of utility, industrial, commercial, and residential consumers. Since this functional unit represents delivered natural gas, the results can be easily connected to downstream systems to allow modeling of natural gas end use scenarios, such as electricity generation by a natural gas-fired power plant.

It is possible to base functional units on other types of flows without changing the structure of a life cycle model. For example, life cycle natural gas emissions can be expressed per unit of natural gas produced (not delivered). This is proposed by ONE Future's "Methane Emissions Estimation Protocol" (ONE Future 2016). Doing so would reduce the calculated emission rate for U.S. natural gas by approximately 23%, the difference between U.S. natural gas consumption and gross production (EIA 2019c), (EIA 2019e). A functional unit based on produced natural gas makes it harder to model the connection between the upstream natural gas supply chain and downstream natural gas consumers.

This analysis expresses results in terms of CH_4 emission rate and total GHG emissions. CH_4 emission rate is the mass of CH_4 emissions per mass of natural gas delivered to the end user. GHG emissions include carbon dioxide (CO_2), CH_4, and nitrous oxide (N_2O) and provide a perspective on the tradeoffs between venting and fugitive emission sources (which have a high proportion of CH_4 to CO_2), and combustion emission sources (which, conversely, have a high proportion of CO_2 to CH_4).

3. DATA

The data used in this analysis comprise all stages of the natural gas supply chain: production, gathering and boosting, processing, transmission (including compression, storage, and pipeline emissions), and distribution. ONE Future's GHGRP submittals were the key data source, but were supplemented by data for ONE Future facilities below the GHGRP reporting threshold, Subpart W of GHGRP for all the U.S. facilities (EPA 2017), and other data sources for liquids unloading variability. The scope and representativeness of these data sources are discussed below.

3.1 ONE FUTURE DATA

Most data for this analysis were collected by ONE Future members and were derived from their 2017 Subpart W reporting efforts for the GHGRP, a reporting program administered by EPA. ONE Future also provided some non-GHGRP data that represent facilities which did not have to report to GHGRP since they did not meet the minimum reporting threshold. The ONE Future data represent natural gas production, gathering and boosting, and processing in 15, 8, and 5 basins, respectively. Of the 15 production and 8 gathering and boosting basins, only 5 can be connected to other stages to form geographically complete scenarios.

ONE Future's **production** facilities represent a range of operational capacities, spanning 5 orders of magnitude for annual production (0.059 billion cubic feet [Bcf]/year [yr] to 830 Bcf/yr) in 2017. Most facilities produce 50 Bcf/yr or less. In total, ONE Future members produced 3,600 Bcf of gas in 2017, representing 12% of 2017 U.S. dry gas production. The non-GHGRP facilities are not necessarily representative of low throughput facilities compared to GHGRP facilities; there are two GHGRP facilities with lower throughputs than the two non-GHGRP facilities. ONE Future's production volumes are shown in **Exhibit 3-1**, which shows the facility level production throughputs organized by basin, where each row represents an individual facility.

Exhibit 3-1: Representativeness of ONE Future Production Volumes

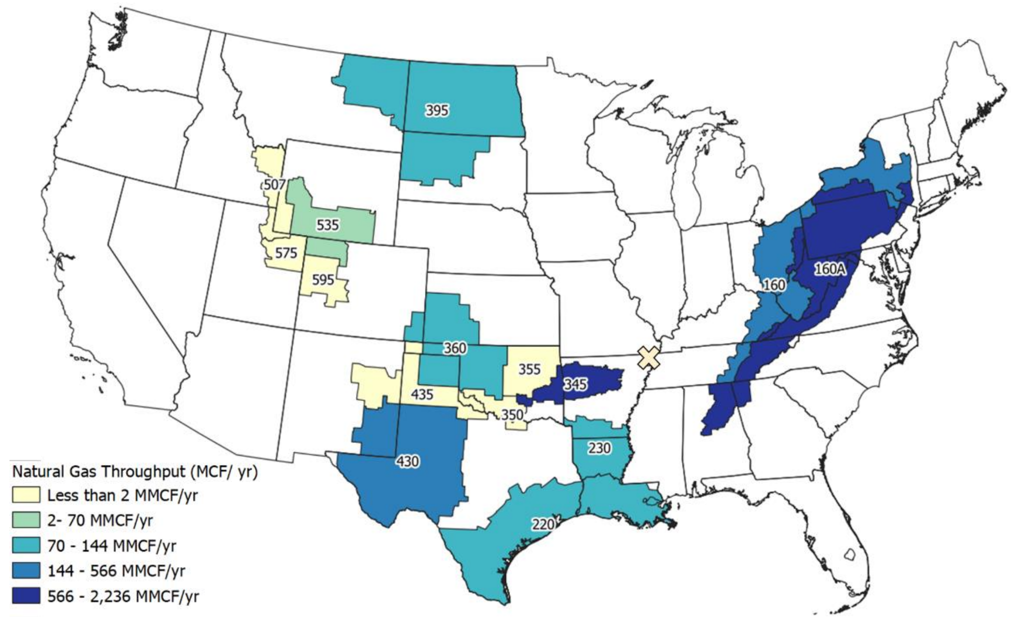
Basin Code	Basin Name	Natural Gas (Mcf/yr)	Oil/Condensate (bbl/yr)	Natural Gas Energy Equivalents (MMBtu/yr)*	Reporter Type
160A	Appalachian Basin (Eastern Overthrust Area)	2.88E+07	5.49E+04	3.78E+07	GHGRP
		7.02E+08	1.99E+06	8.35E+08	GHGRP
		5.22E+07	1.50E+05	5.22E+07	GHGRP
		8.27E+08	8.40E+05	1.02E+09	GHGRP
		6.26E+08	3.16E+06	6.89E+08	GHGRP
160	Appalachian Basin	5.91E+07	5.31E+04	7.29E+07	GHGRP
		8.53E+07	1.09E+06	1.08E+08	GHGRP
220	Gulf Coast Basin (LA, TX)	5.05E+06	1.41E+06	6.24E+06	GHGRP
		4.63E+07	5.71E+06	5.32E+07	GHGRP
		5.80E+07	5.07E+06	8.56E+07	GHGRP

Basin Code	Basin Name	Natural Gas (Mcf/yr)	Oil/Condensate (bbl/yr)	Natural Gas Energy Equivalents (MMBtu/yr)*	Reporter Type
230	Arkla Basin	8.29E+05	7.35E+04	1.01E+06	GHGRP
		1.31E+08	3.57E+02	1.29E+08	GHGRP
250	Upper Mississippi Embayment	5.86E+05	-	5.90E+05	non-GHGRP
345	Arkoma Basin	4.88E+08	-	4.91E+08	GHGRP
		7.81E+07	-	7.71E+07	GHGRP
350	South Oklahoma Folded Belt	6.18E+05	3.02E+04	7.63E+05	GHGRP
355	Chautauqua Platform	5.87E+04	2.31E+03	7.25E+04	GHGRP
360	Anadarko Basin	7.10E+07	2.73E+06	8.76E+07	GHGRP
395	Williston Basin	7.97E+07	3.34E+07	1.59E+08	GHGRP
		2.71E+07	1.86E+07	4.34E+07	GHGRP
430	Permian Basin	3.64E+07	6.32E+06	4.61E+07	GHGRP
		1.26E+08	3.22E+07	1.56E+08	GHGRP
		5.14E+06	2.09E+05	6.34E+06	GHGRP
		3.15E+07	3.93E+06	3.89E+07	GHGRP
435	Palo Duro Basin	7.45E+05	2.56E+05	9.21E+05	GHGRP
507	Central Western Overthrust	1.44E+06	4.94E+03	1.78E+06	GHGRP
535	Green River Basin	4.98E+07	2.39E+05	6.15E+07	GHGRP
		5.55E+05	4.69E+04	6.85E+05	non-GHGRP
575	Uinta Basin	1.87E+06	3.16E+03	2.31E+06	GHGRP
595	Piceance Basin	2.34E+05	5.57E+03	2.89E+05	GHGRP
	Subtotal: 160A	2.24E+09	6.19E+06	2.64E+09	GHGRP
	Subtotal: 160	1.44E+08	1.15E+06	1.81E+08	GHGRP
	Subtotal: 220	1.09E+08	1.22E+07	1.45E+08	GHGRP
	Subtotal: 230	1.32E+08	7.38E+04	1.30E+08	GHGRP
	Subtotal: 250	5.86E+05	-	5.90E+05	GHGRP
	Subtotal: 345	5.66E+08	0.00E+00	5.68E+08	GHGRP
	Subtotal: 350	6.18E+05	3.02E+04	7.63E+05	GHGRP
	Subtotal: 355	5.87E+04	2.31E+03	7.25E+04	GHGRP
	Subtotal: 360	7.10E+07	2.73E+06	8.76E+07	GHGRP
	Subtotal: 395	1.07E+08	5.20E+07	2.03E+08	GHGRP
	Subtotal: 430	1.99E+08	4.27E+07	2.47E+08	GHGRP
	Subtotal: 435	7.45E+05	2.56E+05	9.21E+05	GHGRP
	Subtotal: 507	1.44E+06	4.94E+03	1.78E+06	GHGRP
	Subtotal: 535	5.03E+07	2.86E+05	6.22E+07	combined
	Subtotal: 575	1.87E+06	3.16E+03	2.31E+06	GHGRP
	Subtotal: 595	2.34E+05	5.57E+03	2.89E+05	GHGRP
	Total	3.62E+09	1.18E+08	4.27E+09	combined

* Natural gas equivalents calculated using 5.8 million British thermal units (MMBtu)/barrel (bbl) oil and condensate and 1,235 Btu/standard cubic feet (scf) natural gas (provided by the member companies and representative of the production stage only).

Exhibit 3-2 shows the geographical distribution and 2017 throughput for ONE Future's production operations.

Exhibit 3-2: 2017 Geographic Production Basins for ONE Future Members*



* Basin code 250 – Upper Mississippi Embayment has been plotted as an approximate point ("X") due to the absence of relevant shapefile.

ONE Future's **gathering and boosting** data comprise 21 facilities: 19 GHGRP facilities and 2 non-GHGRP facilities. These facilities span 8 natural gas basins and have a total throughput of 2,580 Bcf per year. The throughput of these facilities is highly variable, ranging from 0.558 to 760 Bcf/yr, with an average throughput of 123 Bcf/yr. The lowest throughput (0.558 Bcf/yr) comes from one of the non-GHGRP facilities. The other non-GHGRP facility has a throughput of 2.54 Bcf/yr and is the fourth lowest throughput of the data set. **Exhibit 3-3** shows the facility level gathering and boosting throughputs, organized by basin.

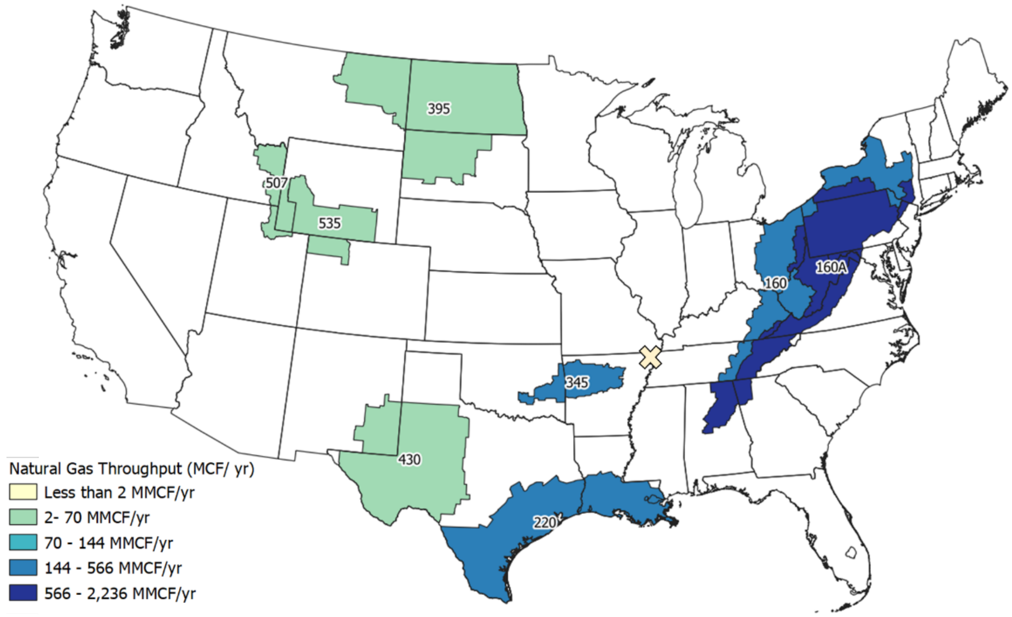
Exhibit 3-3: Representativeness of ONE Future Gathering and Boosting Data

Basin Code	Basin Name	NG Transferred (Mcf/yr)	Reporter Type
160A	Appalachian Basin (Eastern Overthrust Basin)	3.86E+08	GHGRP
		7.59E+08	GHGRP
		1.97E+08	GHGRP
		6.51E+07	GHGRP
		5.10E+07	GHGRP
160	Appalachian Basin	2.76E+08	GHGRP
		6.82E+07	GHGRP
		3.88E+07	GHGRP

Basin Code	Basin Name	NG Transferred (Mcf/yr)	Reporter Type
		2.54E+06	non-GHGRP
220	Gulf Coast Basin (LA, TX)	1.14E+08	GHGRP
		5.63E+07	GHGRP
250	Upper Mississippi Embayment	5.58E+05	non-GHGRP
345	Arkoma Basin	4.42E+08	GHGRP
		4.67E+07	GHGRP
395	Williston Basin	3.87E+07	GHGRP
		8.71E+06	GHGRP
430	Permian Basin	6.31E+05	GHGRP
		1.91E+06	GHGRP
		4.77E+06	GHGRP
507	Central Western Overthrust	7.05E+06	GHGRP
535	Green River Basin	1.69E+07	GHGRP
	Subtotal: 160A	1.46E+09	GHGRP
	Subtotal: 160	3.86E+08	combined
	Subtotal: 220	1.70E+08	GHGRP
	Subtotal: 250	5.58E+05	non-GHGRP
	Subtotal: 345	4.89E+08	GHGRP
	Subtotal: 395	4.74E+07	GHGRP
	Subtotal: 430	7.31E+06	GHGRP
	Subtotal: 507	7.05E+06	GHGRP
	Subtotal: 535	1.69E+07	GHGRP
	Total	2.58E+09	combined

Exhibit 3-4 shows the geographical distribution and 2017 throughput for ONE Future's gathering and boosting operations.

Exhibit 3-4: 2017 Geographic Gathering and Boosting Basins for ONE Future Members*



* Basin code 250 – Upper Mississippi Embayment has been plotted as an approximate point ("X") due to the absence of relevant shapefile.

ONE Future represents 10 **processing** facilities across 5 basins, with a total output of 214 Bcf/yr. ONE Future's processing data represent GHGRP facilities exclusively (no non-GHGRP processing facilities). The average plant output is 21 Bcf/yr, but output is highly variable, with a minimum of 0.48 Bcf/yr and a maximum of 58 Bcf/yr. For comparison, U.S. processing plants had 20,400 Bcf of throughput in 2017 (EIA 2019f). ONE Future represents 1% of U.S. processing capacity.

Eight of the ten facilities also separate hydrocarbon liquids at processing. The ratio of gas to heavy hydrocarbon output ranges from 2,400 scf/bbl to 5,200,000 scf/bbl. The total ratio of gas to heavy hydrocarbon processing across all facilities is 10,700 scf/bbl. On an energy basis, natural gas accounts for 74% of product; this is skewed by one plant in the Williston Basin, where natural gas is 39% of energy produced. This North Dakota plant represents the third highest throughput among ONE Future processing facilities.

The processing stage presented two unique data challenges in this analysis. First, the data contained one facility with a low natural gas to natural gas liquids production share, making the co-product allocation between gas and liquids an important method decision (discussed in **Section 4.4**). Second, the data set had a low total facility count.

The processing throughput data are shown on a facility level in **Exhibit 3-5.**

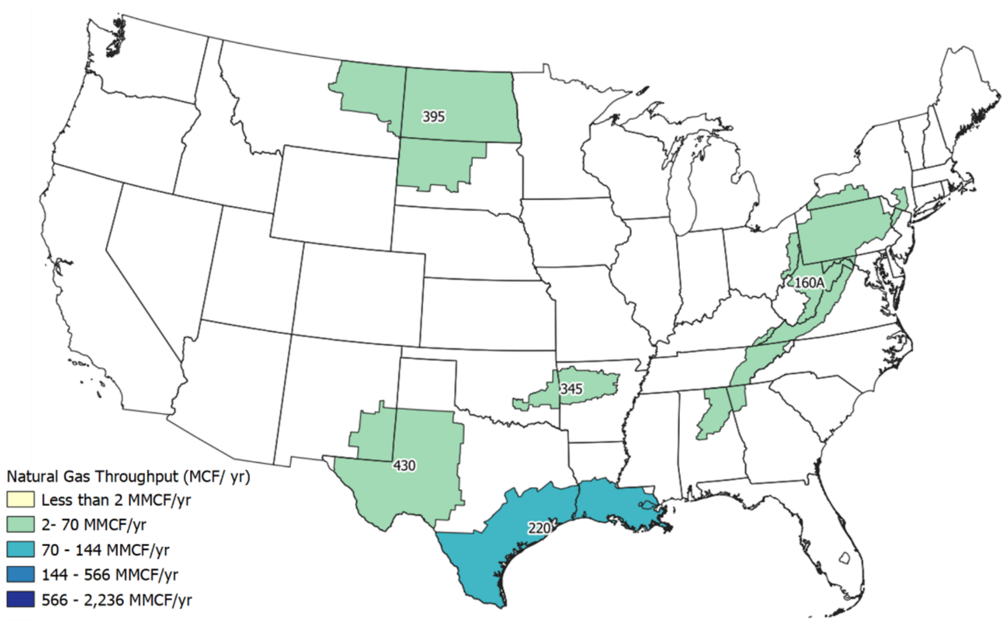
Exhibit 3-5: Representativeness of ONE Future Processing Data

Basin Code	Basin Name	NG Output (Mcf/facility-yr)	Gas/Liquids Ratio (scf/bbl)	NG Energy Share of Co-products*
160A	Appalachian Basin (Eastern Overthrust Area)	5.83E+05	9.60E+04	96.2%
		5.03E+07	1.66E+04	81.6%
220	Gulf Coast Basin (LA, TX)	1.39E+07	5.24E+06	100%
		5.77E+07	-	100%
345	Arkoma Basin	1.42E+07	-	100%
395	Williston Basin	3.92E+07	2.42E+03	39.3%
430	Permian Basin	4.85E+05	3.03E+04	89.0%
		1.15E+07	2.72E+04	87.9%
		6.84E+06	4.78E+04	92.7%
		1.89E+07	9.55E+04	96.2%
	Subtotal: 160A	5.09E+07	1.68E+04	81.7%
	Subtotal: 220	7.17E+07	2.69E+07	100%
	Subtotal: 345	1.42E+07	-	100%
	Subtotal: 395	3.92E+07	2.42E+03	39.3%
	Subtotal: 430	3.78E+07	4.84E+04	92.8%
	Total	2.14E+08	1.07E+04	74.0%

*Energy density of natural gas = 1,020 Btu/scf and natural gas liquids (NGL) = 3.82 MMBtu/bbl (provided by the member companies and representative of the processing stage only).

Exhibit 3-6 shows the geographical distribution and 2017 throughput for ONE Future's processing operations.

Exhibit 3-6: 2017 Geographic Processing Basins for ONE Future Members



ONE Future provided data for 297 **transmission compression, storage, and pipeline** facilities (these three activities compose the transmission stage). These data comprise 280 GHGRP facilities and 17 non-GHGRP facilities. The 280 GHGRP facilities comprise 243 transmission compression facilities, 22 storage stations, 7 transmission pipelines, and 8 combined facilities.

One of the combined facilities aggregates the throughput data (12.7 Tcf/yr) for 142 compression facilities. ONE Future provided facility level emission data for each of these 142 facilities, but all throughputs for these facilities were combined into a single value. The data on centrifugal and reciprocating compressor energy was used to estimate the throughput for the associated transmission compression facilities using a Kernel-nearest neighbor approach (explained in more detail in **Appendix C**). This was done to avoid discarding the variability in data at a facility level.

ONE Future provided data for 17 non-GHGRP facilities in the transmission stage. These facilities represent different combinations of compression, storage, and pipeline operations, and the data are aggregated inconsistently across the data set. Due to data limitations, the exact function and throughput of each of these non-GHGRP records is not known. Further, the throughputs for some of these facilities are included in the records for the GHGRP facilities. This analysis addressed this data gap by focusing on three facilities that account for 96% of the emissions from the 17 facilities. The emissions from these three non-GHGRP facilities were added to the emissions for all GHGRP transmission compression facilities according to the ratio of the operator's total throughput for transmission compression to the throughput for all ONE Future transmission compression. In summary, this method adds most (96%) of the non-GHGRP transmission facility emissions to those for GHGRP transmission facilities without discarding data for operator throughput. Another option would be the aggregation of all transmission emissions by all transmission throughput, but doing so would have obfuscated what is known about facility variability.

Transmission (compression, storage, and pipeline) is the only stage that is not regionalized in this analysis. Transmission, by definition, is an activity that spans multiple regions as natural gas is transported from a production basin to an end user. Thus, in this analysis, transmission is modeled as an average activity without geographic stratification and acts as a link between the geographically specific sources and consumers of natural gas.

ONE Future's **distribution** represents 21 facilities in 18 states. Total volumes of received gas and delivered gas are 2.08 Tcf and 2.02 Tcf, respectively (this represents a loss rate of 3.2%, but it is not supported by our data for emissions and energy consumption). In this analysis, unit process flows are tracked on an output basis, so the 2.02 Tcf is our basis for distribution throughput. The facility throughputs range from 1.1 Bcf to 440 Bcf, spanning 3 orders of magnitude. The mean and median throughputs are 99.2 Bcf and 41.7 Bcf, respectively, indicative of a skewed probability distribution where a small number of facilities represent a large volume of throughput. For comparison, in 2017 15.6 Tcf of natural gas was delivered to non-utility end users (EIA 2019c); ONE Future represents approximately 13% of U.S. distribution for the reporting year of 2017.

ONE Future's data represent 161,000 miles of distribution lines. There are four types of materials used for distribution mains: cast iron, unprotected steel, protected steel, and plastic. Across the different regions, total mileage per facility spans three orders of magnitude, ranging from 105 to 33,149 miles/facility. One of the facilities is the single largest contributor to total mileage (33,149), of which 24,155 miles are protected steel distribution mains. For comparison, the U.S. has 1.3 million miles of distribution mains pipelines (BTS 2019); ONE Future represents 12.4% of U.S. distribution mains pipeline mileage.

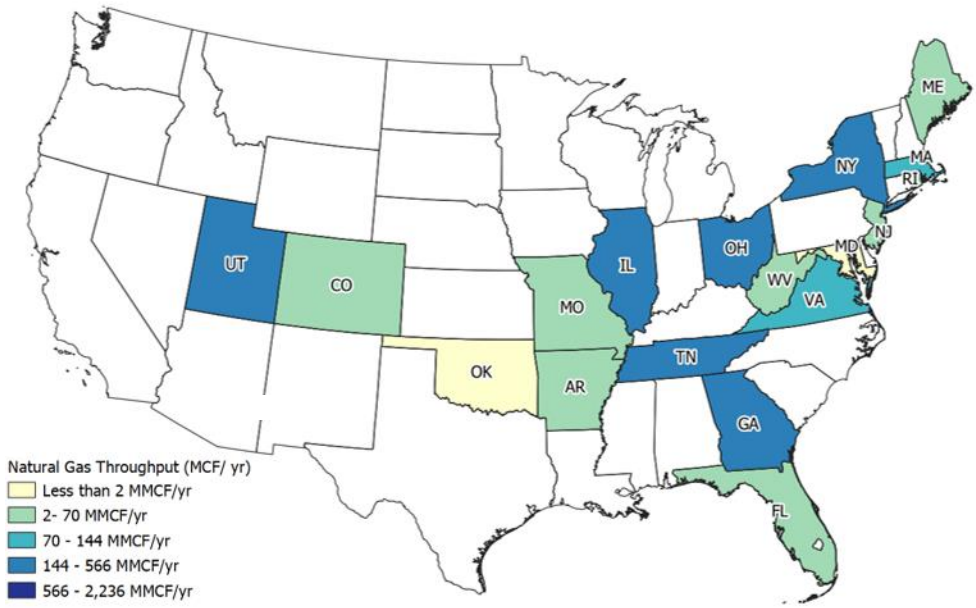
All distribution facilities are GHGRP facilities. There are no non-GHGRP facilities in ONE Future's distribution stage. The facility level throughputs are shown in **Exhibit 3-7**.

Exhibit 3-7: Representativeness of ONE Future Distribution Data

<table>
<tr><th rowspan="2">State Code</th><th rowspan="2">State Name</th><th colspan="2">NG delivered to end users (Mcf)</th></tr>
<tr><th>Facilities</th><th>State Subtotals</th></tr>
<tr><td>AR</td><td>Arkansas</td><td>6.57E+06</td><td>6.57E+06</td></tr>
<tr><td>CO</td><td>Colorado</td><td>2.33E+06</td><td>2.33E+06</td></tr>
<tr><td>FL</td><td>Florida</td><td>1.23E+07</td><td>1.23E+07</td></tr>
<tr><td>GA</td><td>Georgia</td><td>1.97E+08</td><td>1.97E+08</td></tr>
<tr><td>IL</td><td>Illinois</td><td>4.39E+08</td><td>4.39E+08</td></tr>
<tr><td rowspan="2">MA</td><td rowspan="2">Massachusetts</td><td>2.46E+07</td><td rowspan="2">1.36E+08</td></tr>
<tr><td>1.11E+08</td></tr>
<tr><td>MD</td><td>Maryland</td><td>1.08E+06</td><td>1.08E+06</td></tr>
<tr><td>ME</td><td>Maine</td><td>3.26E+06</td><td>3.26E+06</td></tr>
<tr><td>MO</td><td>Missouri</td><td>2.81E+06</td><td>2.81E+06</td></tr>
<tr><td>NJ</td><td>New Jersey</td><td>4.84E+07</td><td>4.84E+07</td></tr>
<tr><td rowspan="3">NY</td><td rowspan="3">New York</td><td>1.53E+08</td><td rowspan="3">5.17E+08</td></tr>
<tr><td>1.79E+08</td></tr>
<tr><td>1.85E+08</td></tr>
<tr><td>OH</td><td>Ohio</td><td>2.82E+08</td><td>2.82E+08</td></tr>
<tr><td>OK</td><td>Oklahoma</td><td>1.33E+06</td><td>1.33E+06</td></tr>
<tr><td>RI</td><td>Rhode Island</td><td>3.84E+07</td><td>3.84E+07</td></tr>
<tr><td>TN</td><td>Tennessee</td><td>1.36E+07</td><td>1.36E+07</td></tr>
<tr><td>UT</td><td>Utah</td><td>1.80E+08</td><td>1.80E+08</td></tr>
<tr><td>VA</td><td>Virginia</td><td>1.01E+08</td><td>1.01E+08</td></tr>
<tr><td>WV</td><td>West Virginia</td><td>3.44E+07</td><td>3.44E+07</td></tr>
<tr><td colspan="2">Total</td><td colspan="2">2.02E+09</td></tr>
</table>

Exhibit 3-8 shows the geographical distribution and 2017 throughput for ONE Future's distribution operations.

Exhibit 3-8: 2017 Geographic Distribution States for ONE Future Members



3.2 U.S. SCENARIO

This analysis uses a U.S. scenario to assess differences between ONE Future's systems and the U.S. natural gas sector. The U.S. scenario is based on NETL's life cycle natural gas model (Littlefield et al. 2019) and Subpart W data from GHGRP (EPA 2017). It is representative of 2017 operations.

The results were also compared at a scenario level (discussed in **Section 6.2**), where the source-based scenarios for ONE Future data were compared to the respective technobasins at the national level. A technobasin is a combination of an extraction technology (conventional, unconventional, and associated) and a production basin.

3.3 ONE FUTURE DATA COMPARISON WITH U.S. DATA

To provide further context on the representativeness of ONE Future's data (which comprises facilities above and below the GHGRP threshold), **Exhibit 3-9** compares the scale of ONE Future's data to the scale of total U.S. natural gas activity.

Exhibit 3-9: ONE Future Data Representativeness Compared to Total U.S. Activity in 2017

Parameter	Units	ONE Future 2017	U.S. 2017 (GHGRP)	U.S. 2017 (EIA)	U.S. 2017 (BTS)
Gas produced from wells	MMcf	3,375,704	26,656,563	29,203,550	N/A
Gas transferred through gathering and boosting facility	MMcf	2,580,687	29,367,801	N/A	N/A
Gas leaving processing plant	MMcf	213,745	N/A	20,38,771	N/A
Gas processing plants	count	10	449	510	N/A
Transmission compressors	count	1,557	3,046	N/A	N/A
Transmission stations	count	243	532	N/A	N/A
Transmission pipeline	miles	32,388	167,006	N/A	300,693
Storage capacity	MMcf	449,354	4,042,673	9,260,590	N/A
Storage gas withdrawn	MMcf	435,985	1,476,967	3,590,479	N/A
Distribution mains	miles	161,054	N/A	N/A	1,296,664
Distribution gas delivered to consumer	MMcf	2,016,225	12,320,166	15,649,185	N/A

*EIA data points are higher than GHGRP data points because of the reporting threshold of GHGRP.

3.4 LIQUIDS UNLOADING

Liquids unloading is an occasional maintenance activity that clears liquids from a well bore to improve well productivity. The emissions from unloading events are a function of unloading frequency, duration, wellhead pressure, well diameter, and types of unloading technologies. These parameters are highly variable across natural gas production sites. Four ONE Future members provided detailed unloading data, which represented three production basins. The key data elements included were (1) well venting duration, (2) tubing or casing diameter, (3) plunger-lift technologies (if used), (4) well shut-in pressure, (5) natural gas flow-rate during unloading, and (6) cumulative natural gas produced. However, after inspection of the data, it was identified that the useable data points only represented one basin, Appalachian Basin (Eastern Overthrust Area). Using the provided data, the CH_4 venting rate per unit of production from unloading events was calculated to be 1.83E-04 (with a 95% confidence interval of 1.74E-04 to 1.91E-04) for Appalachian Basin (Eastern Overthrust Area). For all the other scenarios, the basin level CH_4 venting rates from Zaimes et al. were used. The average venting rate for ONE Future is a production weighted average of the venting rates for all scenarios from Zaimes et al. These venting rates are on the basis of emitted CH_4 per produced natural gas. The CH_4 venting rates for all basins and the average for ONE Future are shown in **Exhibit 3-10.**

Exhibit 3-10: Methane Venting Rates from Liquids Unloading

Scenario	CH_4 Venting Rate			Source
	Low	Expected	High	
Gulf Coast Basin (LA TX)	0.026%	0.062%	0.098%	(Zaimes et al. 2019)
Appalachian Basin (Eastern Overthrust Area)	0.017%	0.018%	0.019%	Provided by ONE Future
Permian Basin	0.009%	0.010%	0.011%	(Zaimes et al. 2019)
Williston Basin	0.00%	0.00%	0.00%	(Zaimes et al. 2019)
Arkoma Basin	0.188%	0.680%	1.172%	(Zaimes et al. 2019)
ONE Future Average	0.044%	0.130%	0.216%	Calculated

4. MODELING APPROACH

This analysis uses NETL's natural gas life cycle model to calculate energy and material flows (Littlefield et al. 2019). The development of this model required the development of unit processes, connections between supply chain stages, and choices about apportioning environmental burdens between co-products.

4.1 UNIT PROCESSES

Unit processes are the building blocks of a life cycle model and account for the inputs and outputs of a single node in a supply chain. The unit processes used in this analysis account for GHG emissions from venting, fugitive, flaring, and combustion processes that are a direct part of the natural gas supply chain. GHG emissions from indirect emission sources, such as diesel production or electricity generation, are accounted for by ancillary unit processes. All emissions are apportioned per unit of natural gas using the throughput of each unit process, which is ultimately scaled to the functional unit of 1 MJ of natural gas through a network of many interconnected unit processes.

NETL's life cycle natural gas model (Littlefield et al. 2019) has 148 specific sources of GHG emissions, but all of these emission sources fall into one of three broad types of unit processes:

- Venting, fugitive, and flaring emissions
- Combustion for process energy (engines, turbines, and external boilers)
- Ancillary processes

4.1.1 Venting, Fugitive, and Flaring Emissions

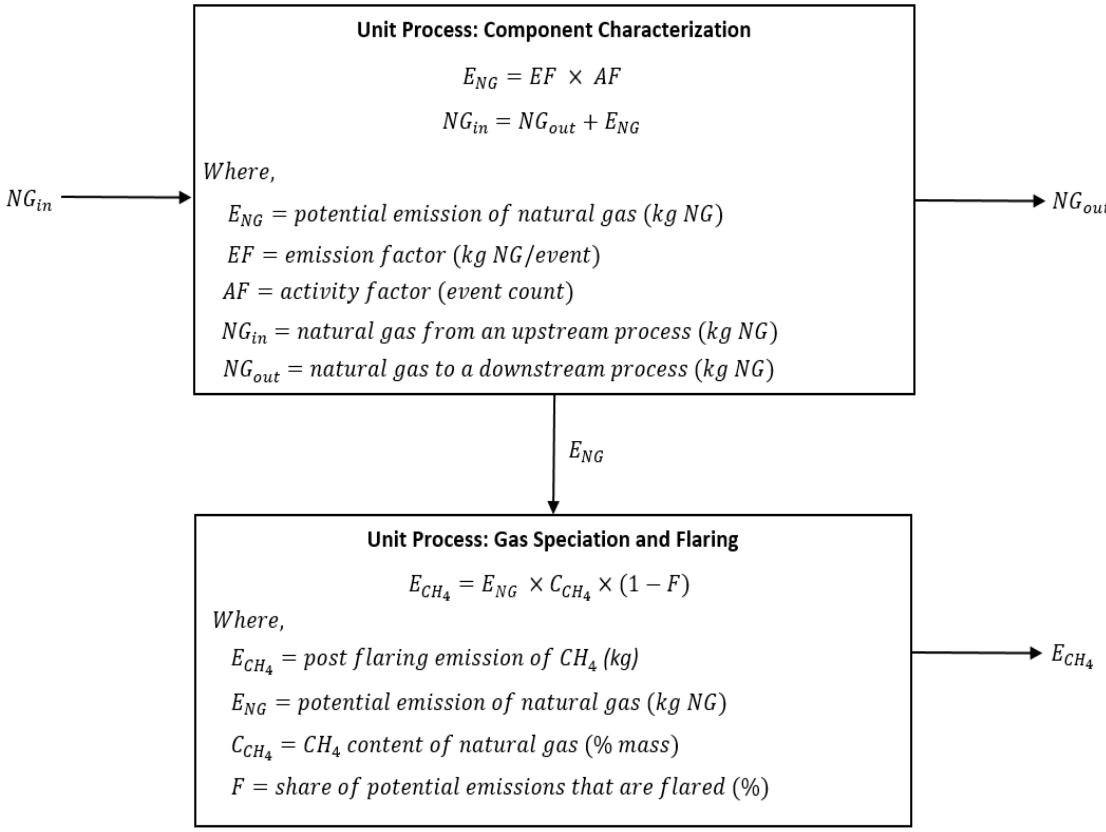
Venting is the intentional release of emissions to air and occurs in all stages of the natural gas supply chain. Examples of venting include gas emitted from acid gas removal (AGR) and dehydrator systems, occasional blow downs of compressors or other equipment, routine operation of pneumatic devices that use natural gas to actuate control equipment, and liquids unloading events that remove wellbore liquids that impede natural gas production.

Fugitive emissions are unintentional releases from equipment malfunctions (e.g., stuck dump valves) or infrastructure that is not performing as designed (e.g., leaks from connectors, valve stems, or pipelines). Fugitive emissions are the only emission source from the natural gas supply chain that can be correctly referred to as "leaks." Fugitive emissions occur in all supply chain stages. Production has fugitive emissions from connectors, flanges, open-ended lines, pressure relief valves, pumps, and valves. In addition to these specific emission sources, the GHGRP data also have a fugitive emission category for "other" fugitives. Gathering and boosting has fugitive emissions from equipment leaks and pipelines. Processing has fugitive emissions from equipment leaks. Transmission compression and storage have fugitive emissions from equipment leaks and pipeline leaks. Distribution has fugitive emissions from transmission and distribution stations, metering and regulating stations, mains and services, and customer meters.

In instances where vapor recovery is feasible, vented streams can be sent to flares and combusted. Flares convert CH_4 and volatile organic compounds in natural gas to CO_2, which is environmentally preferable because it reduces the potential environmental impacts of the emissions. Flaring is feasible in instances where there are large or continuous vent streams, such as the potential emissions from a well completion event when large volumes of flowback water are handled or a large natural gas processing facility that is continuously refining product streams. Flaring is usually not feasible for episodic venting (i.e., occasional, sporadic venting) or when the vented flow rate is not sufficient to sustain flaring. For example, the emissions from pneumatic devices and liquids unloading are intermittent and spatially scattered, which makes flaring unfeasible.

Exhibit 4-1 shows how whole gas is speciated into CO_2, CH_4, and N_2O, via direct release to air or flaring. The computation of these emissions first requires the computation of the potential emission of “whole gas.” Whole gas represents the complete chemical profile of natural gas (CH_4, CO_2, other hydrocarbons, hydrogen sulfide [H_2S], and inert gases such as helium or argon). In instances where an emission factor is in terms of CH_4 only, it is necessary to divide it by the CH_4 content in the whole gas to convert it to a quantity of whole gas. The whole gas is then factored by the flaring activity (the share of events that are controlled with flaring). Gas that is not flared is emitted as individual chemical species using the same chemical profile as the whole gas. When gas is flared, CH_4 and other hydrocarbons are converted to CO_2, H_2S is converted to S_2O, and inert gases pass through the flare. Flares have a combustion effectiveness of 98%, so 2% of the emissions from flare stacks are whole gas that is not combusted.

Exhibit 4-1: Unit Process Math for Venting and Flaring of Potential Emissions



4.1.2 Combustion for Process Energy

The natural gas supply chain consumes a portion of product natural gas to fuel the engines, turbines, and other equipment that are used to move and process natural gas. There are three categories of equipment that consume natural gas for process energy: reciprocating engines, gas turbines, external combustion units.

Reciprocating engines and gas turbines are used as prime movers for reciprocating compressors and centrifugal compressors, respectively. The fuel consumed by reciprocating engines and gas turbines is a function of their thermal efficiencies, factored by the compression efficiencies of their associated compressors. Thermal efficiency represents the efficiency at which input fuel energy is converted to output work of the engine or turbine. The compression of a gas requires work (specifically, the movement of a piston or impeller to displace gas). Compression efficiency represents the efficiency at which compressor input energy performs work on a gas. By equating gas compression with the combined efficiencies of prime movers and compressors, the corresponding fuel requirements and fuel combustion emissions can be determined.

Reciprocating engines and gas turbines have different fuel combustion characteristics. Both types of prime movers emit uncombusted hydrocarbons, including CH_4, in their exhaust gas, but reciprocating engines also emit CH_4 through piston rod packing. For reciprocating compressors, the nitrogen oxides (NO_X) emission factor is highly variable and depends on engine type (2-stroke lean-burn, 4-stroke lean-burn, and 4-stroke rich-burn) (EPA 2000b). The NO_X emission factors for gas turbines compressors are also variable, but of lower magnitude than those for reciprocating compressors (EPA 2000a). There are tradeoffs between combustion efficiency and NO_x emissions for lean- and rich-burn engines. Compared to rich burn engines, lean burn engines have more methane exhaust slip and lower NO_x emissions. These tradeoffs are outside the scope of this analysis, but they do explain why natural gas infrastructure has engines with relatively high CH_4 exhaust slip.

The production stage in NETL's life cycle model includes a unit process for diesel combustion (Littlefield et al. 2019). This unit process accounts for the quantity of upstream diesel used at the production site and the direct emissions from the combustion of the diesel. Diesel combustion emissions are representative of an uncontrolled diesel industrial engine.

In addition to the internal combustion engine technologies described above, external combustion units are used to provide heat for the regeneration of solvents used by dehydrators, AGR units, and other equipment. The capacities (Btu/hour) and combustion characteristics (flame temperature and combustion effectiveness) of these different heat applications are variable, but this analysis applies a single set of emission factors to the natural gas fuel combusted (EPA 1998). This is a simplification that assumes that the CO_2, CH_4, and N_2O combustion emission intensity does not vary significantly across this category of equipment.

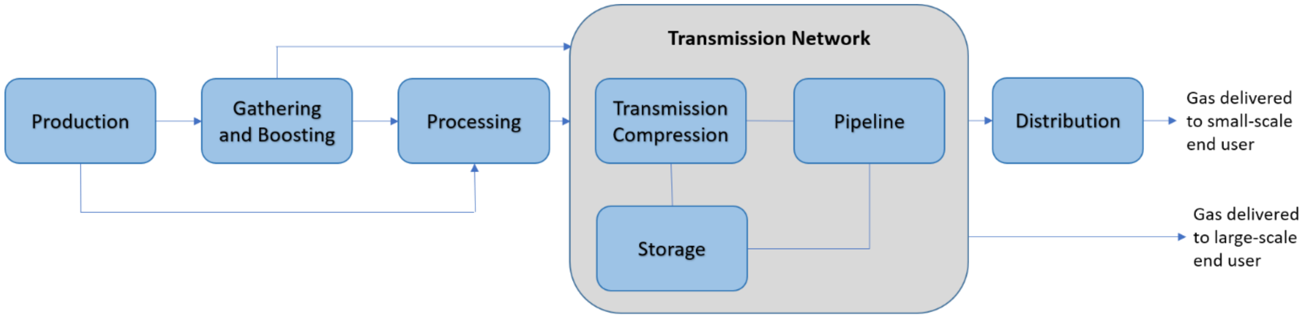
4.1.3 Ancillary Processes

Ancillary processes account for indirect contributors to the natural gas supply chain. These processes have cradle-to-gate burdens aggregated into a single process with no adjustable parameters. The ancillary processes comprise electricity (used to power a fraction of transmission compressors), diesel (used to power engines used during well construction), and steel and concrete (used as materials for the construction of wells, production facilities, gathering pipelines, and gathering and boosting facilities). The electricity data are based on NETL's grid mix explorer and represent the mix of electricity generation technologies used for the 2016 U.S. electricity consumption mix (Jamieson et al. 2019). The diesel data are representative of NETL's life cycle model of the petroleum supply chain (Cooney et al. 2017).

4.2 SUPPLY CHAIN STAGE SCALING

The life cycle model used in this analysis normalizes natural gas system flows to a single basis, the delivery of 1 MJ of natural gas to consumers. **Exhibit 4-2** shows the stage connectivity used by NETL's life cycle natural gas model (Littlefield et al. 2019).

Exhibit 4-2: Natural Gas Supply Chain Stages



The relationships among supply chain stages do not necessarily represent a single pathway with all stages connected in series. The following complexities must be resolved to normalize all emissions to a basis of 1 MJ of delivered natural gas:

- Most (but not all) natural gas goes through gathering and boosting facilities.
- Most (but not all) natural gas goes through processing facilities.
- Natural gas goes through multiple transmission stations.
- Storage facilities do not represent a natural gas throughput but an internal loop within the transmission network with storage and withdrawal.
- Some natural gas is consumed at the city gate and travels only through transmission, while the remainder travels all the way through distribution.

The scaling parameters in **Exhibit 4-3** should be interpreted in the context of an average unit of natural gas flowing through the supply chain. For example, using the information from the expected column in **Exhibit 4-3**, the pathway for average natural gas can be described as follows: after leaving a production site, 90% of natural gas goes through gathering and boosting stations; 61% goes through a processing plant, travels 600 miles through 10 transmission stations, and 55% goes through distribution.

Exhibit 4-3: Stage Scaling Parameters

Stage (or sub-stage)	Triangular Distributions			Units	Rationale
	Low	Expected	High		
Production		1		facility count	Natural gas is extracted from a well exactly one time.
Gathering and Boosting	0.8	0.9	1	fraction	The fraction of natural gas that goes through gathering and boosting is based on a recent measurement study (Marchese et al. 2015).
Processing	0.56	0.61	0.66	fraction	The total volume of U.S. annual processing throughput is 61% of annual natural gas delivered (EIA 2019d).
Transmission Compression	6.8	10.2	14.5	station count	Transmission station count is based on literature review of inter- and intra-state transmission station counts, reconciled by average facility throughput to estimate the number of transmission stations between processing and delivery.
Transmission Storage		0.37		dimensionless	The United States has 0.37 units of storage capacity per unit of delivered natural gas. This factor is the ratio of total underground storage capacity (9.2 Tcf) to annual gas delivered (25 Tcf) (EIA 2019d).
Transmission Pipelines	540	600	660	pipeline miles	Data for pipeline blowdown events are translated to an emission factor in terms of emissions per pipeline mile, thus requiring a corresponding activity factor in terms of pipeline miles traveled by average natural gas. The average distance of transmission is 600 miles (Littlefield et al. 2019).
Distribution		0.55		fraction	The share of natural gas that goes through distribution (55%) is based on unpublished data provided by the American Gas Association (AGA 2018) and supported by public data from EIA-176.

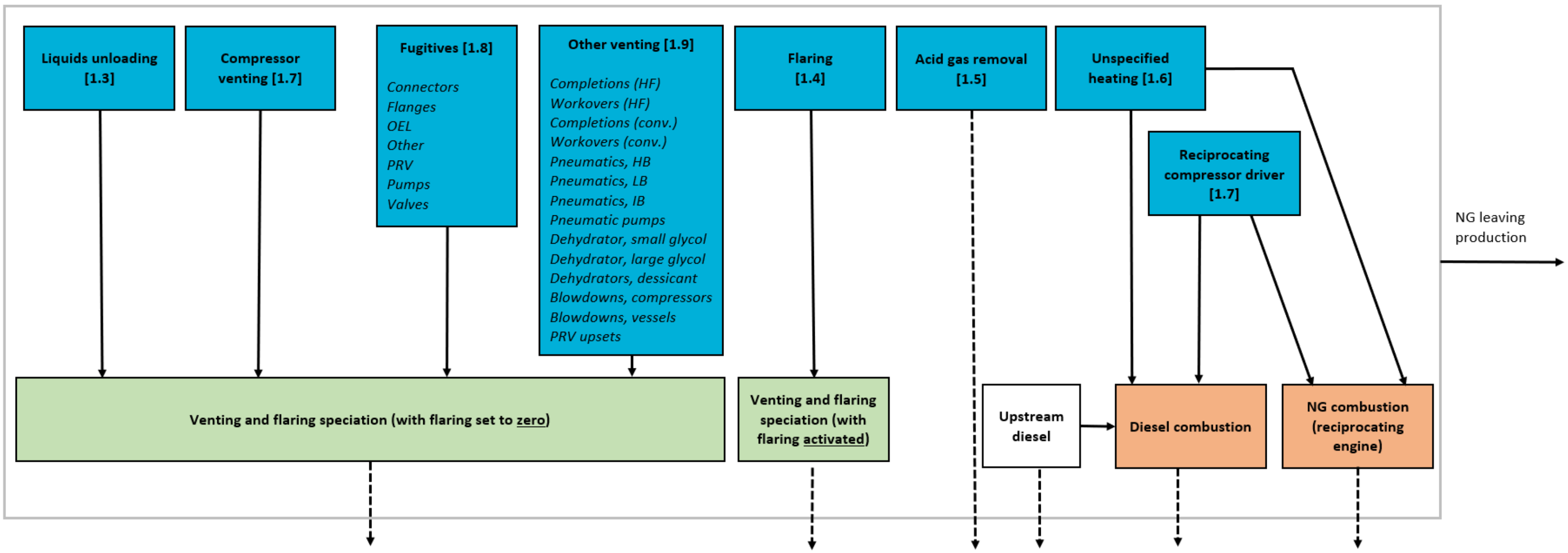
The scaling parameters shown in **Exhibit 4-3** are inputs to the model. When scaling the inputs and outputs for each supply chain stage, the natural gas model also accounts for the natural gas losses in each stage (natural gas losses comprise venting and fugitive emissions as well as natural gas consumed for fuel). The model has a fixed output (1 MJ of delivered natural gas); a loss at one point in the supply chain induces an increase in upstream flows to maintain a fixed output.

4.3 INTRASTAGE MAPPING

The following figures (**Exhibit 4-4** through **Exhibit 4-10**) show the emission sources and unit process connectivity within each natural gas supply chain stage. These figures demonstrate the following:

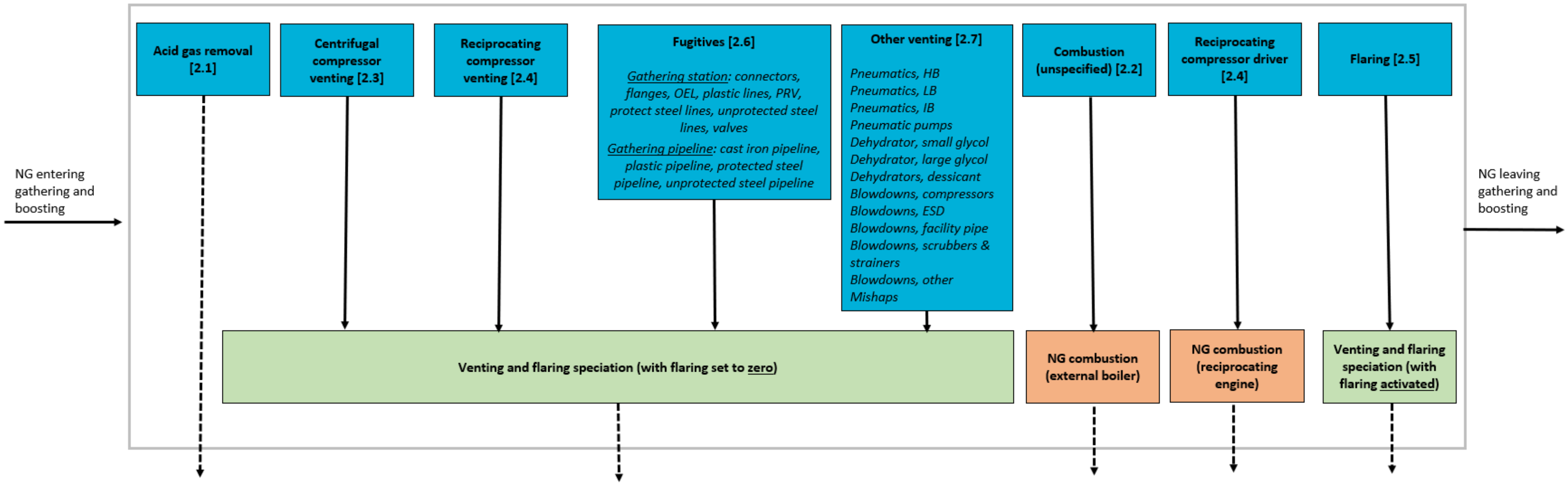
- **Speciation of venting, fugitive, and flaring emissions**. In instances where emissions are directly released to the atmosphere, the flaring parameter is set to zero. When flaring is employed, the flaring parameter is activated. AGR is one exception; it is a process that vents CO_2 and CH_4, but at different proportions than calculated for other venting, fugitive, and flaring emissions. AGR is a stand-alone unit process that emits GHG emissions according to the composition of natural gas and the effectiveness of the amine solvents used by AGR units.
- **Combustion of fuels for process energy**. In instances where natural gas is used for compressor drivers, combustion of natural gas in an engine is modeled for reciprocating compressors, and combustion of natural gas in a turbine is modeled for centrifugal compressors. When natural gas is combusted for process heat, the combustion of natural gas in an external combustion boiler is modeled. Diesel combustion for process heat is modeled using data for uncontrolled, industrial diesel engines.
- **Use of ancillary processes.** Ancillary processes comprise upstream diesel emissions (used as an input to onsite heat generation) and electricity generation (used by transmission compressor drivers). These processes account for the cradle-to-delivery emissions for diesel and grid electricity.

Exhibit 4-4: Unit Process Mapping for Natural Gas Production



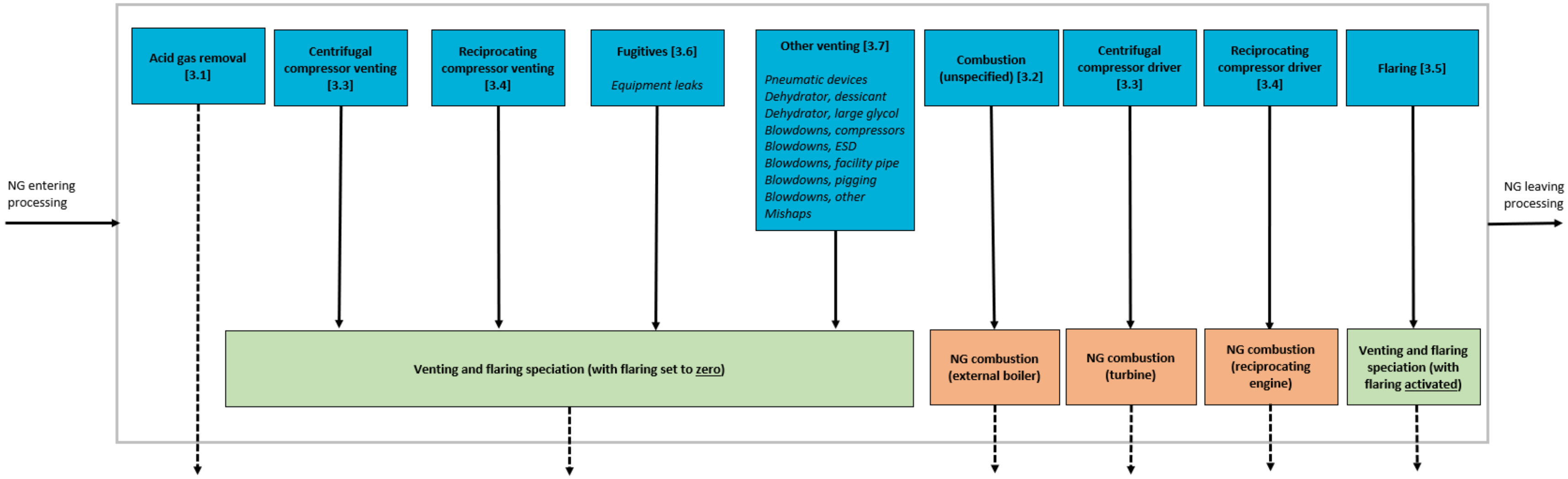
The GHG emissions for <u>natural gas production</u> are modeled using seven unit process groups (shown as blue boxes). The reference identifications (IDs) for these unit process groups range from [1.3] to [1.9] and correspond directly to the unit process numbering convention in NETL's life cycle natural gas model (Littlefield et al. 2019). *Some unit process groups represent a single emission source (e.g., liquids unloading [1.3]) while others represent multiple emission sources (e.g., other venting [1.9]). In instances where there are multiple emission sources in a unit process group, each emission source is specified in italics. Unit process groups [1.1] and [1.2] (not shown here) are included in NETL's life cycle natural gas model* (Littlefield et al. 2019) *but are outside the scope of this study. Unit process group [1.7] is shown twice in this figure because it is connected to venting and flaring speciation and diesel and natural gas combustion operations. The solid arrows between unit processes represent various reference flows: the flow of whole gas to another unit process for calculation of GHG emissions, the flow of fuel to a combustion process, or the upstream requirements of diesel. The dashed arrows represent GHG emissions released to air. The output of this stage is 1 unit of produced natural gas; all flows within this stage are scaled to this output. Acronyms: HF (hydraulic fracturing), conv. (conventional), HB (high bleed), LB (low bleed), IB (intermittent bleed), and PRV (pressure release valve).*

Exhibit 4-5: Unit Process Mapping for Natural Gas Gathering and Boosting



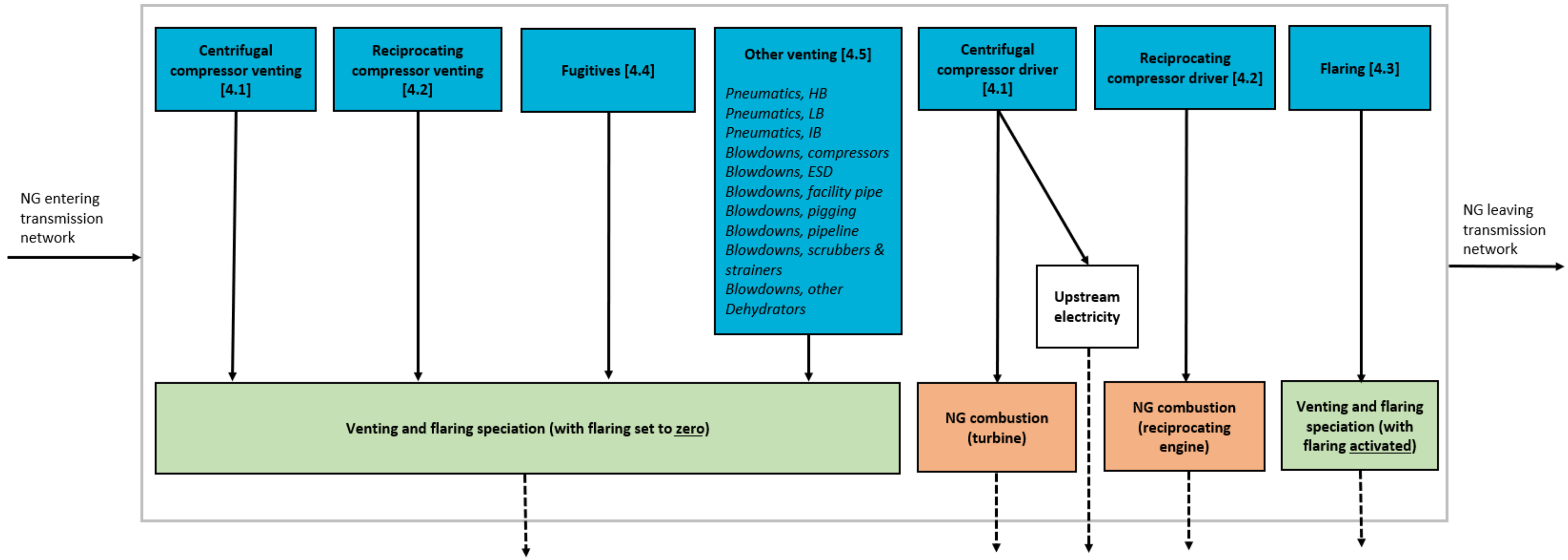
The GHG emissions for natural gas gathering and boosting *are modeled using seven unit process groups (shown as blue boxes). The reference IDs for these unit process groups range from [2.1] to [2.7] and correspond directly to the unit process numbering convention in NETL's life cycle natural gas model* (Littlefield et al. 2019). *Some unit process groups represent a single emission source (e.g., AGR [2.1] or centrifugal compressor venting [2.3]) while others represent multiple emission sources (e.g., fugitives [2.6]). In instances where there are multiple emission sources in a unit process group, each emission source is specified in italics. Unit process group [2.4] is shown twice in this figure because it is connected to venting and flaring speciation and natural gas combustion operations. The solid arrows between unit processes represent one of two types of reference flows: the flow of whole gas to another unit process for calculation of GHG emissions or the flow of fuel to a combustion process. The dashed arrows represent GHG emissions released to air. The input to this stage is natural gas from production. The output of this stage is 1 unit of natural gas to be sent to processing or transmission network; all flows within this stage are scaled to this output. Acronyms: OEL (open ended lines), PRV (pressure release valve), HB (high bleed), LB (low bleed), IB (intermittent bleed), and ESD (emergency shutdown).*

Exhibit 4-6: Unit Process Mapping for Natural Gas Processing



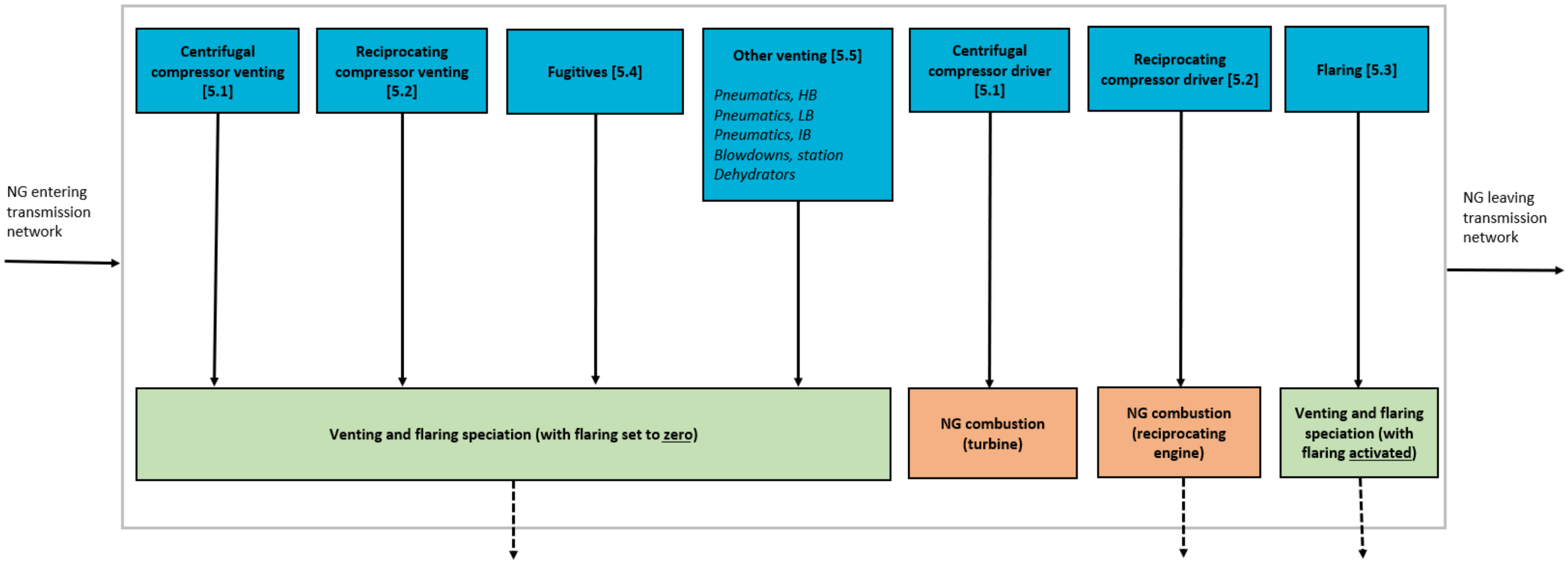
The GHG emissions for natural gas processing are modeled using seven unit process groups (shown as blue boxes). The reference IDs for these unit process groups range from [3.1] to [3.7] and correspond directly to the unit process numbering convention in NETL's life cycle natural gas model (Littlefield et al. 2019). *Some unit process groups represent a single emission source (e.g., AGR [3.1] or centrifugal compressor venting [3.3]) while others represent multiple emission sources (e.g., other venting [3.7]). In instances where there are multiple emission sources in a unit process group, each emission source is specified in italics. Unit process groups [3.3] and [3.4] are shown twice in this figure because they are connected to venting and flaring speciation and natural gas combustion operations. The solid arrows between unit processes represent one of two types of reference flows: the flow of whole gas to another unit process for calculation of GHG emissions or the flow of fuel to a combustion process. The dashed arrows represent GHG emissions released to air. The input to this stage is natural gas from production or gathering and boosting. The output of this stage is 1 unit of natural gas sent to transmission network; all flows within this stage are scaled to this output. Acronym: ESD (emergency shutdown).*

Exhibit 4-7: Unit Process Mapping for Natural Gas Transmission Compression



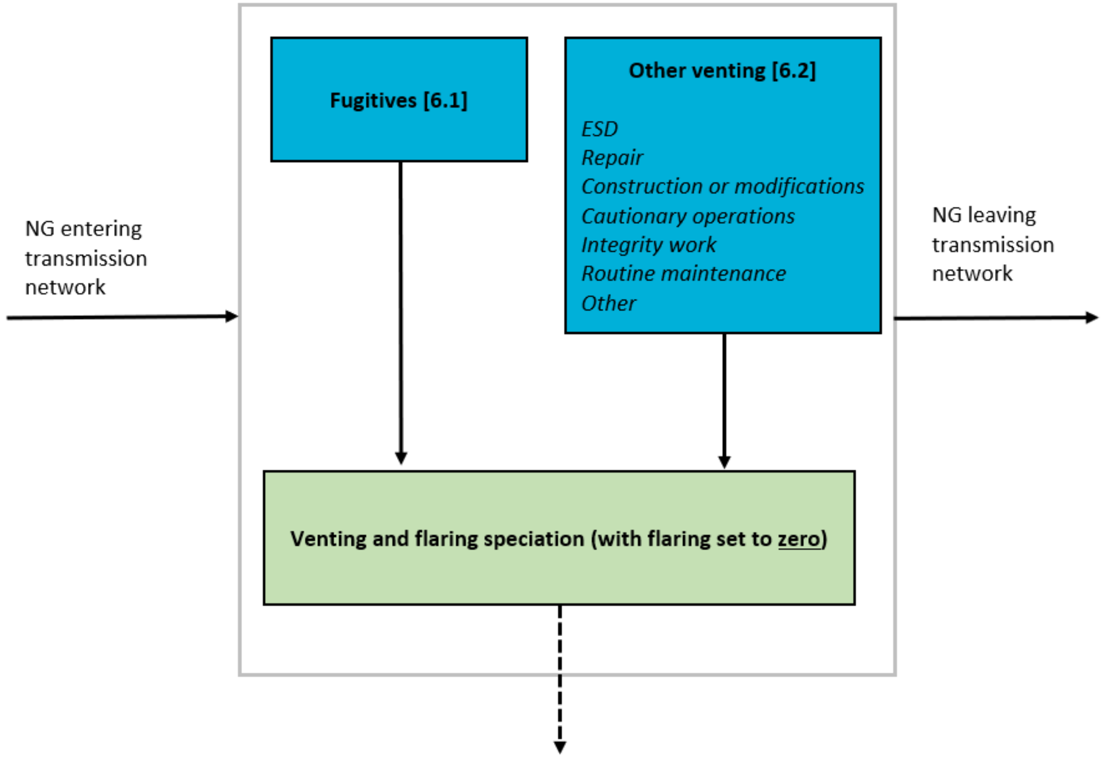
The GHG emissions for <u>*natural gas transmission compression*</u> *are modeled using five unit process groups (shown as blue boxes). The reference IDs for these unit process groups range from [4.1] to [4.5] and correspond directly to the unit process numbering convention in NETL's life cycle natural gas model* (Littlefield et al. 2019)*. Most unit process groups represent a single emission source; the one exception is other venting [4.5], which has 11 unique emission sources shown in italics. Unit process groups [4.1] and [4.2] are shown twice in this figure because they are connected to venting and flaring speciation and natural gas combustion operations. The solid arrows between unit processes represent various types of reference flows: the flow of whole gas to another unit process for calculation of GHG emissions, the flow of fuel to a combustion process, or the amount of upstream electricity required for compression energy. The dashed arrows represent GHG emissions released to air. The input to this stage is natural gas from processing or gathering and boosting. The output of this stage is 1 unit of natural gas sent to a large-scale end user (e.g., a power plant) or distribution; all flows within this stage are scaled to this output. Acronyms: HB (high bleed), LB (low bleed), IB (intermittent bleed), and ESD (emergency shutdown).*

Exhibit 4-8: Unit Process Mapping for Natural Gas Transmission Storage



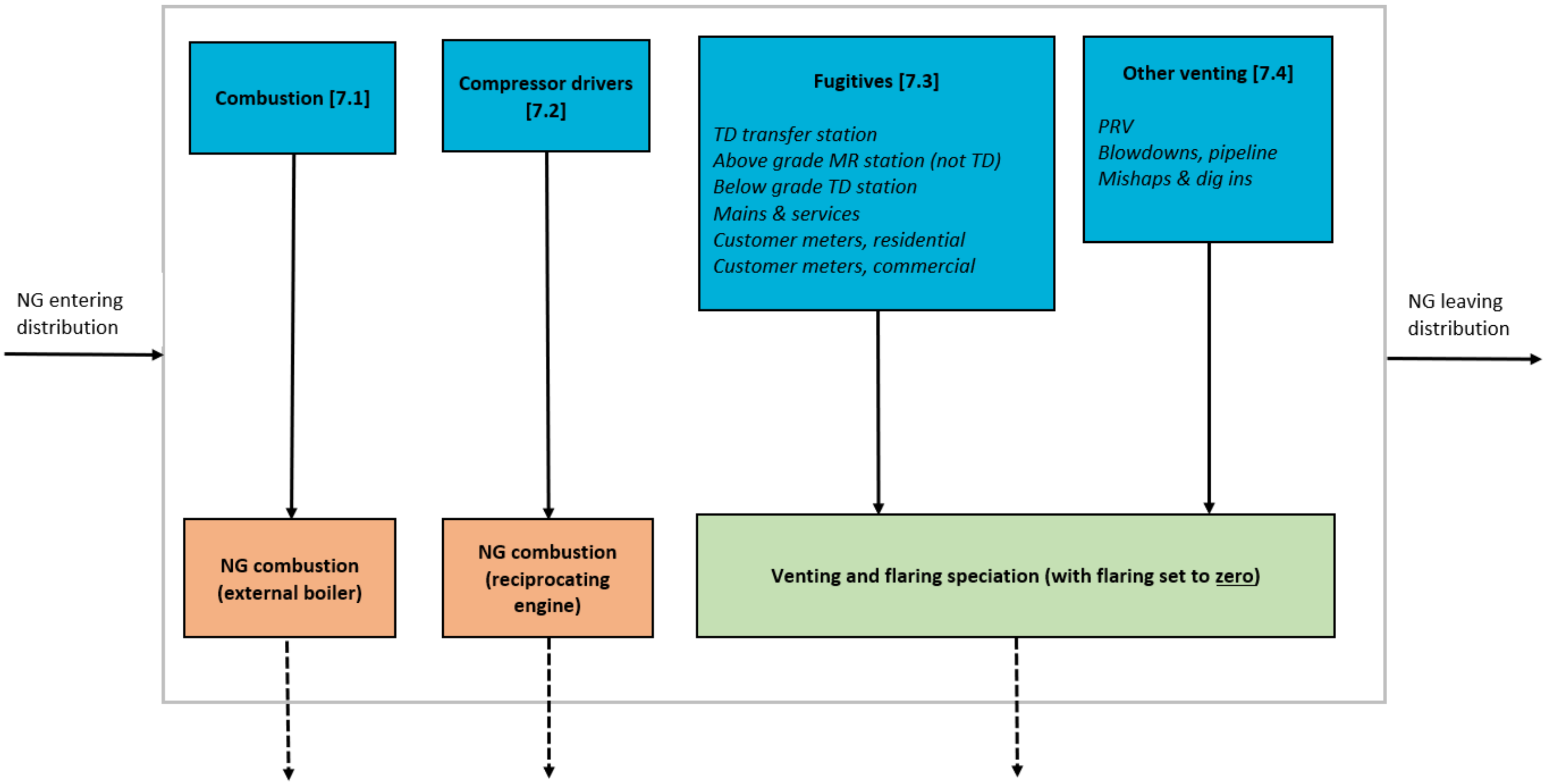
The GHG emissions for <u>*natural gas transmission storage*</u> *are modeled using five unit process groups (shown as blue boxes). The reference IDs for these unit process groups range from [5.1] to [5.5] and correspond directly to the unit process numbering convention in NETL's life cycle natural gas model* (Littlefield et al. 2019). *Most unit process groups represent a single emission source; the one exception is other venting [5.5], which has five unique emission sources shown in italics. Unit process groups [5.1] and [5.2] are shown twice in this figure because they are connected to venting and flaring speciation and natural gas combustion operations. The solid arrows between unit processes represent the flow of whole gas to another unit process for calculation of GHG emissions or the flow of fuel to a combustion process. The dashed arrows represent GHG emissions released to air. The output of this stage is 1 unit of natural gas storage capacity; natural gas transmission storage is a sub-stage that refers to the throughput of natural gas transmission compression stations to scale emissions to a life cycle basis. Acronyms: HB (high bleed), LB (low bleed), and IB (intermittent bleed).*

Exhibit 4-9: Unit Process Mapping for Natural Gas Transmission Pipelines



The GHG emissions for a natural gas transmission pipeline are modeled using two unit process groups (shown as blue boxes). The reference IDs for these unit process groups range from [6.1] to [6.2] and correspond directly to the unit process numbering convention in NETL's life cycle natural gas model (Littlefield et al. 2019). *Other venting [6.2] has seven unique emission sources shown in italics. The solid arrows between unit processes represent the flow of whole gas to another unit process for calculation of GHG emissions. The dashed arrow represents GHG emissions released to air. The input to this stage is natural gas from a transmission compression station. The output of this stage is the unit transport of natural gas (i.e., 1 kilogram (kg)-kilometer (km)). In addition to scaling flows based on the amount of natural gas throughput, this stage scales flow according to transport distance, which is a parameter in NETL's life cycle natural gas model* (Littlefield et al. 2019). *Acronym: ESD (emergency shutdown).*

Exhibit 4-10: Unit Process Mapping for Natural Gas Distribution



The GHG emissions for natural gas distribution are modeled using four unit process groups (shown as blue boxes). The reference IDs for these unit process groups range from [7.1] to [7.4] and correspond directly to the unit process numbering convention in NETL's life cycle natural gas model (Littlefield et al. 2019). *Combustion [7.1] and compressor drivers [7.2] represent a single emission source; fugitives [7.3] and other venting [7.4] represent multiple emission sources shown in italics. The solid arrows between unit processes represent flow of whole gas to another unit process for calculation of GHG emissions or the flow of fuel to a combustion process. The input to this stage is natural gas from transmission network. The output of this stage is 1 unit of natural gas sent to a small-scale end user (industrial, commercial, or residential consumers). Acronyms: MR (metering and regulating), TD (transmission-distribution), and PRV (pressure relief valve).*

4.4 CO-PRODUCT MANAGEMENT

The production of natural gas co-produces other valuable hydrocarbons (NGL and oil) that share the same infrastructure as natural gas during production, gathering and boosting, and processing. Natural gas is mixed with other products at the wellhead, in separator equipment, through gathering and boosting systems, and at processing facilities. An objective of most LCAs is to assign emissions to a single product or service, so it is necessary to apportion the emissions from these shared systems among the co-products. The co-production of natural gas, NGL, and crude oil should not be confused with the handling of associated gas at oil wells. In instances where associated gas is flared at oil wells, the associated gas is not a part of the natural gas supply chain—it is a flared byproduct of the petroleum supply chain.

The co-products are in gas and liquid forms. The heat content of each co-product is used to convert gas and liquid volumes to an energy basis. The following heat contents were used for this conversion:

- Crude oil and condensate = 5.8 MMBtu/bbl (EIA 2016)
- NGL = 3.7 MMBtu/bbl (EIA 2016)
- Natural gas = 1,235 Btu/scf (this is the production gas heating value provided by ONE Future members and is not representative of all natural gas)

When co-products share the same unit process, the emissions from the unit process are divided by the throughput of natural gas equivalents based on the heating value listed above instead of the throughput of actual natural gas. Doing so reduces the share of emissions attributed to natural gas, thus allocating emissions between natural gas and its co-products.

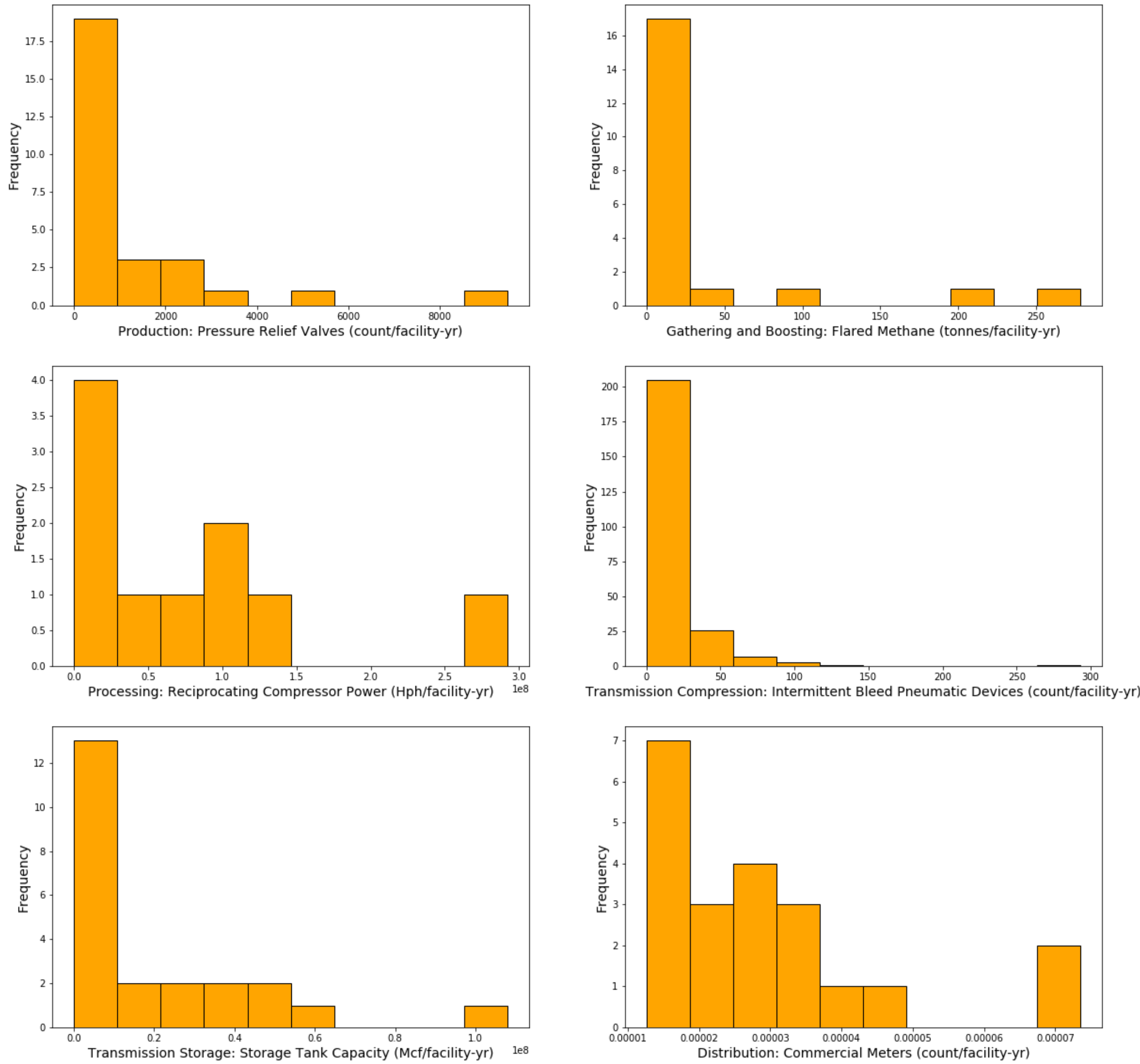
5. UNCERTAINTY

Uncertainty can be caused by inconsistent definitions, random sampling error, lack of representativeness, and natural variability (Rypdal and Winiwarter 2001). NETL has no basis for questioning the first three sources of uncertainty (inconsistent definitions, random sampling error, and lack of representativeness). Variability is one source of uncertainty that is addressed in this analysis.

The variability in ONE Future's data is a function of both natural and technological phenomena. For example, the quantity of natural gas available for recovery, the composition of natural gas, and the production ratio of gas, oil, and NGL are natural phenomena that vary from basin to basin. Examples of technological variability include the profile of pneumatic controllers (which comprise low-, intermittent-, and high-bleed devices), the mix of compression technologies (centrifugal and reciprocating), and the type of seals used around the rotating shafts of centrifugal compressors (wet and dry seals). Variability leads to uncertainty because system parameters are expressed as distributions of likely values, not single-point, deterministic values.

Most of the parameters in the partner data have positively skewed probability distribution functions. **Exhibit 5-1** shows examples of skewed probability distribution functions from the ONE Future data representing different stages in the supply chain.

Exhibit 5-1: Examples of a Positively-Skewed Distributions from ONE Future's Data



Positively-skewed distributions have high, albeit infrequent, values that affect the overall mean of the distributions. These high values cannot be treated as outliers and excluded from the data set. Doing so would require an arbitrary decision on where to truncate the long tail of a skewed distribution. This differs from the identification of outliers in normal distributions. Due to the symmetry of normal distributions, the identification of outliers in normal distributions is not as problematic as for skewed distributions.

Another complication with skewed distributions is that a high number of samples is required to reliably fit them with a curve or determine their statistical parameters (mean, standard deviation, etc.). For example, the distribution of discrete values in the transmission compression stage in **Exhibit 5-1** comprises 243 data points, which is a large sample size for emission sources in the natural gas sector. Nonetheless, the 243 data points exemplify an irregular distribution for which the statistical parameters (i.e., mean, standard deviation, etc.) are highly uncertain. All other stages represented in this figure individually have less than 30 data points each; the fitting of continuous curves to these data points would not be reliable.

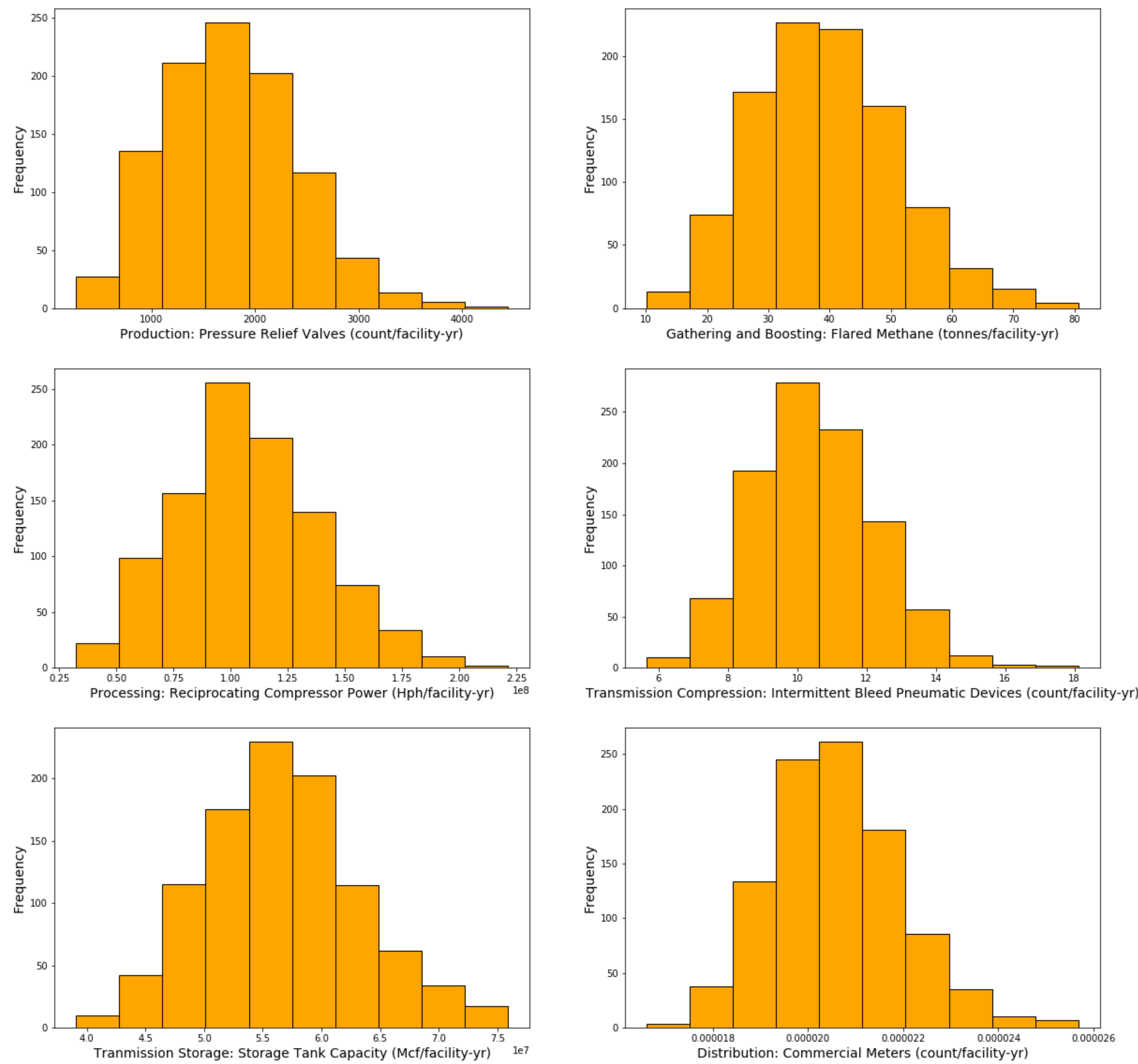
Fortunately, the objective of this analysis is to calculate the average emissions from natural gas, not the probability that a randomly selected unit of natural gas has a given GHG emission profile. This objective can be accomplished using stochastic methods that sample from sets of discrete data points, precluding the need to fully understand the way in which the data are distributed. This analysis uses non-parametric statistical bootstrapping to generate sample averages from the data and then compute the confidence intervals of the averages. Non-parametric means that a curve is not fit to the data. Rather, discrete data points are sampled using a probability distribution function based on the throughput of each facility (i.e., data points are more likely to be sampled from facilities with high natural gas throughputs). Bootstrapping is a sampling method that constrains the size of each sample average by the number of actual data points (something that Monte Carlo alone does not do). This constraint translates to higher uncertainty when there are fewer data points and lower uncertainty when there are many data points. As shown in **Equation 5-1,** the standard error of the sample mean (σ_x) is the standard deviation of the sample population (s) divided by the square root of the sample size (n). By using statistical bootstrapping, this analysis characterizes the uncertainty in average emissions by considering both the variability and size of sample data.

Equation 5-1

$$\boldsymbol{\sigma_x = \frac{s}{\sqrt{n}}}$$

Exhibit 5-2 provides examples of the mean probability distribution functions generated in this analysis. It was constructed by sampling from the data in **Exhibit 5-1** and demonstrates how the *average* values from repeated samplings from a skewed distribution approach a normal distribution (the central limit theorem). This is a robust way of handling the skewed probability distributions for natural gas system activity because curve fitting or correlation analysis are not required, and the distribution of sample averages accounts for data scatter and number of data points.

Exhibit 5-2: Example of a Sample Average Distribution from ONE Future's Data



The above type of simulation was conducted for all parameters in the ONE Future data set, allowing the calculation of average values and the standard deviation of the average values. This method simplifies the development of parameters for the life cycle model, while accurately representing the partner data. The descriptive statistics for the mean values of all ONE Future parameters are shown in **Appendix A.**

In addition to the uncertainty caused by the variability discussed above, there are a few other sources of uncertainty in this analysis:

- Uncertainty is caused by the linking of ONE Future supply chain stages into a single, integrated supply chain (as discussed in **Section 4.3**).
- Uncertainty is caused by the combined modeling of transmission facilities within the GHGRP and those below the GHGRP reporting threshold. The two types of facilities are mixed based on their relative natural gas throughputs.
- Uncertainty is caused by variability in liquids unloading (as discussed in **Section 3.4**). This variability represents the positively-skewed probability distributions for unloading events and unloading durations.

6. RESULTS

The results show how CH_4 and other GHG emissions from the ONE Future scenarios compare to the corresponding U.S. scenarios. The results point to key emission contributors and sources of uncertainty.

6.1 ONE FUTURE AVERAGE AND U.S. AVERAGE SCENARIOS

This analysis focuses on CH_4 emissions across the supply chain and how they vary geographically. To provide a full GHG perspective, this analysis also accounts for the corresponding CO_2 emissions from venting and combustion processes.

6.1.1 CH_4 Emissions

This analysis uses two metrics to express results for CH_4 emissions:

- **CH_4 emissions** (grams of CH_4 emitted per MJ of delivered natural gas)
- **CH_4 emission rates** (mass of CH_4 emissions per mass of natural gas delivered)

Exhibit 6-1 and **Exhibit 6-2** show the CH_4 emissions and CH_4 emission rates for the ONE Future and U.S. scenarios, respectively. Results are grouped into stages. Error bars represent 95% mean confidence intervals for CH_4 emissions. The gray, shaded areas represent 95% mean confidence intervals for CH_4 emission rates.

The average CH_4 emissions for the ONE Future scenario are 0.13 gram (g) CH_4/MJ, with a 95% confidence interval from 0.09 – 0.19 g CH_4/MJ. The average CH_4 emissions for the U.S. scenario are 0.18 g CH_4/MJ, with a 95% confidence interval of 0.13–0.26 g CH_4/MJ.

The average CH_4 emission rate for the ONE Future scenario is 0.76%, with a 95% confidence interval of 0.49 – 1.08%. The average CH_4 emission rate for the U.S. scenario is 1.06%, with a 95% confidence interval of 0.75–1.46%.

In production, processing, and pipeline stages of the supply chain, the expected value of CH_4 emissions is lower for ONE Future as compared to the U.S. average. In gathering and boosting, transmission compression, storage, and distribution stages, the expected CH_4 emissions for ONE Future is higher than the U.S. average. The error bars for the ONE Future average scenario overlap the error bars on the corresponding U.S. average results for all stages except for production.

Exhibit 6-1: Life Cycle Natural Gas CH_4 Emissions and Emission Rate for ONE Future (2017 data)

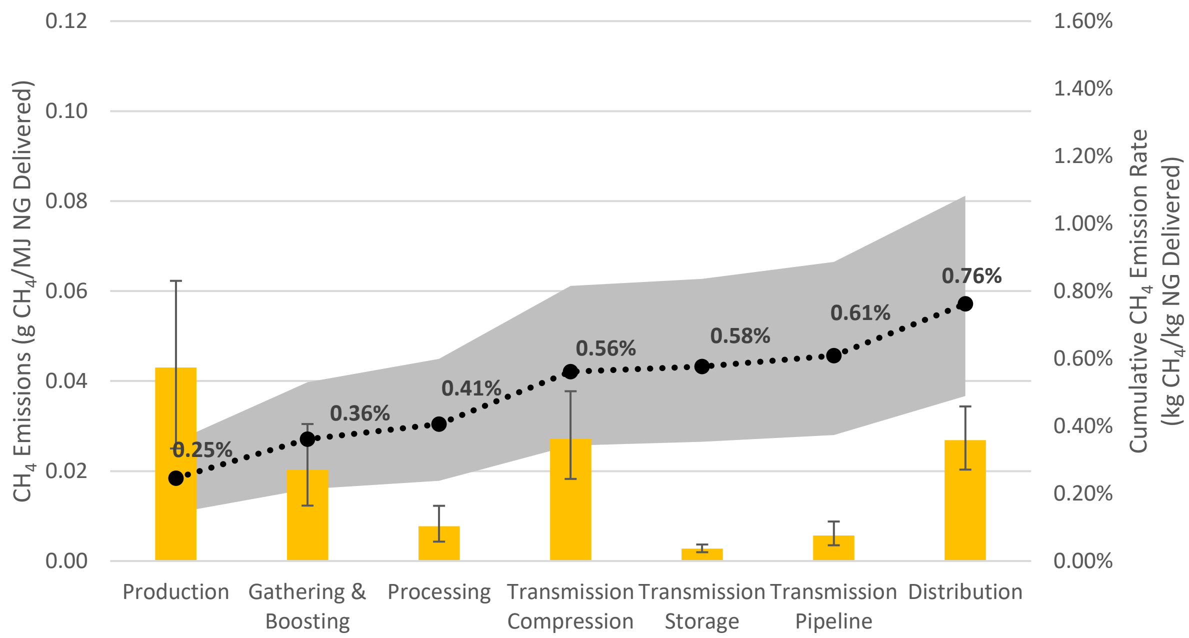


Exhibit 6-2: Life Cycle Natural Gas CH_4 Emissions and Emission Rate for the U.S. (2017 data)

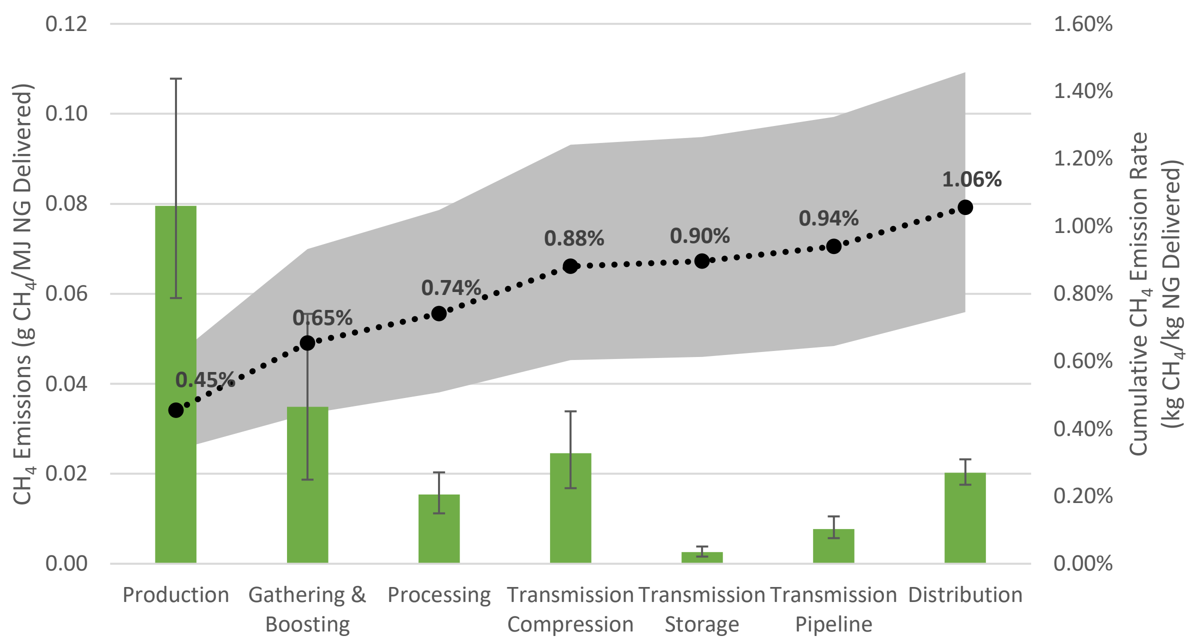


Exhibit 6-1 and **Exhibit 6-2** show cumulative CH_4 emission rates, which are the sum of all CH_4 emissions from production to each point in the supply chain. **Exhibit 6-3** shows emission rates for each stage in the supply chain, allowing a better interpretation of the CH_4 emission contribution from individual stages. The average values represent mean emission rates, and the

P2.5 and P97.5 values represent 95% mean confidence intervals around mean emission rates. These values are on the basis of natural gas delivered to end users, so their sums are equivalent to cumulative life cycle CH_4 emission rates.

Exhibit 6-3: Life Cycle Natural Gas CH_4 Emission Rates by Supply Chain Stages

Stage	ONE Future			U.S.		
	P2.5	Average	P97.5	P2.5	Average	P97.5
Production	0.143%	0.246%	0.356%	0.337%	0.454%	0.616%
Gathering and Boosting	0.070%	0.116%	0.174%	0.107%	0.199%	0.317%
Processing	0.025%	0.044%	0.070%	0.064%	0.088%	0.116%
Transmission Compression	0.104%	0.155%	0.216%	0.096%	0.140%	0.193%
Transmission Storage	0.011%	0.016%	0.021%	0.009%	0.015%	0.022%
Transmission Pipeline	0.020%	0.032%	0.050%	0.032%	0.044%	0.060%
Distribution	0.116%	0.153%	0.196%	0.100%	0.116%	0.133%
Total	**0.49%**	**0.76%**	**1.08%**	**0.75%**	**1.06%**	**1.46%**

Expanding the stage results to detailed emission categories provides more insight on the differences between the two scenarios. **Exhibit 6-4** and **Exhibit 6-5** show detailed CH_4 emissions for the ONE Future average and U.S. average scenarios, respectively.

Exhibit 6-4: Detailed Life Cycle CH_4 Emissions for ONE Future Natural Gas Supply Chain

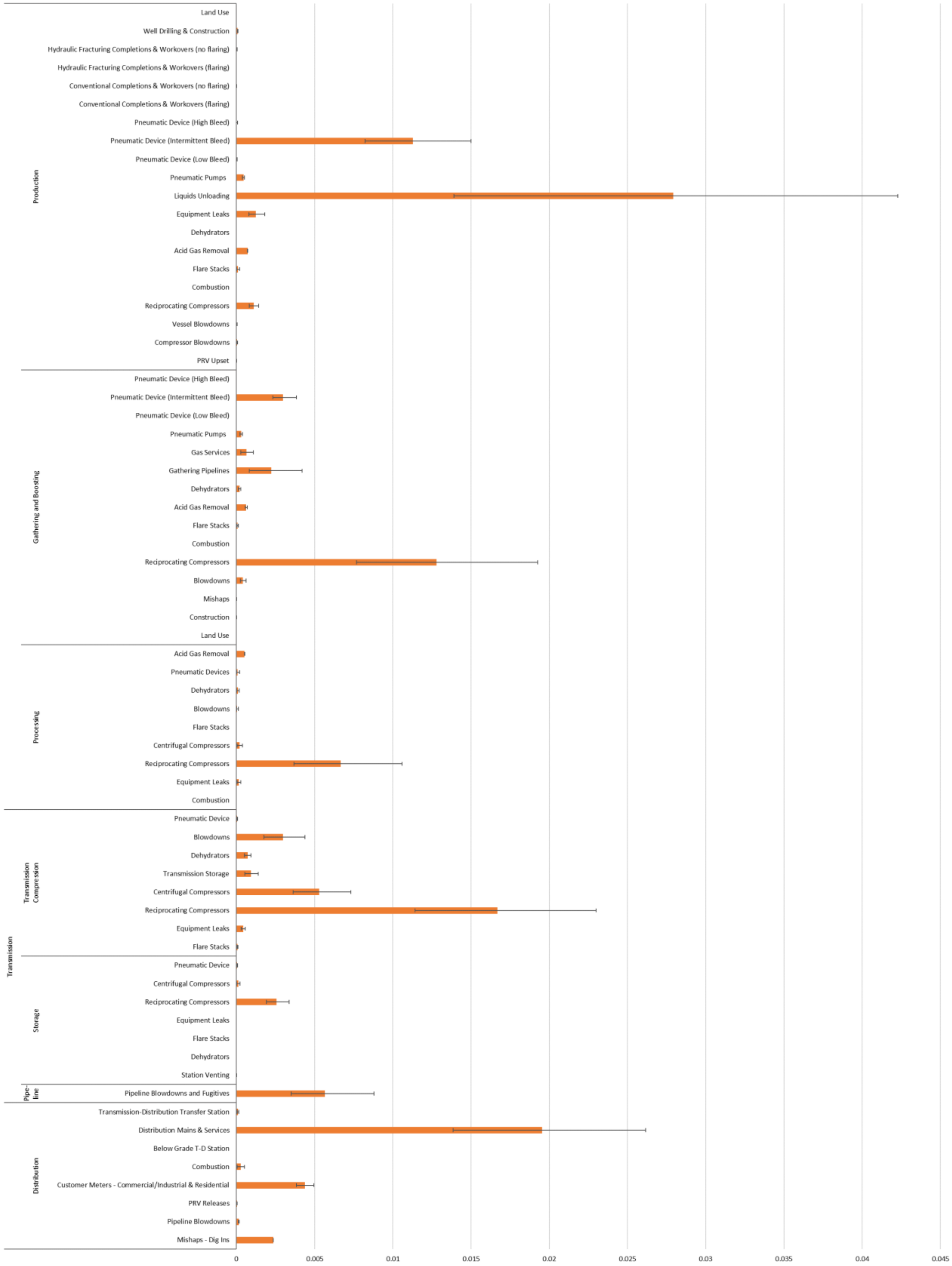


Exhibit 6-5: Detailed Life Cycle CH_4 Emissions for U.S. Natural Gas Supply Chain

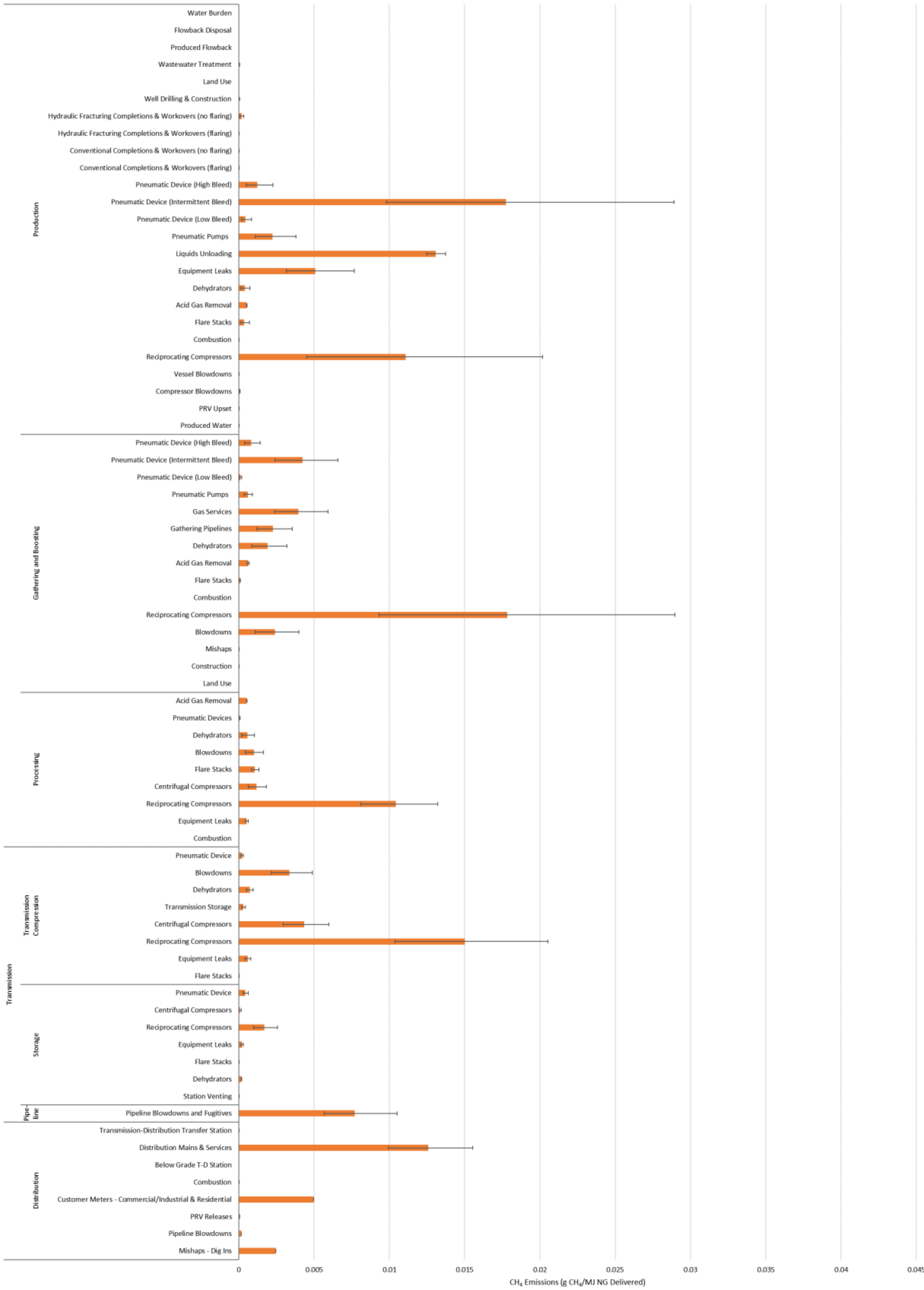


Exhibit 6-6 allows interpretation of the detailed results for the ONE Future average scenario by ranking the top life cycle CH_4 emission contributors from **Exhibit 6-4**. The 15 emission sources shown in **Exhibit 6-6** account for more than 93% of ONE Future's life cycle CH_4 emissions.

Exhibit 6-6: Top ONE Future Methane Emission Sources

Contribution to Total ONE Future CH_4 Emissions	Stage	Emission Source
20.9%	Production	Liquids Unloading
14.6%	Distribution	Distribution Mains & Services
12.5%	Transmission Compression	Reciprocating Compressors
9.6%	Gathering and Boosting	Reciprocating Compressors
8.5%	Production	Pneumatic Device (Intermittent Bleed)
5.0%	Processing	Reciprocating Compressors
4.2%	Transmission Pipeline	Pipeline Blowdowns and Fugitives
4.0%	Transmission Compression	Centrifugal Compressors
3.3%	Distribution	Customer Meters - Commercial/Industrial & Residential
2.2%	Gathering and Boosting	Pneumatic Device (Intermittent Bleed)
2.2%	Transmission Compression	Blowdowns
1.9%	Transmission Storage	Reciprocating Compressors
1.8%	Distribution	Mishaps - Dig Ins
1.7%	Gathering and Boosting	Gathering Pipelines
0.9%	Production	Equipment Leaks

The top five contributors to the CH_4 emissions from the ONE Future average scenario are liquids unloading at production, distribution mains and services at distribution, reciprocating compressors at transmission compression, reciprocating compressors at gathering and boosting, and intermittent bleed pneumatic devices at production. The CH_4 emissions from reciprocating compressors are prevalent through various stages of the supply chain; they are a significant emission from gathering and boosting, processing, transmission compression, and storage.

Liquids unloading is the highest contributor to the CH_4 emissions from the ONE Future average scenario. It accounts for the high variability in unloading frequencies, technologies, and practices. This variability is not accounted for by the reported emissions from plunger and manual unloading methods but is accounted for by NETL's simulation of liquids unloading parameters as described in **Section 3.4**.

The emissions from distribution mains and services are a function of system age and pipeline materials. ONE Future includes companies with large inventories of leak-prone pipe and companies with high shares of cast iron pipe.

Reciprocating compressors in transmission compression, gathering and boosting, processing, and storage stages are all top emitters of CH_4; and in all these stages together, it accounts for

29% of the total CH_4 emissions. This is an emission source that shows up as a significant emitter in four stages, thus representing an opportunity for many operators in the supply chain.

CH_4 emissions from intermittent bleed pneumatic devices are a function of the number of devices at a facility and their emission factors. Due to the high activity of intermittent bleed devices relative to high bleed devices, the total emissions from intermittent bleed devices are higher than those from high bleed devices.

Exhibit 6-7 shows the same emission sources as **Exhibit 6-6,** but it also shows the differences in CH_4 emissions between the ONE Future average and U.S. average scenarios. The heat map moves from green to red to indicate the emission sources where ONE Future has the largest decrease to the largest increase as compared to the U.S. supply chain (dark green represents sources with a greater than 30% reduction in ONE Future's average emission intensity as compared to the U.S. average, light green represents 6% to 30% reductions, yellow represents changes within 5% of the U.S. average, light red represents 6% and 30% increase, and dark red represents greater than 30% increase).

Exhibit 6-7: Comparison of Emission Source CH_4 Emissions between ONE Future and the U.S.

Contribution to total ONE Future CH_4 Emissions	Stage	Emission Source	Difference between ONE Future and U.S.	
			g CH_4/MJ*	Percent**
20.9%	Production	Liquids Unloading	1.48E-02	113%
14.6%	Distribution	Distribution Mains & Services	6.95E-03	55%
12.5%	Transmission Compression	Reciprocating Compressors	1.68E-03	11%
9.6%	Gathering and Boosting	Reciprocating Compressors	-5.04E-03	-28%
8.5%	Production	Pneumatic Device (Intermittent Bleed)	-6.48E-03	-36%
5.0%	Processing	Reciprocating Compressors	-3.75E-03	-36%
4.2%	Transmission Pipeline	Pipeline Blowdowns and Fugitives	-2.07E-03	-27%
4.0%	Transmission Compression	Centrifugal Compressors	9.65E-04	22%
3.3%	Distribution	Customer Meters - Commercial/Industrial & Residential	-5.67E-04	-11%
2.2%	Gathering and Boosting	Pneumatic Device (Intermittent Bleed)	-1.27E-03	-30%
2.2%	Transmission Compression	Blowdowns	-4.05E-04	-12%
1.9%	Transmission Storage	Reciprocating Compressors	8.66E-04	51%
1.8%	Distribution	Mishaps - Dig Ins	-7.97E-05	-3%
1.7%	Gathering and Boosting	Gathering Pipelines	-4.00E-05	-2%
0.9%	Production	Equipment Leaks	-3.82E-03	-75%

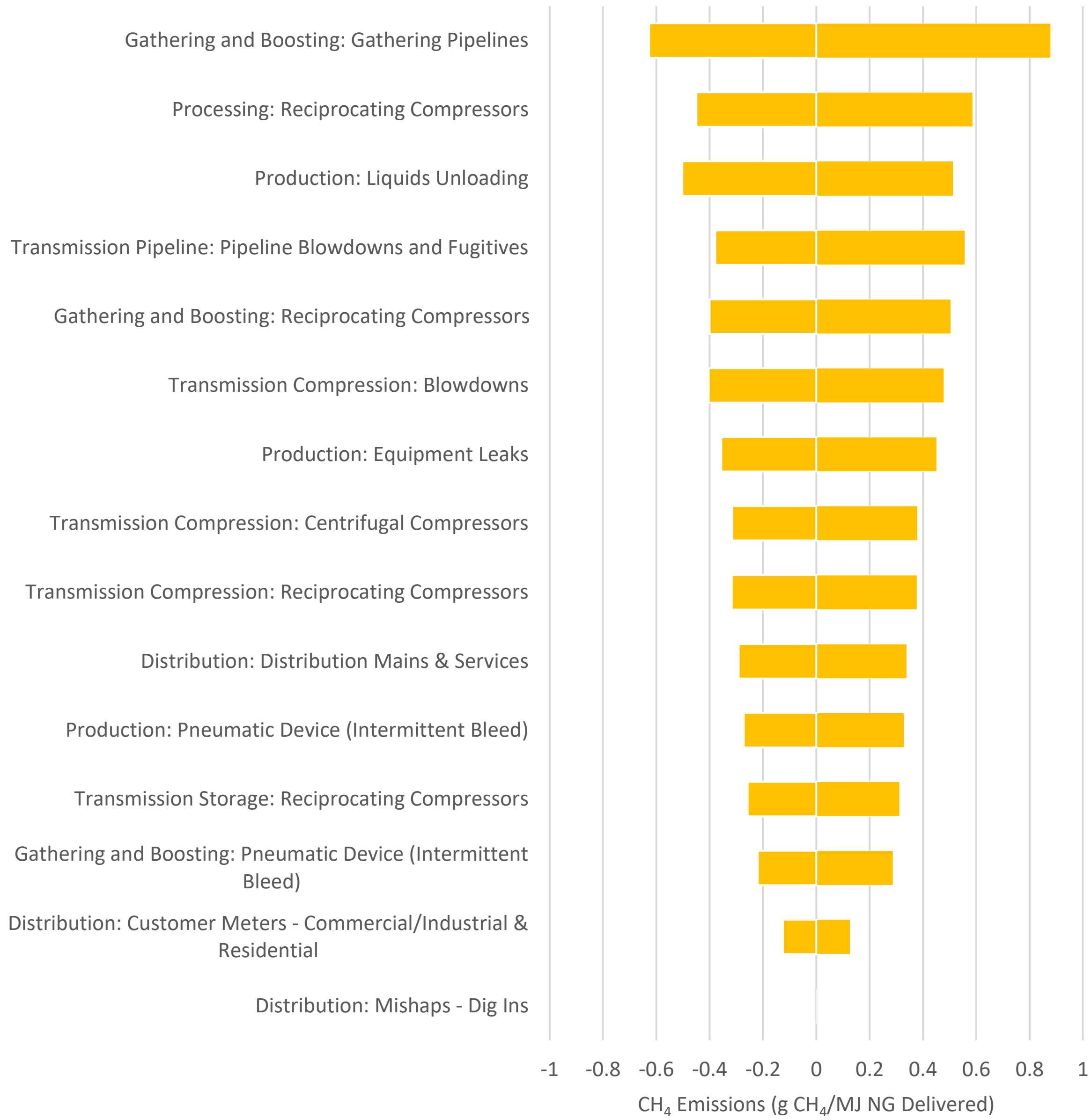
* Negative values for these emission-intensity differences represent instances where ONE Future is lower than the U.S. Conversely, positive values represent instances where ONE Future is greater than the U.S.
** Percent differences are calculated as follows: (ONE Future – U.S.)/(U.S.) * 100%.

The top five differences between ONE Future average and the U.S. average emission intensities are liquids unloading at production, equipment leaks at production, distribution mains and services at distribution, reciprocating compressors at transmission storage, and intermittent bleed pneumatic devices at production. Three of these emission sources have higher intensity for ONE Future than for the U.S.

There are two emission sources in **Exhibit 6-7** that represent greater than 10% contribution to total emission intensity from the ONE Future average scenario, while also representing a significant difference in CH_4 emission intensity between the ONE Future average and U.S. average scenarios. The emission intensity of liquids unloading at production represents 20.9% of total emission intensity from the ONE Future average scenario and is 113% higher for ONE Future than for the U.S. The emission intensity of distribution mains and services represent 14.6% of total emission intensity from the ONE Future average scenario and is 55% higher for ONE Future than for the U.S.

The ranking of emission source uncertainty provides yet another way to interpret the CH_4 emission results. **Exhibit 6-8** ranks the top contributors to CH_4 emission uncertainty for the ONE Future average scenario. The top five sources of uncertainty are gathering pipeline at gathering and boosting, reciprocating compressors at processing, liquids unloading at production, pipeline blowdowns and fugitives at transmission pipeline, and reciprocating compressors at gathering and boosting. The uncertainty for all these emission sources is a function of the variability in the underlying data as discussed in **Section 5**. Note that even though the emission source "Distribution: Mishaps – Dig Ins" is one of the top 15 CH_4 emitters in the ONE Future supply chain, it doesn't have any uncertainty because an average activity and emission factor is used to fill a gap in the provided data.

Exhibit 6-8: Uncertainty in the Top 15 CH_4 Emitters in ONE Future Supply Chain



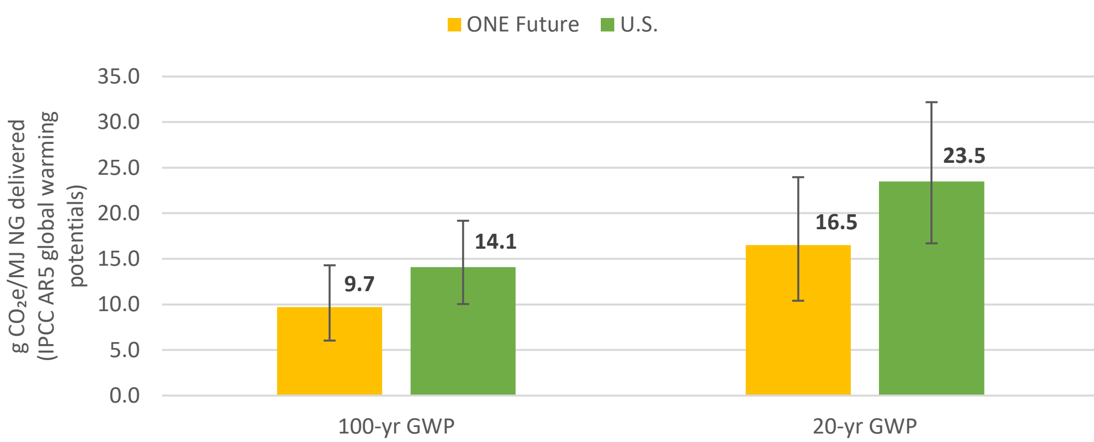
6.1.2 GHG Emissions

This work focuses mostly on CH_4 emissions, but the inclusion of CO_2 and N_2O is also necessary to provide a complete assessment of GHG impacts. Global warming potentials (GWPs) are necessary to normalize CO_2, CH_4, and N_2O to the basis of carbon dioxide equivalents (CO_2e). GWPs are impact factors that account for the unique radiative forcing from different GHG emission species (CO_2, CH_4, N_2O, etc.) to normalize GHG emissions into a single metric (CO_2e). Different GHG emission species have different time series behaviors, such as unique decay rates and feedback relationships with other environmental variables. Due to these different time series behaviors, GWP weighting factors vary over different time horizons of interest; e.g., 100-year compared to 20-year time horizon. NETL uses 100-year and 20-year GWPs developed by the Intergovernmental Panel on Climate Change (IPCC) in its fifth assessment report (AR5) (IPCC 2013), as illustrated in **Exhibit 6-9**. The 100-year and 20-year CO_2e for the ONE Future and U.S. average scenarios are shown in **Exhibit 6-10**. The error bars represent the 95% confidence interval of the mean.

Exhibit 6-9: IPCC AR5 Global Warming Potentials

GHG	20-year	100-year
CO_2	1	1
CH_4	87	36
N_2O	268	298

Exhibit 6-10: Life Cycle GHG Emissions for Delivered Natural Gas



In terms of IPCC 100-year GWPs, the ONE Future and U.S. average scenarios emit 9.7 and 14.1 g CO_2e/MJ of delivered natural gas, respectively. The uncertainty bounds for 100-year CO_2e overlaps for the two scenarios. On a 100-year GWP timeframe, the life cycle GHGs for delivered natural gas are not statistically different between ONE Future and the U.S.

In terms of IPCC 20-year GWPs, the ONE Future and U.S. scenarios emit 16.5 and 23.5 g CO_2e/MJ of delivered natural gas, respectively. Like the 100-year GWP results, the 20-year GWP results for the two scenarios also overlap. Therefore, on a 20-year GWP timeframe, the life cycle GHGs for delivered natural gas are not statistically different between ONE Future and the U.S.

Detailed GHG profiles for the two scenarios are shown in **Exhibit 6-11** and **Exhibit 6-12**. These figures use 100-year GWPs and provide more insight into the GHG profiles of the two scenarios.

Exhibit 6-11: Detailed Life Cycle Natural Gas GHG Emissions for ONE Future

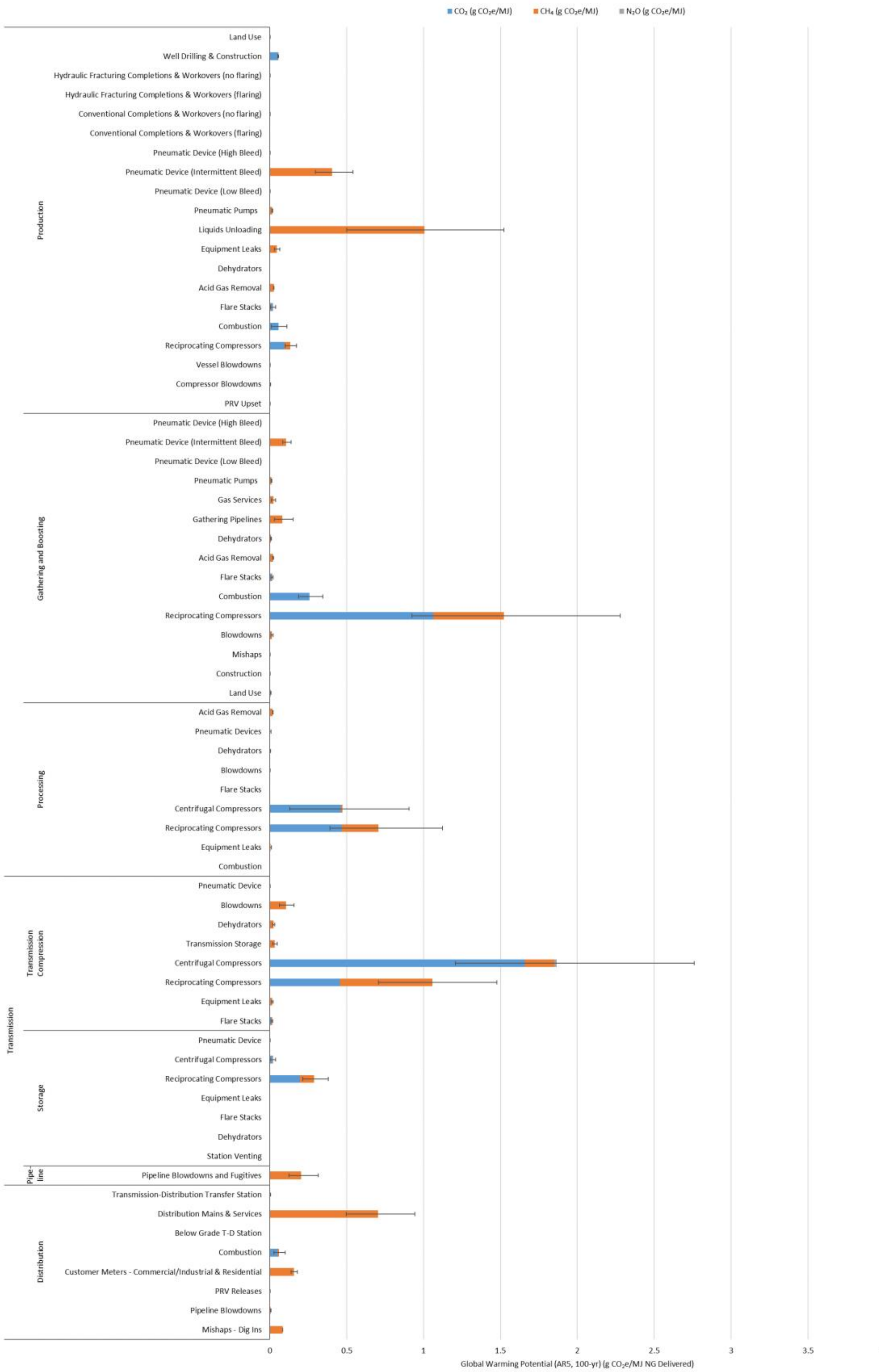
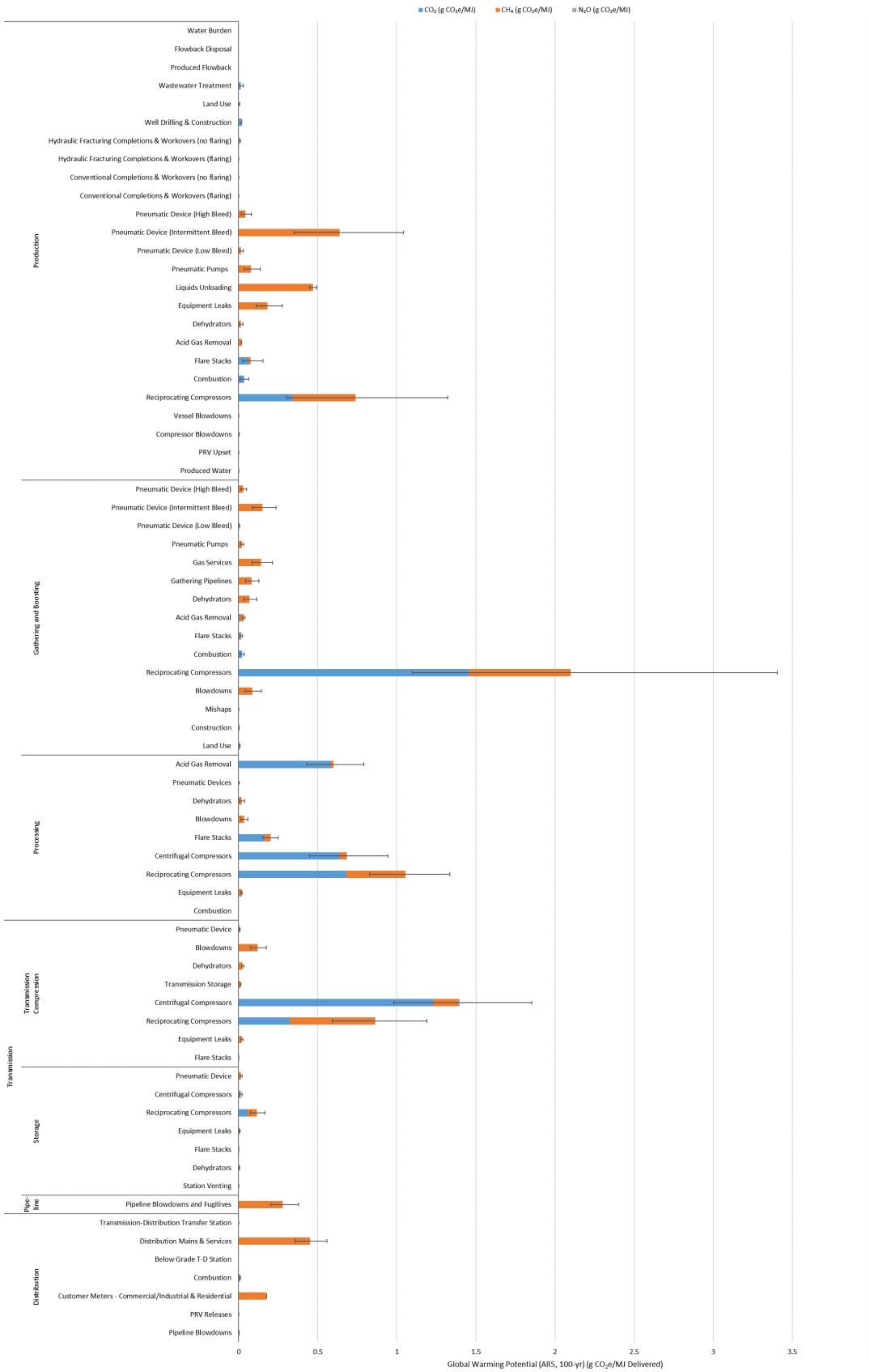


Exhibit 6-12: Detailed Life Cycle Natural Gas GHG Emissions for U.S.



Emissions from centrifugal and reciprocating compressors are the predominant source of CO_2 from the natural gas supply chain. The technology options for compressor drivers (reciprocating engines and gas turbines) and the various sources of fugitive emissions from compressors represent a tradeoff between CO_2 and CH_4 emissions. Engines and turbines have different exhaust profiles for CO_2 and CH_4, driven by their different heat rates and combustion efficiencies. Reciprocating and centrifugal compressors have different emission sources, such as venting emissions from reciprocating rod packing or the seals (wet or dry) used for centrifugal compressors. No single combination of driver and compressor has the lowest CO_2 and CH_4 emissions across all emission sources.

Other sources of CO_2 emissions comprise flaring, purchased electricity, and venting or fugitive emissions of naturally occurring CO_2. These CO_2 emission sources are small in comparison to the CO_2 emissions from compressor operation. Combustion emissions also include N_2O, but for natural gas systems, the scale of N_2O emissions is small in comparison to CO_2 and CH_4 emissions.

6.2 REGIONALIZED SCENARIOS

Emission differences among different locations are a key driver of natural gas system variability. This analysis explores geographic variability at production, gathering and boosting, processing, and distribution. Key findings on regional variability are discussed below.

6.2.1 CH_4 Emissions

Exhibit 6-13 shows the CH_4 emissions and CH_4 emission rates for regionalized ONE Future scenarios (illustrated in **Exhibit 2-2**). These regional scenarios are defined by different sources (production basins) and destinations (end user states). Results are grouped into stages, and error bars represent 95% mean confidence intervals.

The CH_4 emissions for the source-based scenarios are more variable than the destination-based scenarios. From a life cycle perspective, the results show that upstream (production through processing) variability contributes more to total supply chain uncertainty than the variability during natural gas distribution. The expected CH_4 emissions from the 5 *source-based* scenarios range from 0.10 g CH_4/MJ to 0.35 g CH_4/MJ. The transmission compression, storage, and pipeline, and distribution stages in these scenarios represent the ONE Future average. The high uncertainty in the source-based scenarios is due to the variability in production, gathering and boosting, and processing stages. The expected CH_4 emissions from the eighteen *destination-based* scenarios range from 0.10 g CH_4/MJ to 0.18 g CH_4/MJ. The production, gathering and boosting, processing, transmission compression, storage, and transmission pipeline stages in these scenarios represent the ONE Future average. Thus, the variability in all the stages except distribution are collapsed to represent the average. The expected CH_4 emission rates vary from 0.56% to 2.02% and 0.60% to 1.05% for the source-based scenarios and the destination-based scenarios, respectively.

Exhibit 6-13: CH_4 Emissions and CH_4 Emission Rate Results for All ONE Future Scenarios

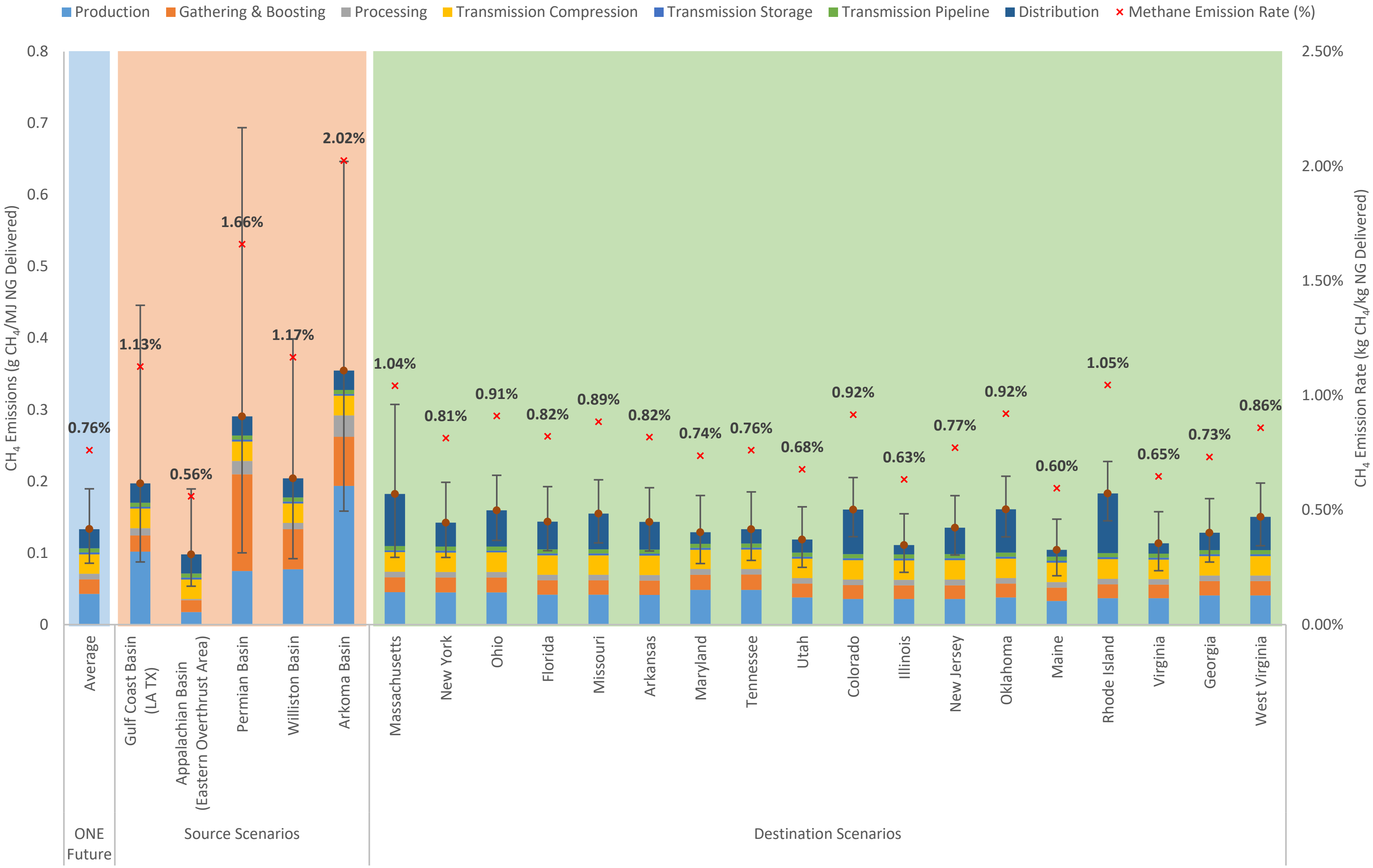


Exhibit 6-14 supplements **Exhibit 6-13** and explains the high variability among the source-based scenarios. It shows the throughputs and the cumulative CH_4 emission rates for production, gathering and boosting, and processing. The scenarios are arranged in descending order of natural gas throughput. The emission rates are the mass of methane emitted per mass of natural gas delivered; therefore, either a high emission value or a low throughput can lead to a high emission rate. For the ONE Future scenarios, as shown in **Exhibit 6-14,** compared to other basins, the Arkoma Basin has a high production throughput, but even higher production emissions, thus leading to a high emission rate in the production stage. Conversely, compared to other basins, the Permian Basin has low emissions from gathering and boosting, but has the lowest gathering and boosting throughput, thus leading to a high emission rate for gathering and boosting.

Exhibit 6-13 shows that Rhode Island, Massachusetts, Colorado, and Oklahoma have the highest emissions in the distribution stage among the destination-based scenarios. **Exhibit 6-15** provides more detail for the destination-based scenarios. It shows three graphs that plot the emission rates, throughputs, cast iron pipeline miles, and methane emissions from all distribution main pipelines in the distribution stage. Cast iron mains have the highest emission factors among all the pipeline materials in the distribution mains category. **Exhibit 6-15** shows that Massachusetts and Rhode Island have the highest emission rate in the distribution stage and the highest emissions from cast iron pipelines, while their throughputs are mid-level; thus, their high emission rates can be attributed to the high emissions from cast iron pipelines. Colorado and Oklahoma have low methane emissions, but they also have low throughputs; thus, their high emission rates can be attributed to the low throughputs. Similar conclusions can be drawn for other states like Ohio and Illinois that have higher shares of emissions from unprotected and protected steel pipelines, respectively.

Exhibit 6-13 shows the cradle-through-delivery CH_4 emission rate for each scenario. **Exhibit 6-14** shows the gate-to-gate CH_4 emission rates for production and gathering and boosting for the five source-based scenarios. **Exhibit 6-15** shows the gate-to-gate CH_4 emission rates for the distribution stage of the eighteen destination-based scenarios. **Exhibit 6-16** shows the cradle-through-delivery emission rates for each stage in the supply chain for each scenario. The average values represent mean emission rates, and the P2.5 and P97.5 values represent the 95% confidence intervals around mean emission rates. These values are still on the basis of natural gas delivered to consumers, so their sums are equivalent to the cumulative life cycle CH_4 emission rate for the respective scenarios.

Exhibit 6-14: ONE Future Source-Based Scenarios Throughputs, CH_4 emissions and CH_4 Emission Rates for Production, Gathering and Boosting and Processing Stages

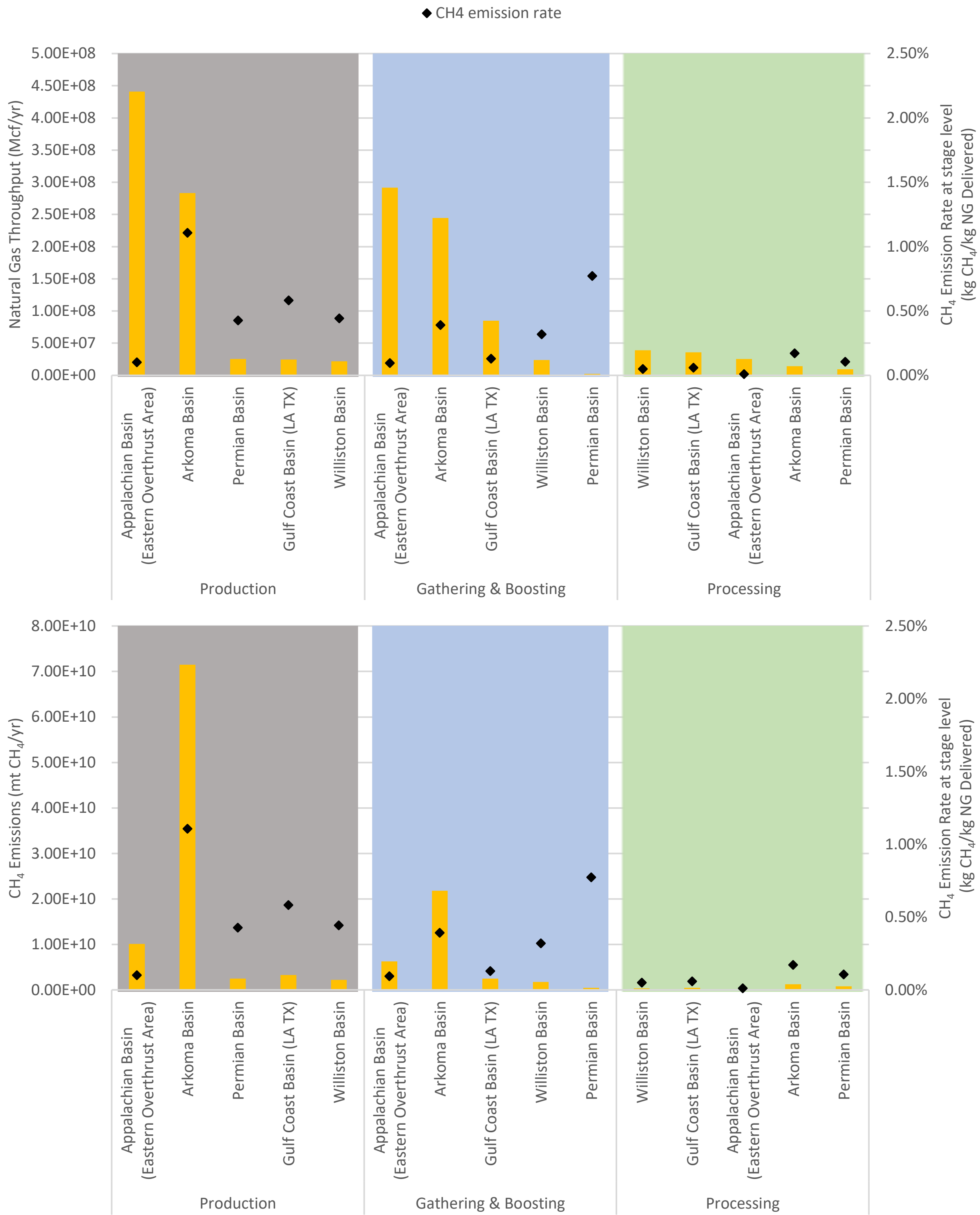
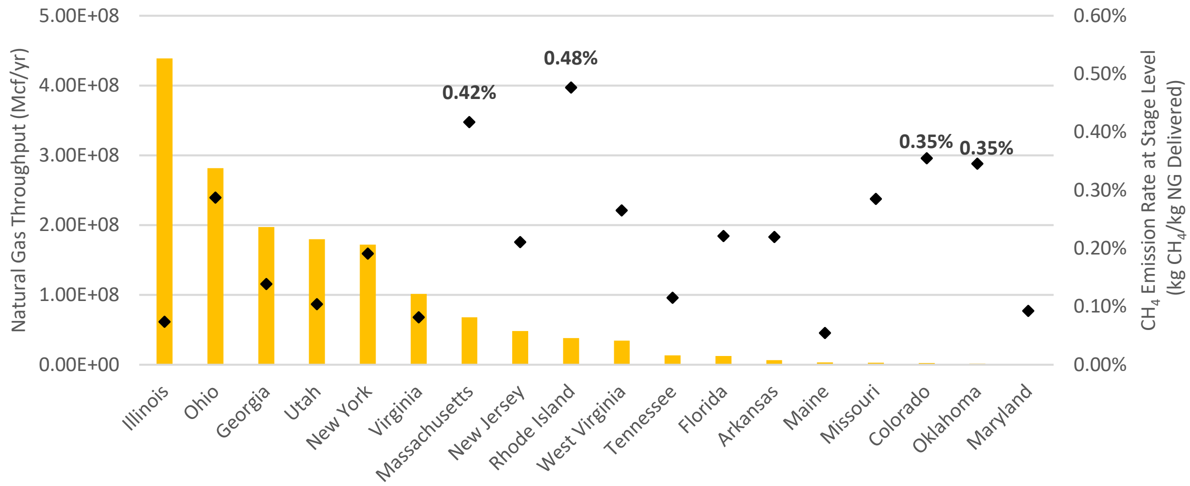
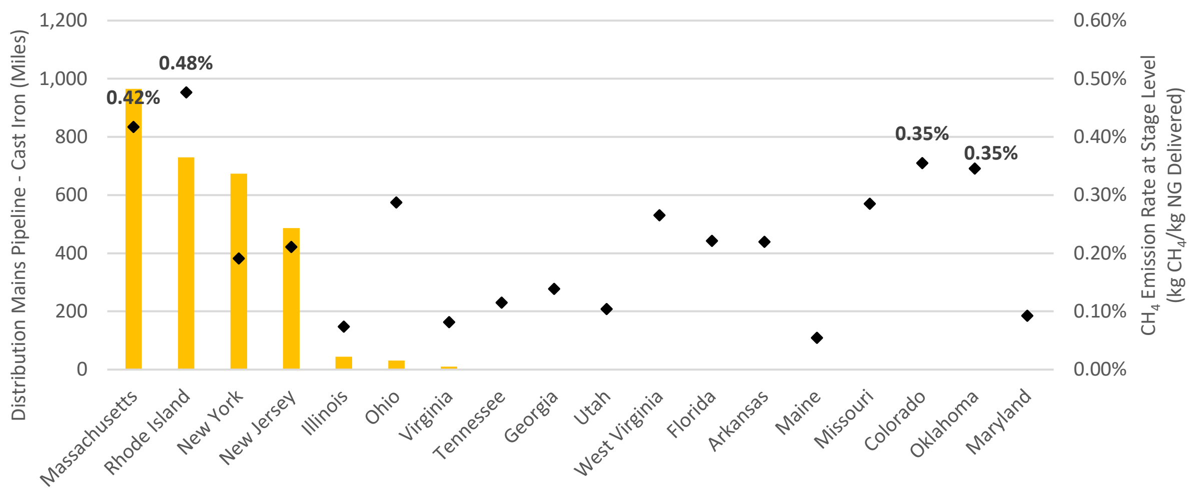


Exhibit 6-15: ONE Future Destination-Based Scenarios Throughputs, Cast Iron Pipeline Miles, CH_4 Emissions and CH_4 Emission Rates for Distribution Stage





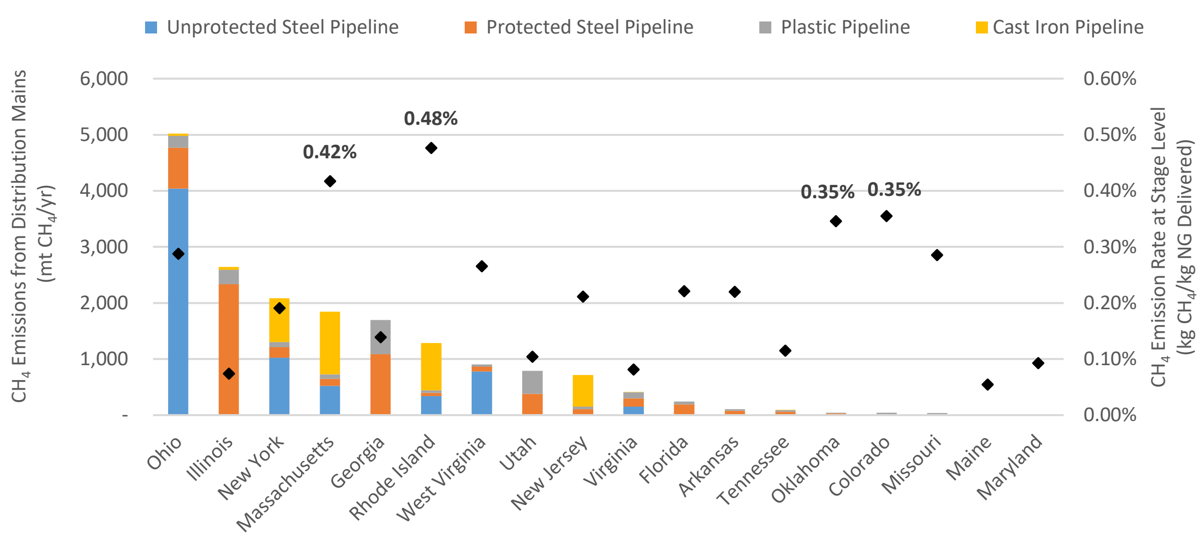


Exhibit 6-16: All ONE Future Scenarios CH_4 Emission Rates

Basin/ State	Production			Gathering and Boosting			Processing			Transmission Compression			Transmission Storage			Transmission Pipeline			Distribution		
	P2.5	Average	P97.5	P2.5	Average	P97.5	P2.5	Average	P97.5	P2.5	Average	P97.5	P2.5	Average	P97.5	P2.5	Average	P97.5	P2.5	Average	P97.5
Gulf Coast Basin (LA TX)	0.14%	0.58%	1.76%	0.08%	0.13%	0.19%	0.03%	0.06%	0.11%	0.11%	0.16%	0.22%	0.01%	0.02%	0.02%	0.02%	0.03%	0.05%	0.11%	0.15%	0.20%
Appalachian Basin (Eastern Overthrust Area)	0.03%	0.10%	0.30%	0.02%	0.09%	0.27%	0.00%	0.01%	0.02%	0.10%	0.15%	0.22%	0.01%	0.02%	0.02%	0.02%	0.03%	0.05%	0.11%	0.15%	0.20%
Permian Basin	0.07%	0.43%	1.31%	0.23%	0.77%	1.87%	0.02%	0.11%	0.30%	0.10%	0.15%	0.22%	0.01%	0.02%	0.02%	0.02%	0.03%	0.05%	0.12%	0.15%	0.19%
Williston Basin	0.13%	0.44%	1.06%	0.10%	0.32%	0.68%	0.04%	0.05%	0.05%	0.10%	0.15%	0.22%	0.01%	0.02%	0.02%	0.02%	0.03%	0.05%	0.11%	0.15%	0.20%
Arkoma Basin	0.37%	1.11%	2.05%	0.13%	0.39%	0.97%	0.15%	0.17%	0.19%	0.10%	0.15%	0.21%	0.01%	0.02%	0.02%	0.02%	0.03%	0.05%	0.12%	0.15%	0.19%
Massachusetts	0.15%	0.26%	0.37%	0.07%	0.12%	0.18%	0.02%	0.04%	0.08%	0.11%	0.16%	0.22%	0.01%	0.02%	0.02%	0.02%	0.03%	0.05%	0.15%	0.42%	0.84%
New York	0.15%	0.26%	0.37%	0.07%	0.12%	0.17%	0.02%	0.04%	0.07%	0.10%	0.16%	0.22%	0.01%	0.02%	0.02%	0.02%	0.03%	0.05%	0.16%	0.19%	0.23%
Ohio	0.15%	0.26%	0.37%	0.07%	0.12%	0.17%	0.02%	0.04%	0.07%	0.11%	0.16%	0.22%	0.01%	0.02%	0.02%	0.02%	0.03%	0.05%	0.29%	0.29%	0.29%
Florida	0.14%	0.24%	0.34%	0.07%	0.11%	0.17%	0.02%	0.04%	0.07%	0.11%	0.16%	0.22%	0.01%	0.02%	0.02%	0.02%	0.03%	0.05%	0.22%	0.22%	0.22%
Missouri	0.14%	0.24%	0.34%	0.07%	0.11%	0.17%	0.02%	0.04%	0.07%	0.10%	0.16%	0.21%	0.01%	0.02%	0.02%	0.02%	0.03%	0.05%	0.29%	0.29%	0.29%
Arkansas	0.14%	0.24%	0.34%	0.07%	0.11%	0.17%	0.02%	0.04%	0.07%	0.11%	0.15%	0.21%	0.01%	0.02%	0.02%	0.02%	0.03%	0.05%	0.22%	0.22%	0.22%
Maryland	0.16%	0.28%	0.40%	0.07%	0.12%	0.18%	0.02%	0.04%	0.07%	0.10%	0.15%	0.21%	0.01%	0.02%	0.02%	0.02%	0.03%	0.05%	0.09%	0.09%	0.09%
Tennessee	0.16%	0.28%	0.40%	0.07%	0.12%	0.18%	0.02%	0.04%	0.07%	0.11%	0.15%	0.22%	0.01%	0.02%	0.02%	0.02%	0.03%	0.05%	0.12%	0.12%	0.12%
Utah	0.13%	0.22%	0.31%	0.07%	0.11%	0.16%	0.02%	0.04%	0.07%	0.11%	0.15%	0.21%	0.01%	0.02%	0.02%	0.02%	0.03%	0.05%	0.10%	0.10%	0.10%
Colorado	0.12%	0.21%	0.30%	0.07%	0.11%	0.16%	0.02%	0.04%	0.07%	0.11%	0.15%	0.21%	0.01%	0.02%	0.02%	0.02%	0.03%	0.05%	0.35%	0.35%	0.35%
Illinois	0.12%	0.20%	0.29%	0.06%	0.11%	0.16%	0.02%	0.04%	0.07%	0.10%	0.15%	0.21%	0.01%	0.02%	0.02%	0.02%	0.03%	0.05%	0.07%	0.07%	0.07%
New Jersey	0.12%	0.21%	0.30%	0.07%	0.11%	0.16%	0.02%	0.04%	0.07%	0.10%	0.15%	0.22%	0.01%	0.02%	0.02%	0.02%	0.03%	0.05%	0.21%	0.21%	0.21%
Oklahoma	0.13%	0.22%	0.31%	0.07%	0.11%	0.17%	0.02%	0.04%	0.07%	0.10%	0.16%	0.22%	0.01%	0.02%	0.02%	0.02%	0.03%	0.05%	0.35%	0.35%	0.35%
Maine	0.11%	0.19%	0.27%	0.06%	0.11%	0.16%	0.02%	0.04%	0.07%	0.10%	0.15%	0.21%	0.01%	0.02%	0.02%	0.02%	0.03%	0.05%	0.05%	0.05%	0.05%
Rhode Island	0.12%	0.21%	0.30%	0.07%	0.11%	0.16%	0.02%	0.04%	0.07%	0.11%	0.16%	0.22%	0.01%	0.02%	0.02%	0.02%	0.03%	0.05%	0.48%	0.48%	0.48%
Virginia	0.12%	0.21%	0.30%	0.07%	0.11%	0.16%	0.02%	0.04%	0.07%	0.11%	0.15%	0.21%	0.01%	0.02%	0.02%	0.02%	0.03%	0.05%	0.08%	0.08%	0.08%
Georgia	0.13%	0.23%	0.34%	0.07%	0.11%	0.17%	0.02%	0.04%	0.07%	0.10%	0.16%	0.22%	0.01%	0.02%	0.02%	0.02%	0.03%	0.05%	0.14%	0.14%	0.14%
West Virginia	0.14%	0.23%	0.33%	0.07%	0.11%	0.17%	0.02%	0.04%	0.07%	0.10%	0.16%	0.22%	0.01%	0.02%	0.02%	0.02%	0.03%	0.05%	0.27%	0.27%	0.27%

Appendix G shows the results at a more granular level with detailed CH_4 emissions from different sources within each stage for all the ONE Future scenarios.

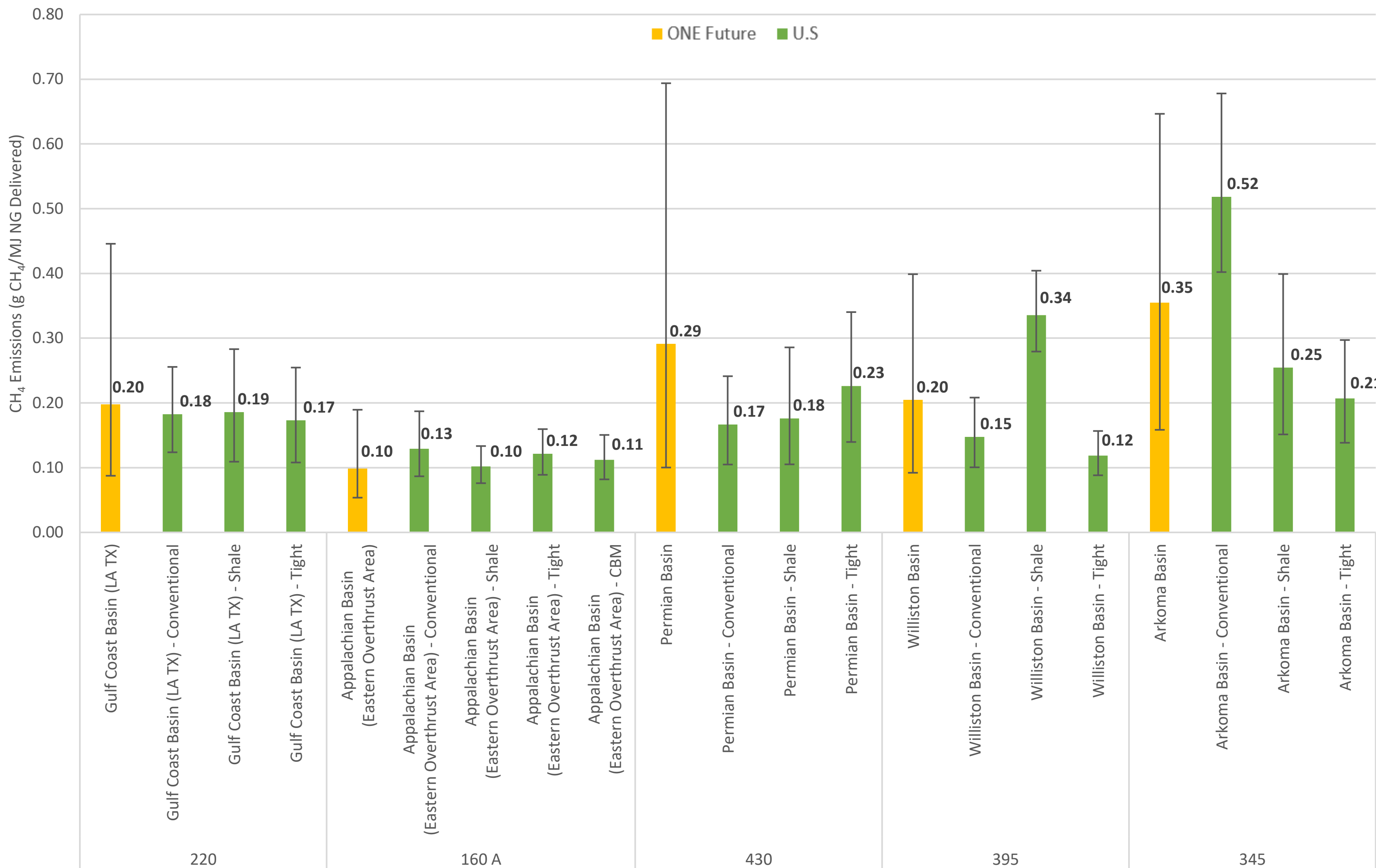
Exhibit 6-17 compares the ONE Future source-based scenarios with corresponding scenarios for all U.S. GHGRP reporters in 2017. The U.S. scenarios are shown as technobasins (basins and extraction technology), whereas the ONE Future scenarios are only at basin level (with no specification of extraction technologies). All other ONE Future scenarios except the Appalachian Basin (Eastern Overthrust Area) have higher uncertainty than their U.S. peers; this is most likely due to a lower number of data points for ONE Future scenarios compared to the U.S. scenarios. Compared to their basin peers, the ONE Future scenarios have higher expected CH_4 emissions for the Gulf Coast Basin (LA TX) and Permian Basin and a lower expected value for the Appalachian Basin (Eastern Overthrust Area). For the Williston Basin and Arkoma Basin, ONE Future has higher expected CH_4 emissions than the geographically-corresponding unconventional U.S. scenarios but a lower emission value than the geographically-corresponding conventional U.S. scenarios. The error bars overlap between ONE Future and U.S. in all scenarios.

This analysis did not regionalize the transmission stage (comprising transmission compression, storage, and pipelines). However, there is variability in the transmission stage at a facility level. ONE Future provided NETL with data for 280 transmission facilities, and 46 out of the 280 facilities contribute to 50% of all the reciprocating compressors in this stage, which is the biggest source of emission in the transmission stage.

6.2.2 GHG Emissions

To provide a complete GHG perspective, this analysis includes CO_2 and N_2O in addition to CH_4. **Appendix H** shows the detailed GHG profiles for all ONE Future scenarios. It uses the 100-year GWPs to calculate the CO_2 equivalents for all emission sources.

Exhibit 6-17: ONE Future Source-Based Scenarios Comparison with U.S. Scenarios



7. MARGINAL ABATEMENT COST ANALYSIS

To complement the LCA, a MAC analysis was performed to evaluate the scale and costs of ONE Future's CH_4 emission reduction opportunities.

7.1 MAC CALCULATIONS AND PARAMETERS

MAC is defined as the cost of reducing a unit of emissions ($/thousand cubic feet (Mcf) or tonne CH_4 reduced) using a particular technology or strategy. The result is a ratio of annualized cost of an emissions mitigation technology to the volume of the corresponding emissions reduction (ICF 2016). The annualized cost of a technology is computed by summing the amortized capital cost and the annual operating cost. The annual cost is reduced by the economic value of recovered gas in instances where it is sold for revenue.

In addition to the mitigation costs per unit of reduced emissions, this analysis also computes the increased revenue from the sale of recovered methane during production (ICF 2016), using the Henry Hub natural gas spot price for 2017 ($2.99/MMBtu) (EIA 2020), which translates to $3.10/Mcf (nominal dollars) when using a heat content of 1.036 MMBtu/Mcf for natural gas (EIA 2019). The methane can only be captured for resale in the production stage because only the production companies own the gas; in other stages, the gas is in the transit mode (not owned by the companies) and hence cannot be captured for resale.

The cost data are representative of capital costs, operating costs, and equipment service lives derived from the EPA's Natural Gas Star Program (EPA 2018), which comprises a series of industry profiles over the last decade. These data are used in past MAC analyses (ICF 2014 and ICF 2016). All costs are escalated using the chemical engineering plant cost index (Chemical Engineering n.d.) to represent the study year (2017).

MAC calculations require parameters such as capital and operating costs of a technology or device, emissions reduction percentage, the service life of an emissions reduction technology, and price of recovered gas. Capital costs are levelized over the lifetimes of new components, which vary from 1 to 10 years. **Exhibit 7-1** shows the escalated values of cost parameters, and the original values that were adapted from ONE Future's MAC analysis report (ICF 2016) are provided in **Appendix D**. The abatement potentials or emission reduction percentages are based on prior reports (ICF 2014, ICF 2016). Device counts and corresponding emission factors from all ONE Future scenarios are also provided in **Appendix D**. Actual abatement potential data is scarce and is a key source of uncertainty when calculating the total abatement potential for the industry. For example, latest research (Ravikumar and Brandt 2017) indicates that abatement potential from leak detection and repair (LDAR) (a key CH_4 emission mitigation strategy in the industry) may be overestimated by EPA and others.

This analysis computes MAC using device counts representative of ONE Future's assets. **Equation 7-1** displays the calculation used to obtain the CH_4 reduction in ONE Future's supply chain, where ***CF*** represents a conversion factor to obtain CH_4 reduced in the desired units, and ***% emission reduction*** implies a reduction in CH_4 emissions from employing a mitigation strategy.

Equation 7-1

$$Emission\ reduction = CH_4\ (emissions/device) \times (device\ count) \times (\%\ emission\ reduction) \times CF$$

7.2 MAC RESULTS

To interpret the MAC results, an understanding of the difference between LCA and MAC is necessary. The LCA conducted herein identifies key sources of CH_4 and CO_2 emissions for a natural gas supply chain representative of the technology profile of ONE Future members in separate scenarios. LCA scales the emission profiles from multiple supply chain stages with disparate throughputs to a common basis (1 MJ of natural gas delivered), allowing comparison of ONE Future to U.S. results. In contrast, the MAC calculates the emission reductions and mitigation costs for ONE Future's equipment and operations.

The MAC results comprise the annualized mitigation cost ($/Mcf CH_4 reduced) and the annual volume of CH_4 reduced by each approach (Mcf/yr). **Exhibit 7-2** displays the annualized CH_4 reduction cost ($/Mcf CH_4 reduced) and CH_4 reductions (Mcf/year) calculated using the MAC parameters from **Exhibit 7-1** for all ONE Future scenarios where data are available. The annualized mitigation cost is independent of scenario, but the annual volume of CH_4 reduced depends on the count of equipment and, hence, varies between scenarios. **Exhibit 7-2** includes abatement costs with and without the payback for sales of recovered natural gas from the production stage. A 100% technology deployment rate is assumed in this analysis.

Select mitigation options require significantly higher costs for CH_4 reduction. Replacement of cast iron distribution pipeline has the highest mitigation cost of all proposed strategies due to the high capital costs for pipeline replacement. Converting intermittent bleed devices to air-based systems in the storage segment of ONE Future’s supply chain has the second highest mitigation cost.

Low cost options (i.e., those with per Mcf mitigation costs less than the sales price of natural gas) include redesign of blowdown systems and emergency shutdown (ESD) practices (at transmission compression facilities), replacement of high bleed pneumatics with low bleed devices (at production sites in Gulf Coast (LA TX), Permian Basin, and Williston Basin), and replacement of rod packing in reciprocating compressors (in the transmission network). These 5 low-cost options account for 1.4 Bcf CH_4/yr in emission reductions and have mitigation costs less than $1.70/Mcf of CH_4 recovered. Pipeline pump-down before maintenance (for transmission pipelines) represents a CH_4 emission reduction option with intermediate costs ($36/Mcf recovered) and high potential for total emission reductions (1.7 Bcf CH_4/yr). Replacing intermittent bleed pneumatics with air-powered devices (at production sites in all scenarios) represents a large emission reduction opportunity (2.4 Bcf CH_4/yr) but at a high cost (at least $81/Mcf recovered).

A marginal abatement cost curve (MACC) is shown in **Exhibit 7-3**. To improve readability, a partial MACC focusing on opportunities that are less than $25/Mcf recovered is shown in **Exhibit 7-4**. The cost estimates exclude discount rate, and the recovered gas from the production segment is sold at $3.10/Mcf (EIA 2020).

Exhibit 7-1: MAC Parameters

Emission Reduction Opportunities for This Analysis	Mapping with ONE Future's MAC Emissions Mitigation Strategies	Unit	Capital Cost, $/unit*	Operating Cost, $/unit-year*	Service Life, Years*	Percent Reduction (Emissions)*
Production						
High bleed pneumatics	Replace with instrument air systems - high bleed	High bleed device	75,000	5,400	5	100%
High bleed pneumatics	Replace high bleed devices with low bleed devices	High bleed device	3,800	0	5	78%
Intermittent bleed pneumatics	Replace with instrument air systems - intermittent bleed	Intermittent bleed device	75,000	5,400	5	100%
Gathering and Boosting						
High bleed pneumatics	Replace with instrument air systems - high bleed	High bleed device	75,000	5,400	5	100%
High bleed pneumatics	Replace high bleed devices with low bleed devices	High bleed device	3,800	0	5	78%
Intermittent bleed pneumatics	Replace with instrument air systems - intermittent bleed	Intermittent bleed device	75,000	5,400	5	100%
Transmission Compression						
Centrifugal compressors	Wet seal degassing recovery system for centrifugal compressors	Centrifugal compressor	105,000	0	5	95%
Reciprocating compressors	Replacement of reciprocating compressor rod packing systems	Reciprocating compressor	8,300	0	10	31%
Emergency shutdowns	Redesign blowdown systems and alter ESD practices	ESD Valve	18,600	0	5	95%
Pipeline modifications	Pipeline pump-down before maintenance	Compressor	0	38,000	N/A	80%
Transmission Storage						
High bleed pneumatics	Replace with instrument air systems - high bleed	High bleed device	75,000	5,400	5	100%
High bleed pneumatics	Replace high bleed devices with low bleed devices	High bleed device	3,800	0	5	78%
Intermittent bleed pneumatics	Replace with instrument air systems - intermittent	Intermittent bleed device	75,000	5,400	5	100%

Emission Reduction Opportunities for This Analysis	Mapping with ONE Future's MAC Emissions Mitigation Strategies	Unit	Capital Cost, $/unit*	Operating Cost, $/unit-year*	Service Life, Years*	Percent Reduction (Emissions)*
Distribution						
Distribution mains – cast iron	Replacement of cast iron distribution pipelines	Pipeline mile	4,100,000**	0	150	98%
LDAR (Leak Detection and Repair)						
Gas processing fugitives	Processing LDAR	Processing facility	12,000	0	1	40%
Transmission fugitives	Transmission LDAR	Transmission compression facility	10,000	0	1	40%

* From ONE Future Marginal Abatement Cost (MAC) report (ICF 2016). The cost data are escalated using the chemical engineering plant cost index (Chemical Engineering n.d.).

** Pipeline cost data was adopted from American Gas Association (AGA 2013)

Exhibit 7-2: Annualized CH_4 Reduction and Cost for ONE Future Assets

Emissions Mitigation Strategies	Methane Reduced, Mcf/year	Cost per Unit of Emission Reductions			
		$/Mcf CH_4 with recovery revenue	$/Mcf CH_4 without recovery revenue	$/tonne CH_4 with recovery revenue	$/tonne CH_4 without recovery revenue
Production, Gulf Coast (LA TX)					
Replace with instrument air systems - high bleed	4.59E+02	26.53	29.62	1,389.44	1,551.70
Replace high bleed devices with low bleed devices	3.58E+02	1.10	4.20	57.58	219.83
Replace with instrument air systems - intermittent	2.38E+05	81.26	84.36	4,256.73	4,418.99
Production, Appalachian Basin (Eastern Overthrust Area)					
Replace with instrument air systems - high bleed	N/A	N/A	N/A	N/A	N/A
Replace high bleed devices with low bleed devices	N/A	N/A	N/A	N/A	N/A
Replace with instrument air systems - intermittent	1.03E+06	81.26	84.36	4,256.73	4,418.99
Production, Permian Basin					
Replace with instrument air systems - high bleed	5.51E+03	26.53	29.62	1,389.44	1,551.70
Replace high bleed devices with low bleed devices	4.29E+03	1.10	4.20	57.58	219.83
Replace with instrument air systems - intermittent	2.82E+05	81.26	84.36	4,256.73	4,418.99
Production, Williston Basin					
Replace with instrument air systems - high bleed	9.18E+04	26.53	29.62	1,389.44	1,551.70
Replace high bleed devices with low bleed devices	7.16E+04	1.10	4.20	57.58	219.83
Replace with instrument air systems - intermittent	8.06E+01	81.26	84.36	4,256.73	4,418.99
Production, Arkoma Basin					
Replace with instrument air systems - high bleed	N/A	N/A	N/A	N/A	N/A
Replace high bleed devices with low bleed devices	N/A	N/A	N/A	N/A	N/A
Replace with instrument air systems - intermittent	8.01E+05	81.26	84.36	4,256.73	4,418.99
Gathering and Boosting, Gulf Coast (LA TX)					
Replace with instrument air systems - high bleed	9.18E+02	29.62	29.62	1,551.70	1,551.70
Replace high bleed devices with low bleed devices	7.16E+02	4.20	4.20	219.83	219.83
Replace with instrument air systems - intermittent	6.74E+04	84.36	84.36	4,418.99	4,418.99

Emissions Mitigation Strategies	Methane Reduced, Mcf/year	Cost per Unit of Emission Reductions			
		$/Mcf CH_4 with recovery revenue	$/Mcf CH_4 without recovery revenue	$/tonne CH_4 with recovery revenue	$/tonne CH_4 without recovery revenue
Gathering and Boosting, Appalachian Basin (Eastern Overthrust Area)					
Replace with instrument air systems - high bleed	1.45E+04	29.62	29.62	1,551.70	1,551.70
Replace high bleed devices with low bleed devices	1.13E+04	4.20	4.20	219.83	219.83
Replace with instrument air systems - intermittent	8.21E+04	84.36	84.36	4,418.99	4,418.99
Gathering and Boosting, Permian Basin					
Replace with instrument air systems - high bleed	1.61E+03	29.62	29.62	1,551.70	1,551.70
Replace high bleed devices with low bleed devices	1.25E+03	4.20	4.20	219.83	219.83
Replace with instrument air systems - intermittent	5.32E+03	84.36	84.36	4,418.99	4,418.99
Gathering and Boosting, Williston Basin					
Replace with instrument air systems - high bleed	N/A	N/A	N/A	N/A	N/A
Replace high bleed devices with low bleed devices	N/A	N/A	N/A	N/A	N/A
Replace with instrument air systems - intermittent	N/A	N/A	N/A	N/A	N/A
Gathering and Boosting, Arkoma Basin					
Replace with instrument air systems - high bleed	N/A	N/A	N/A	N/A	N/A
Replace high bleed devices with low bleed devices	N/A	N/A	N/A	N/A	N/A
Replace with instrument air systems - intermittent	1.05E+03	84.36	84.36	4,418.99	4,418.99
Transmission Compressors (no regionalization in this stage)					
Centrifugal compressor wet seal degassing recovery system	2.14E+05	23.72	23.72	1,242.34	1,242.34
Reciprocating compressor rod packing system replacement	5.10E+05	1.67	1.67	87.39	87.39
Redesign blowdown systems and alter ESD practices	8.58E+05	1.05	1.05	55.19	55.19
Pipeline pump-down before maintenance	8.53E+04	35.78	35.78	1,874.34	1,874.34
Storage (no regionalization in this stage)					
Replace with instrument air systems - high bleed	8.30E+03	54.88	54.88	2,874.71	2,874.71
Replace high bleed devices with low bleed devices	6.47E+03	7.78	7.78	407.27	407.27
Replace with instrument air systems - intermittent	2.10E+04	311.85	311.85	16,335.19	16,335.19

Emissions Mitigation Strategies	Methane Reduced, Mcf/year	Cost per Unit of Emission Reductions			
		$/Mcf CH_4 with recovery revenue	$/Mcf CH_4 without recovery revenue	$/tonne CH_4 with recovery revenue	$/tonne CH_4 without recovery revenue
Distribution					
Replacement of Cast Iron Distribution Pipelines, Distribution, Massachusetts	1.14E+05	460.62	460.62	24,127.87	24,127.87
Replacement of Cast Iron Distribution Pipelines, Distribution, New York	1.20E+05	460.62	460.62	24,127.87	24,127.87
Replacement of Cast Iron Distribution Pipelines, Distribution, Ohio	1.84E+03	460.62	460.62	24,127.87	24,127.87
Replacement of Cast Iron Distribution Pipelines, Distribution, Tennessee	2.96E+01	460.62	460.62	24,127.87	24,127.87
Replacement of Cast Iron Distribution Pipelines, Distribution, Illinois	2.61E+03	460.62	460.62	24,127.87	24,127.87
Replacement of Cast Iron Distribution Pipelines, Distribution, New Jersey	2.88E+04	460.62	460.62	24,127.87	24,127.87
Replacement of Cast Iron Distribution Pipelines, Distribution, Rhode Island	4.32E+04	460.62	460.62	24,127.87	24,127.87
Replacement of Cast Iron Distribution Pipelines, Distribution, Virginia	5.69E+02	460.62	460.62	24,127.87	24,127.87
Leak Detection and Repair (LDAR) (no regionalization in this stage)					
Processing LDAR	2.86E+03	42.27	42.27	2,214.32	2,214.32
Transmission LDAR	1.13E+05	20.69	20.69	1,084.01	1,084.01

Exhibit 7-3: MAC for ONE Future CH_4 Emission Reduction Options

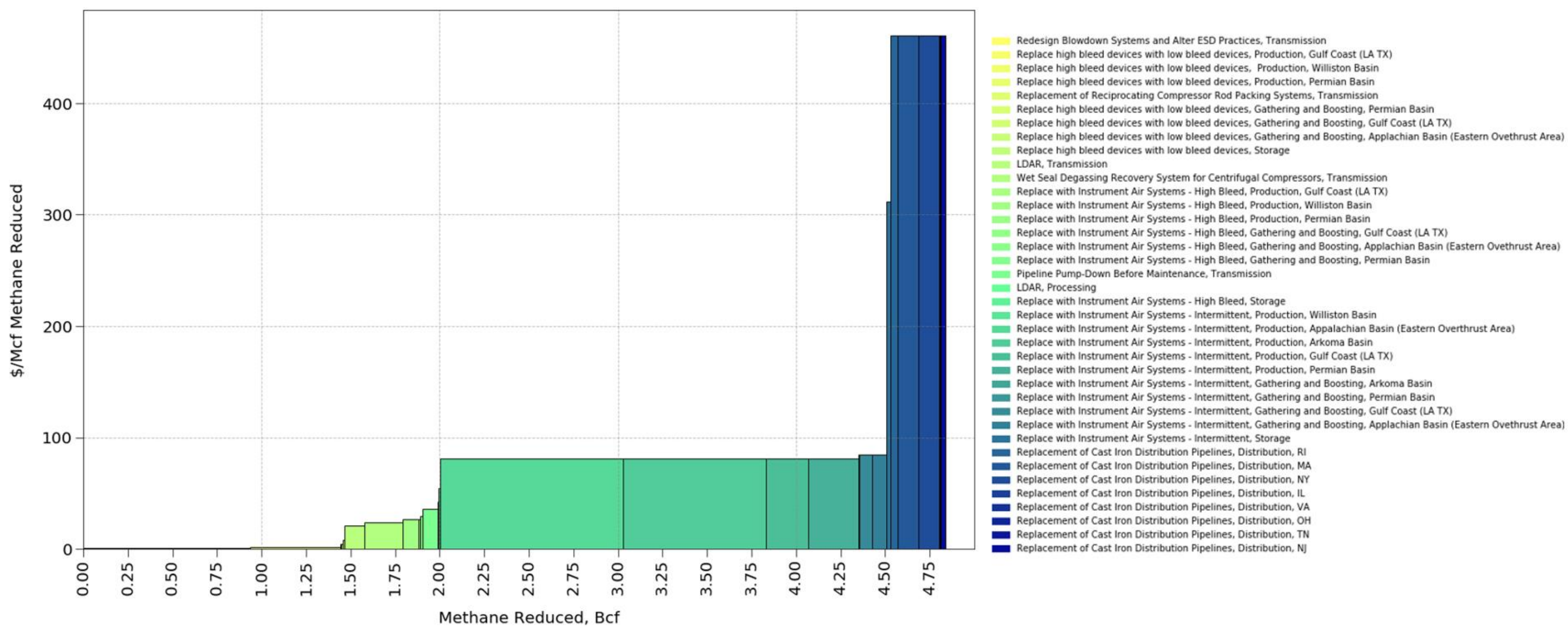
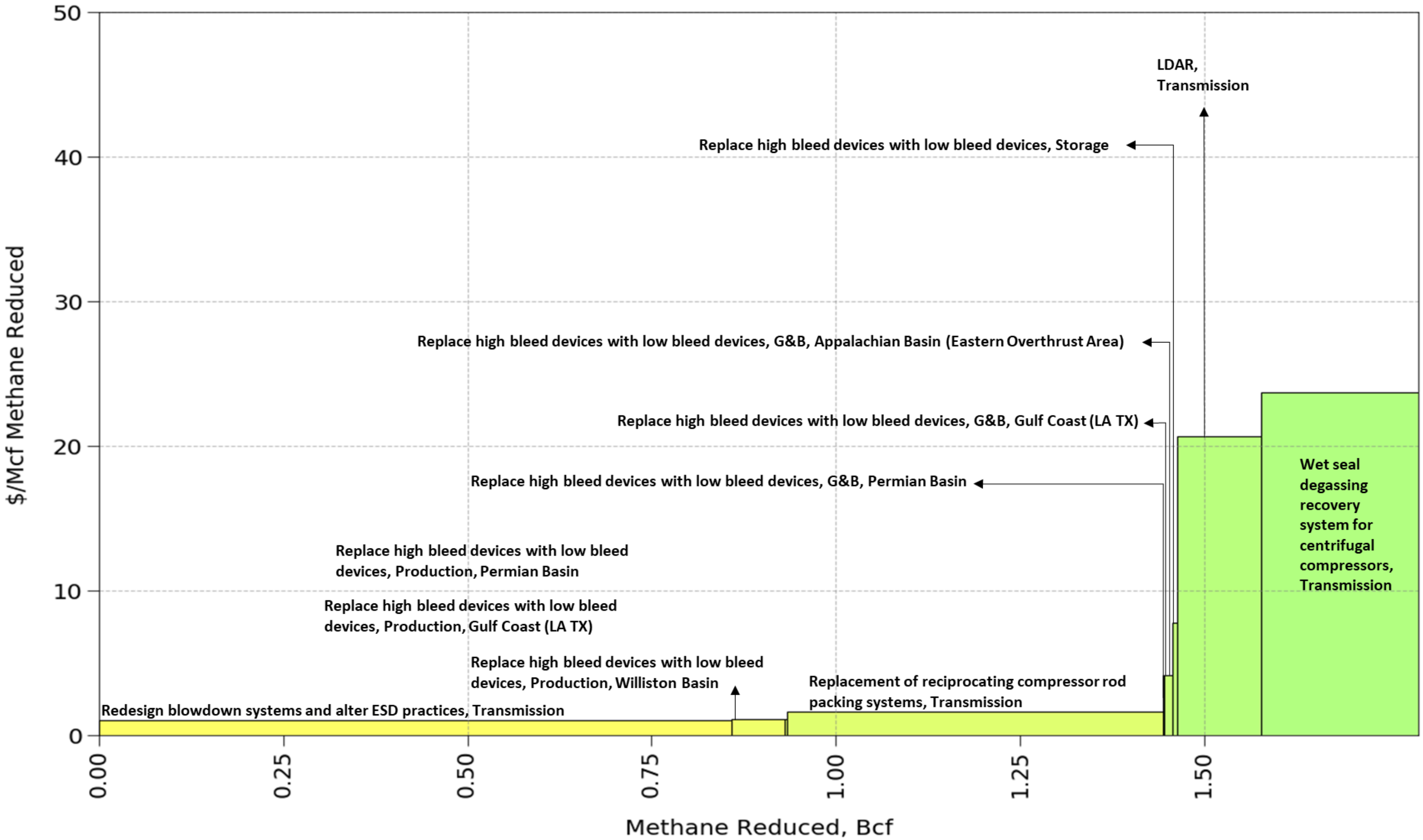


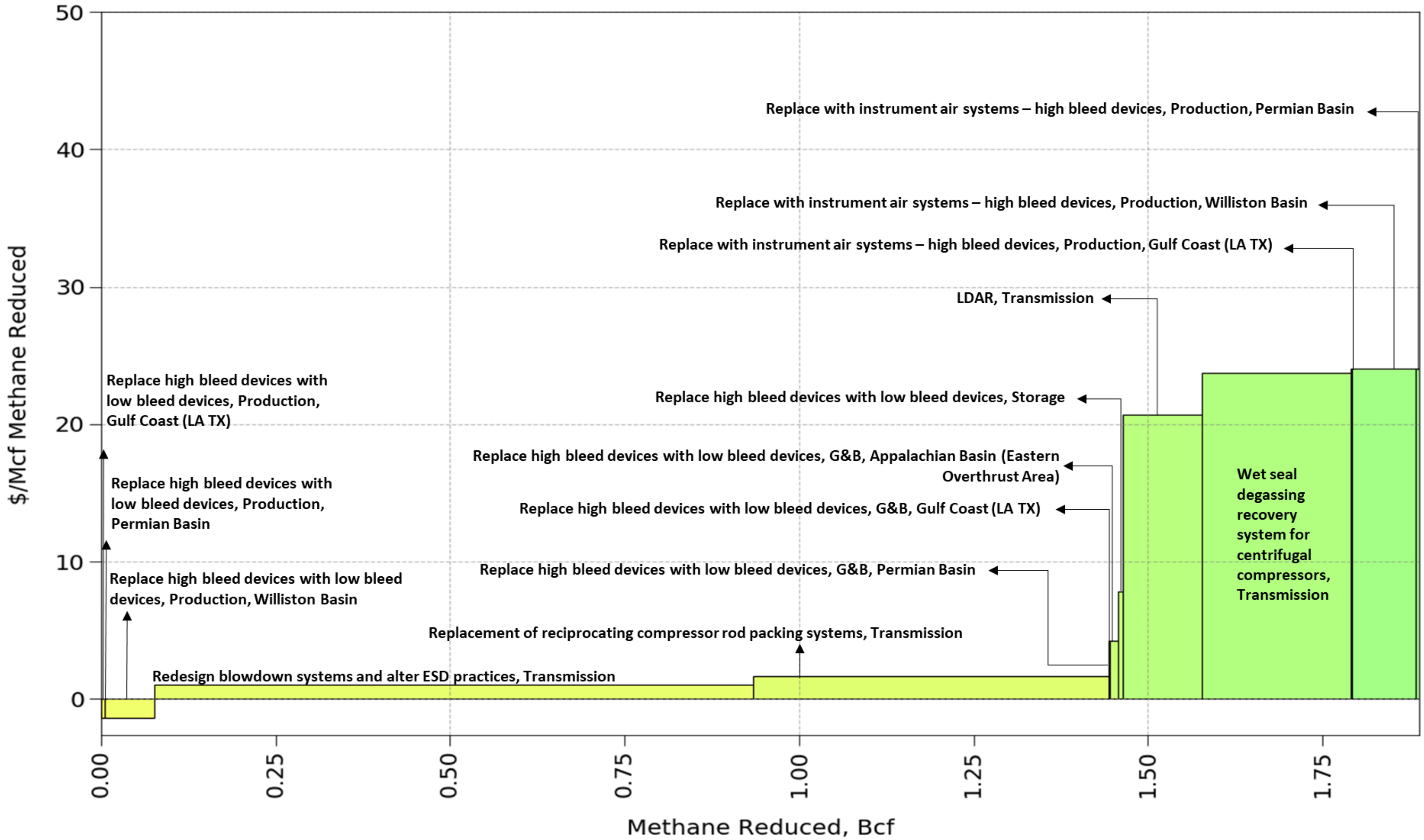
Exhibit 7-4: MAC for ONE Future CH_4 Emission Reduction Options Less than $25/Mcf



As stated above, this analysis uses a natural gas sales price of $3.10/Mcf, which was the Henry Hub natural gas spot price in 2017. This sales price is used to calculate the cost per unit of emission reductions and is applicable only to mitigation opportunities in the production stage. At a higher sales price, the MAC conclusions change slightly. **Exhibit 7-5** shows the ONE Future MAC curve using $5.58/Mcf of natural gas produced, which is the average price of delivered natural gas in 2017 (EIA 2019a).

If the production gas sales price is increased to $5.58/Mcf, the replacement of high bleed pneumatics with low bleed devices in the production stage has a negative recovery cost ($1.40 of revenue per Mcf of recovered natural gas, after paying taxes and royalties). The emission reduction costs for other mitigation options in the production stage (replacing high bleed and intermittent bleed pneumatics with instrument air systems) decrease when the sales price is increased from $3.10/Mcf to $5.58/Mcf. The costs for high bleed replacement decrease from $26.53/Mcf to $24.04/Mcf, but the costs for intermittent bleed devices still have emission reduction costs higher than $25/Mcf (a decrease from $81.27 to $78.78).

Exhibit 7-5: MAC for ONE Future CH_4 Emission Reduction Options Less than $25/Mcf (with Production Natural Gas Sales Price Increased to $5.58/Mcf)



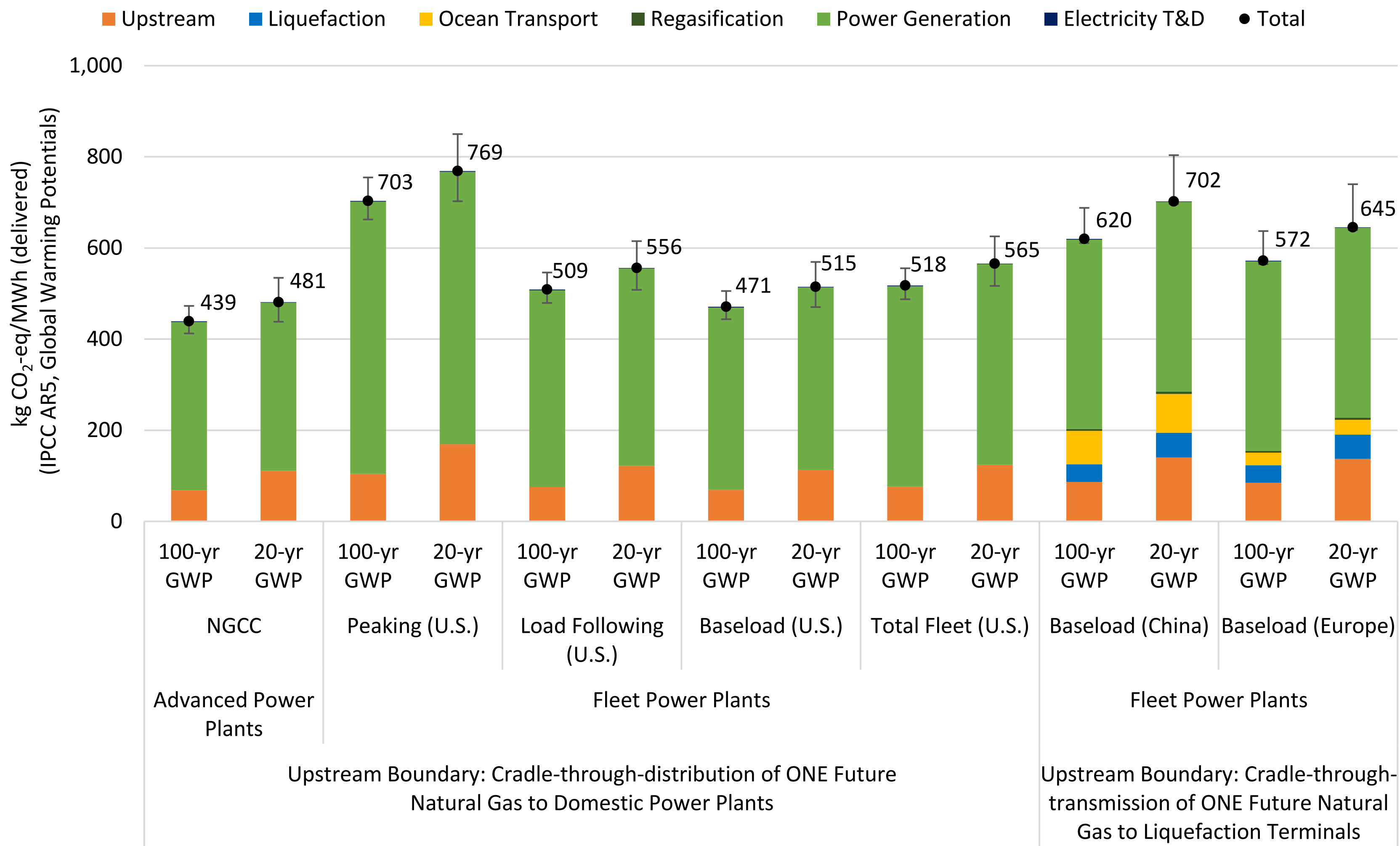
8. NATURAL GAS END USE

This section presents life cycle GHG emission results for an alternative set of boundaries, considering natural gas through end use (cradle to grave). The natural gas end use scenarios comprise electricity from advanced and fleet natural gas power plants in the U.S. and electricity generated from liquefied natural gas (LNG) exported to China or Europe (Roman-White et al. 2019).

The life cycle GHG emissions from natural gas-fired power are computed by expanding the system boundary of the ONE Future natural gas supply chain to include electricity generation, electricity transmission and distribution. For the LNG export scenarios, the system boundary also includes liquefaction, ocean transport to the importing country, and regasification at the importing country. A functional unit of 1 megawatt hour (MWh) delivered to consumers is used as a basis for comparing scenarios. **Appendix E** provides more details on system boundaries, scenario definitions, data sources, efficiencies, and heat factors.

Exhibit 8-1 shows GHG emissions (employing the ONE Future results from **Section 6.1.2**) for natural gas-fired power scenarios, including domestic consumption in natural gas-fired power plants and the export of LNG for consumption by power plants in China and Europe. The results are presented on 100-year and 20-year GWP timeframes. The error bars indicate the variation in the cradle-to-grave emissions in response to changing the ONE Future CH_4 emission rate from the cradle-through-transmission segment of the natural gas supply chain within a 95% confidence interval. It shows that end use combustion accounts for the majority of the life cycle GHG emissions, and 20-year GWP accentuates the CH_4 intensity of upstream natural gas. The expected value of life cycle GHG emission ranges from 439 to 703 when using a 100-year GWP, representing a range of efficiencies from more efficient advanced power plants (natural gas combined cycle [NGCC]) through less efficient peaking power plants; this demonstrates the importance of end use efficiency. In the scenarios where LNG is exported to Asia and Europe, the LNG supply chain (liquefaction, ocean transport, and regasification) accounts for 19 percent and 12 percent of life cycle GHG emission on a 100-year basis, respectively.

Exhibit 8-1: Life Cycle GHG Emissions from ONE Future Natural Gas Used for Electricity



9. CONCLUSIONS AND RECOMMENDATIONS

This analysis uses data provided by ONE Future to model their respective supply chains. It models an average scenario as well as regionalized scenarios.

Key conclusions for average natural gas are as follows:

1. The expected life cycle CH_4 emission rate for ONE Future average natural gas is 0.76% (with a 95% confidence interval ranging of 0.49–1.08%). The expected life cycle CH_4 emission rate for the U.S. average scenario is 1.06%. In terms of IPCC 100-year GWP, the ONE Future and U.S. average scenarios emit 9.7 and 14.1 g CO_2e/MJ of delivered natural gas, respectively.
2. ONE Future represents 1–13% of total throughput in the respective segments of the natural gas industry value chain. The processing segment is the lower bound of this throughput range and represents the only portion of the natural gas supply chain where ONE Future does not have a large presence. Improvements to their operations, if prioritized according to their largest emission sources, will reduce the average CH_4 emission rate for the U.S.
3. A MAC analysis shows five low cost options that account for 1.4 Bcf CH_4/yr in emission reductions and have mitigation costs less than $1.70/Mcf of CH_4 recovered. These options comprise improved ESD and blowdown practices for transmission pipelines, replacement of the three types of pneumatic devices at production sites, and replacement of reciprocating rod packing systems for transmission compressor stations. There are about 4.8 Bcf CH_4/yr of mitigation opportunities that can be achieved using mature technologies, but at high costs (in some instances, as high as $461/Mcf CH_4 reduced).

The regionalized scenarios represent 23 combinations based on 5 source-based scenarios and 18 destination-based scenarios. The regionalized results point to three key conclusions.

1. The average CH_4 emission intensities of the 23 regionalized scenarios range from 0.56-2.02%. The scenario with the highest emission rate (Arkoma Basin) has a particularly high emission intensity from liquids unloading in production stage and represents 16% of ONE Future's total throughput in production stage. Natural gas from Appalachian basin has the lowest emission intensity of all regionalized scenarios and represents the largest share of ONE Future's supply mix. It represents 62%, 56%, and 24% of ONE Future's total throughput in production, gathering and boosting, and processing stages, respectively.
2. Emissions from natural gas distribution, the final stage in the natural gas supply chain, account for a range of life cycle methane emission rates for destination-based scenarios from 0.60-1.05%. However, the variability in upstream stages (production and gathering and boosting) accounts for a wider range of life cycle methane emission rates for source-based scenarios, ranging from 0.56-2.02%.

3. In ONE Future's Phase 1 analysis, the MAC analysis concluded that ONE Future's top mitigation options were different than those for the U.S. natural gas supply chain. In this updated analysis, a regionalized MAC analysis shows that mitigation opportunities have different effectiveness in different regions. For example, replacing high bleed pneumatic devices have one of the lowest costs per Mcf of CH_4 reduced, but applying this strategy in the Williston Basin will reduce 0.07 Bcf of CH_4 emissions as opposed to only 0.004 and 0.0004 Bcf in Gulf Coast (LA, TX) and Permian basins, respectively.

The above conclusions for average and regionalized natural gas point to the following recommendations:

1. The uncertainty in ONE Future's average emissions overlap those for U.S. average natural gas, but ONE Future can still be an example for industry peers by focusing on the points in their supply chain that represent top emission reduction opportunities. For ONE Future, the LCA and MAC analysis show that natural gas from outside of the Appalachian Basin has life cycle methane emission rates higher than 1% and includes top priority opportunities for pneumatic device replacement.
2. The Appalachian Basin has a low emission intensity and should serve as a benchmark for sector wide improvements. Further collaboration between government and industry should identify specific technologies and practices in Appalachian Basin that can be used in other regions. Conversely, government and industry should ensure that the high environmental performance of the Appalachian Basin is sustained as plays within the basin mature.
3. There are significant (1.4 Bcf CH_4/yr) low cost emission mitigation opportunities within ONE Future's assets, but there are even more (4.8 Bcf CH_4/yr) high cost emission mitigation opportunities. These high cost opportunities can be achieved using existing technologies; research should focus on ways to reduce the costs of existing technologies or developing new low cost technologies.
4. There are emission reduction opportunities in the transmission and storage stage, specifically the low-cost opportunity of rod packing replacement on reciprocating compressor systems. The transmission and storage stage is not regionalized in this analysis, so there is no basis for targeting specific locations for this emission reduction opportunity. The ONE Future data shows that 46 of the 280 transmission and storage facilities account for 50% of all the reciprocating compressors in this stage. Therefore, the implementation of relevant emission reduction opportunities at these 46 facilities should be prioritized for maximum emission reduction effectiveness.

The natural gas supply chain has hundreds of unique emission sources and is highly variable. This analysis shows that by understanding the relative contributions of these emission sources and how they differ geographically, government and industry can identify the most effective emission reduction opportunities.

10. REFERENCES

AGA. 2013. Managing the Reduction of the Nation's Cast Iron Inventory. https://www.aga.org/sites/default/files/managing_the_nations_cast_iron_inventory.pdf. American Gas Association. Accessed March 19, 2020.

AGA. 2018. Unpublished Data Provided by a Representative of the American Gas Association.

BTS. 2019. U.S. Oil and Gas Pipeline Mileage. Bureau of Transportation Statistics. https://www.bts.gov/content/us-oil-and-gas-pipeline-mileage. Accessed March 18, 2020.

Chemical Engineering. n.d. The Chemical Engineering Plant Cost Index. http://www.chemengonline.com/pci-home. Accessed May 21, 2020.

Cooney, Gregory, Matthew Jamieson, Joe Marriott, Joule Bergerson, Adam Brandt, and Timothy J. Skone. 2017. Updating the U.S. Life Cycle GHG Petroleum Baseline to 2014 with Projections to 2040 Using Open-Source Engineering-Based Models. Environmental Science & Technology 51(2):977–87.

EIA. 2016. Annual Energy Outlook 2016. Table G.1. Heat Contents. U.S. Energy Information Administration. August 2016. https://www.eia.gov/outlooks/aeo/pdf/0383(2016).pdf. Washington, DC.

EIA. 2019a. Annual Energy Outlook 2019. Table: Natural Gas Supply, Disposition, and Prices. U.S. Energy Information Administration. https://www.eia.gov/outlooks/aeo/data/browser/#/?id=13-AEO2019&cases=ref2019&sourcekey=0. Accessed March 18, 2020.

EIA. 2019b. Energy Information Administration, FAQs. U.S. Energy Information Administration. https://www.eia.gov/tools/faqs/faq.php?id=45&t=8. Accessed March 18, 2020.

EIA. 2019c. Natural Gas Consumption by End Use. U.S. Energy Information Administration. https://www.eia.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm. Accessed March 18, 2020.

EIA. 2019d. Natural Gas Data. U.S. Energy Information Administration. https://www.eia.gov/naturalgas/data.php. Accessed March 18, 2020.

EIA. 2019e. Natural Gas Gross Withdrawals and Production. U.S. Energy Information Administration. https://www.eia.gov/dnav/ng/ng_prod_sum_a_EPG0_FGW_mmcf_a.htm. Accessed March 18, 2020.

EIA. 2019f. Natural Gas Plant Processing. U.S. Energy Information Administration. https://www.eia.gov/dnav/ng/ng_prod_pp_a_EPG0_ygp_mmcf_a.htm. Accessed March 18, 2020.

EIA. 2020. Henry Hub Natural Gas Spot Price. U.S. Energy Information Administration. https://www.eia.gov/dnav/ng/hist/rngwhhdA.htm. Accessed March 18, 2020.

EPA. 1998. AP-42, Fifth Edition, Volume I, Chapter 1: External Combustion Sources. Section 1.4, Natural Gas Combustion. U.S. Environmental Protection Agency. https://www3.epa.gov/ttn/chief/ap42/ch01/. Accessed March 18, 2020.

EPA. 2000a. AP-42, Vol. 1, 3.1: Stationary Gas Turbines. U.S. Environmental Protection Agency. https://www3.epa.gov/ttn/chief/ap42/ch03/index.html. Accessed March 18, 2020.

EPA. 2000b. AP-42, Vol. 1, 3.2: Natural Gas-Fired Reciprocating Engines. U.S. Environmental Protection Agency. https://www3.epa.gov/ttn/chief/ap42/ch03/index.html. Accessed March 18, 2020.

EPA. 2017. Greenhouse Gas Reporting Program. Subpart W. Envirofacts. U.S. Environmental Protection Agency. https://enviro.epa.gov/enviro/ad_hoc_table_column_select_v2.retrieval_list?database_type=GHG&selected_subjects=Petroleum+and+Natural+Gas+Systems&subject_selection=+&table_1=+. Accessed March 18, 2020.

EPA. 2018. Natural Gas STAR Program. Recommended Technologies to Reduce Methane Emissions. U.S. Environmental Protection Agency. https://www.epa.gov/natural-gas-star-program/recommended-technologies-reduce-methane-emissions. Accessed March 18, 2020.

ICF. 2014. Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries. ICF International. March 2014. https://www.edf.org/sites/default/files/methane_cost_curve_report.pdf. Fairfax, VA.

ICF. 2016. Economic Analysis of Methane Emission Reduction Potential from Natural Gas Systems. ICF International. May 2016. https://onefuture.us/wp-content/uploads/2018/07/ICF-Study.pdf. Fairfax, VA.

IPCC. 2013. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. M. B. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley. 14.

Jamieson, Matthew, Cooney, Gregory, Skone, Timothy J. 2019. Grid Mix Explorer Version 4.1. U.S. Department of Energy, National Energy Technology Laboratory. https://netl.doe.gov/energy-analysis/details?id=4056. Pittsburgh, PA.

Littlefield, James, Selina Roman-White, Daniel J. Augustine, Ambica Pegallapati, George G. Zaimes, Srijana Rai, Gregory Cooney, and Timothy J. Skone. 2019. Life Cycle Analysis of Natural Gas Extraction and Power Generation. DOE/NETL-2019/2039. U.S. Department of Energy, National Energy Technology Laboratory. https://www.netl.doe.gov/energy-analysis/details?id=3198. Pittsburgh, PA.

Marchese, Anthony J., Timothy L. Vaughn, Daniel J. Zimmerle, David M. Martinez, Laurie L. Williams, Allen L. Robinson, Austin L. Mitchell, R. Subramanian, Daniel S. Tkacik, Joseph R. Roscioli, and Scott C. Herndon. 2015. Methane Emissions from United States Natural Gas Gathering and Processing. Environmental Science & Technology 49(17):10718–27.

ONE Future. 2016. Methane Emissions Estimation Protocol. ONE Future. August 2016. http://onefuture.us/wp-content/uploads/2018/05/ONE-Future-Methane-Intensity-Protocol-v-1-2016.pdf.

Ravikumar, Arvind, and Adam Brandt. 2017. Designing Better Methane Mitigation Policies: The Challenge of Distributed Small Sources in the Natural Gas Sector. Environmental Research Letters 12(4):044023.

Roman-White, Selina, Srijana Rai, James Littlefield, Gregory Cooney, and Timothy J. Skone. 2019. Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States: 2019 Update. DOE/NETL-2019/2041. U.S. Department of Energy, National Energy Technology Laboratory. https://www.netl.doe.gov/energy-analysis/details?id=4440. Pittsburgh, PA.

Rypdal, Kristin, and Wilfried Winiwarter. 2001. Uncertainties in Greenhouse Gas Emission Inventories - Evaluation, Comparability and Implications. Environmental Science & Policy 4:107–16.

Zaimes, George G., James A. Littlefield, Daniel J. Augustine, Gregory Cooney, Stefan Schwietzke, Fiji C. George, Terri Lauderdale, and Timothy J. Skone. 2019. Characterizing Regional Methane Emissions from Natural Gas Liquid Unloading. Environmental Science & Technology 53(8):4619–29.

This page intentionally left blank.

APPENDIX A: ONE FUTURE PARAMETERS

TABLE OF CONTENTS

LIST OF EXHIBITS

ACRONYMS AND ABBREVIATIONS

bbl	Barrel
CH_4	Methane
CO_2	Carbon dioxide
EUR	Estimated ultimate recovery
gal	Gallon
G&B	Gathering and Boosting
GHGRP	Greenhouse Gas Reporting Program
HF	Hydraulic fracturing
HP	Horsepower
HPh	Horsepower hour
hr	Hour
kg	Kilogram
LA	Louisiana
LDC	Local distribution company
Mcf	Thousand cubic feet
MMBtu	Million British thermal units
MMcf	Million cubic feet
NG	Natural gas
NGLs	Natural gas liquids
ONE Future	Our Nation's Energy Future
PRV	Pressure Relief Valve
scf	Standard cubic feet
T-D	Transmission-Distribution
TX	Texas
yr	Year

A.1 PRODUCTION PARAMETERS FOR ONE FUTURE SCENARIOS

Exhibit A-1. Production Parameters and their Description and Units

Category	Parameter Name	Parameter Description	Units
	NG_prod_v	Annual production, volume	Mcf
	CH4_content	Mass fraction of CH_4 in natural gas	dimensionless
Produced water venting	1_PW_vol	Volume of produced water per mass of produced natural gas	bbl/kg
	1_PW_EF	Methane emission factor per unit of produced water	kg CH_4/bbl
Well drilling	1_WELL_concrete	Mass of concrete used for well casing	kg concrete/well
	1_WELL_steel	Mass of steel used for well casing	kg steel/well
	1_EUR	Estimated ultimate recovery of natural gas	Mcf/well-life
Liquids unloading	1_LU	Methane venting rate per unit of production from unloading events	dimensionless
Production flaring	1_FLARE_NGsent	NG sent to flaring	scf
Production acid gas removal (AGR)	1_AGR_CO2	Annual CO_2 emissions from acid gas removal units at natural gas production sites	tonnes CO_2/yr
	1_AGR_CH4ef	Methane emission factor from acid gas removal at production	kg CH_4/kg NG
Production combustion	1_COMB_fuel_1M	NG combustion in equipment with output of <1MMBtu/hr (does not include compressor drivers)	Mcf
	1_COMB_fuel_5M	NG combustion in equipment with output of <5MMBtu/hr (does not include compressor drivers)	Mcf
	1_COMB_fuel_dl_1M	Diesel combusted by equipment with output of <1MMBtu/hr	gal
	1_COMB_fuel_dl_5M	Diesel combusted by equipment with output of <5MMBtu/hr	gal
Production compression	1_RECIP_cnt	Number of reciprocating compressors	count
	1_RECIP_CH4ef	Methane emission factor from reciprocating compressors	kg/compressor-yr
	1_COMB_fuel_cd	NG combusted by engine used to drive reciprocating compressor	Mcf
	1_COMB_fuel_dl_cd	Diesel combusted by engine used to drive reciprocating compressor	gal
Production fugitives	ELconn_cnt	Number of devices	count
	ELconn_hrs	Operating time for device	hours
	ELconn_EF	Emission factor for device	kg/device-hr

Category	Parameter Name	Parameter Description	Units
Production fugitives	ELflange_cnt	Number of devices	count
	ELflange_hrs	Operating time for device	hours
	ELflange_EF	Emission factor for device	kg/device-hr
	ELoel_cnt	Number of devices	count
	ELoel_hrs	Operating time for device	hours
	ELoel_EF	Emission factor for device	kg/device-hr
	ELother_cnt	Number of devices	count
	ELother_hrs	Operating time for device	hours
	ELother_EF	Emission factor for device	kg/device-hr
	ELprv_cnt	Number of devices	count
	ELprv_hrs	Operating time for device	hours
	ELprv_EF	Emission factor for device	kg/device-hr
	ELpump_cnt	Number of devices	count
	ELpump_hrs	Operating time for device	hours
	ELpump_EF	Emission factor for device	kg/device-hr
	ELvalve_cnt	Number of devices	count
	ELvalve_hrs	Operating time for device	hours
	ELvalve_EF	Emission factor for device	kg/device-hr
	NG_prod_v	Annual production, volume	Mcf
Production venting	HFcomp_nf	Mass of CH_4 emitted per hydraulically fractured completion event without flaring	tonnes
	HFcomp_f	Mass of CH_4 emitted per hydraulically fractured completion event with flaring	tonnes
	HFwork_nf	Mass of CH_4 emitted per hydraulically fractured workover event without flaring	tonnes
	HFwork_f	Mass of CH_4 emitted per hydraulically fractured workover event with flaring	tonnes
	CONcomp_nf	Mass of CH_4 emitted per conventional completion event without flaring	tonnes
	CONcomp_f	Mass of CH_4 emitted per conventional completion event with flaring	tonnes
	CONwork_nf	Mass of CH_4 emitted per conventional workover event without flaring	tonnes
	CONwork_f	Mass of CH_4 emitted per conventional workover event with flaring	tonnes
	PDhb_hr	Operating time for high-bleed pneumatic devices	hours
	PDhb_count	Number of high-bleed pneumatic devices	count
	PDhb_EF	Emission factor for high-bleed pneumatic devices	kg/hr-device
	PDib_hr	Operating time for intermittent-bleed pneumatic devices	hours

Category	Parameter Name	Parameter Description	Units
	PDib_count	Number of intermittent-bleed pneumatic devices	count
Production venting	PDib_EF	Emission factor for intermittent-bleed pneumatic devices	kg/hr-device
	PDlb_HR	Operating time for low-bleed pneumatic devices	hours
	PDlb_count	Number of low-bleed pneumatic devices	count
	PDlb_EF	Emission factor for low-bleed pneumatic devices	kg/hr-device
	Ppump_hr	Operating time for pneumatic pumps	hours
	Ppump_count	Number of pneumatic pumps	count
	Ppump_EF	Emission factor for pneumatic pumps	kg/hr-device
	Dehy_sg	CH_4 emitted from small glycol dehydrator	kg/yr
	Dehy_des	CH_4 emitted from desiccant dehydrator	kg/yr
	Dehy_lg	CH_4 emitted from large glycol dehydrator	kg/yr
	BD_comp_wells	Well count	count
	BD_comp_EF	Emission factor for compressor blowdowns	kg/compressor-yr
	BD_compperwell	Number of compressors per well	compressor/well
	PRV_upset_count	Number of PRV upset events	count
	PRV_upset_EF	Emission factor for PRV upsets	kg/event
	BD_vessel_wells	Number of wells	count
	BD_vessel_heatr	Number of heaters/well	count
	BD_vessel_sep	Number of separators/well	count
	BD_vessel_dehy	Number of dehydrators/well	count
	BD_vessel_EF	Emission factor of CH_4 per vessel	kg CH_4/vessel
	EURv	Estimated ultimate recovery, volume	Mcf
	declinecurve_HF	Percentage of area under the decline curve achieved in the first year of natural gas production for hydraulic fracturing completions and workovers	percent
	declinecurve_CON	Percentage of area under the decline curve achieved in the first year of natural gas production for conventional completions and workovers	percent

Exhibit A-2. Production Parameters for Average and Gulf Coast Basin (LA TX)

Category	Parameter Name	ONE Future Average			Gulf Coast Basin (LA TX)		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5
	NG_prod_v	4.40E+08	5.39E+08	6.33E+08	2.19E+06	2.46E+07	4.32E+07
	CH4_content	6.90E-01	7.25E-01	7.61E-01	6.26E-01	6.70E-01	7.13E-01
Produced water venting	1_PW_vol	3.35E-03	3.35E-03	3.35E-03	3.35E-03	3.35E-03	3.35E-03
	1_PW_EF	1.42E-02	1.42E-02	1.42E-02	1.42E-02	1.42E-02	1.42E-02
Well drilling	1_WELL_concrete	1.28E+04	1.60E+04	1.92E+04	1.28E+04	1.60E+04	1.92E+04
	1_WELL_steel	1.28E+04	1.60E+04	1.92E+04	1.28E+04	1.60E+04	1.92E+04
	1_EUR	2.99E+06	2.99E+06	2.99E+06	1.20E+07	1.20E+07	1.20E+07
Liquids unloading	1_LU	4.43E-04	1.30E-03	2.16E-03	2.60E-04		9.80E-04
Production flaring	1_FLARE_NGsent	2.03E+07	1.08E+08	3.72E+08	7.00E+05	2.54E+08	7.54E+08
Production acid gas removal (AGR)	1_AGR_CO2	0.00E+00	9.16E+01	3.53E+02	0.00E+00	0.00E+00	0.00E+00
	1_AGR_CH4ef	3.73E-05	3.73E-05	3.73E-05	3.73E-05	3.73E-05	3.73E-05
Production combustion	1_COMB_fuel_1M	3.49E+03	4.12E+05	1.26E+06	0.00E+00	1.79E+06	3.25E+06
	1_COMB_fuel_5M	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	1_COMB_fuel_dl_1M	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	1_COMB_fuel_dl_5M	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Production compression	1_RECIP_cnt	9.08E+01	1.31E+02	1.78E+02	0.00E+00	4.30E+01	9.20E+01
	1_RECIP_CH4ef	1.58E-01	1.73E-01	1.82E-01	0.00E+00	1.21E-01	1.82E-01
	1_COMB_fuel_cd	6.68E+05	9.19E+05	1.20E+06	0.00E+00	4.02E+05	1.01E+06
	1_COMB_fuel_dl_cd	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Production fugitives	ELconn_cnt	1.54E+05	2.31E+05	3.05E+05	1.98E+04	8.65E+04	1.54E+05
	ELconn_hrs	7.84E+03	8.46E+03	8.74E+03	7.37E+03	7.99E+03	8.76E+03
	ELconn_EF	8.37E-05	1.22E-04	1.64E-04	2.19E-04	2.36E-04	2.67E-04
	ELflange_cnt	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	ELflange_hrs	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	ELflange_EF	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	ELoel_cnt	2.77E+03	5.88E+03	9.42E+03	9.05E+02	3.61E+03	6.70E+03
	ELoel_hrs	7.84E+03	8.47E+03	8.74E+03	7.46E+03	8.02E+03	8.76E+03
	ELoel_EF	7.51E-04	8.55E-04	9.49E-04	4.00E-04	4.30E-04	4.88E-04
	ELother_cnt	4.27E+01	1.16E+02	2.00E+02	0.00E+00	3.33E+00	1.00E+01
	ELother_hrs	1.46E+03	2.35E+03	3.28E+03	0.00E+00	1.04E+03	3.13E+03
	ELother_EF	2.60E-02	1.04E-01	5.42E-02	0.00E+00	2.36E-02	7.08E-02
	ELprv_cnt	7.01E+02	1.78E+03	3.08E+03	2.93E+02	1.41E+03	2.65E+03
	ELprv_hrs	7.84E+03	8.47E+03	8.74E+03	7.29E+03	7.97E+03	8.76E+03
	ELprv_EF	8.57E-04	1.32E-03	1.82E-03	2.49E-03	2.67E-03	3.04E-03
	ELpump_cnt	0.00E+00	3.05E-02	2.67E-01	0.00E+00	3.33E+00	1.00E+01
	ELpump_hrs	0.00E+00	5.81E+01	2.92E+02	0.00E+00	2.92E+03	8.76E+03
	ELpump_EF	0.00E+00	3.67E-04	1.87E-03	0.00E+00	1.60E-02	4.79E-02
	ELvalve_cnt	4.12E+04	6.27E+04	8.48E+04	6.24E+03	2.69E+04	4.94E+04

Category	Parameter Name	ONE Future Average			Gulf Coast Basin (LA TX)		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5
Production fugitives	ELvalve_hrs	7.84E+03	8.46E+03	8.74E+03	7.36E+03	7.99E+03	8.76E+03
	ELvalve_EF	6.81E-04	9.53E-04	1.25E-03	1.56E-03	1.68E-03	1.90E-03
Production venting	HFcomp_nf	2.70E+01	5.80E+01	9.34E+01	0.00E+00	2.61E+00	4.30E+00
	HFcomp_f	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	HFwork_nf	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	HFwork_f	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	CONcomp_nf	2.32E-01	5.69E-01	9.74E-01	0.00E+00	2.05E+00	4.60E+00
	CONcomp_f	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	CONwork_nf	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	CONwork_f	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	PDhb_hr	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03
	PDhb_count	0.00E+00	3.47E+01	1.16E+02	0.00E+00	6.67E-01	2.00E+00
	PDhb_EF	0.00E+00	4.11E-02	1.00E-01	0.00E+00	1.57E-01	4.70E-01
	PDib_hr	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03
	PDib_count	2.91E+03	4.07E+03	5.27E+03	0.00E+00	9.86E+02	2.89E+03
	PDib_EF	1.83E-01	2.08E-01	2.28E-01	0.00E+00	5.42E-02	1.30E-01
	PDlb_HR	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03
	PDlb_count	1.70E+02	4.63E+02	8.53E+02	2.89E+02	9.67E+02	1.41E+03
	PDlb_EF	1.60E-03	4.12E-03	7.19E-03	7.01E-03	1.42E-02	2.02E-02
	Ppump_hr	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03
	Ppump_count	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
	Ppump_EF	1.10E+01	3.38E+01	6.05E+01	5.70E+00	7.55E+00	1.05E+01
	Dehy_sg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Dehy_des	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Dehy_lg	1.08E-01	2.09E-01	3.19E-01	0.00E+00	6.03E-04	1.80E-03
	BD_comp_wells	2.78E+03		3.31E+03	3.70E+02		2.98E+03
	BD_comp_EF	7.74E+01	7.74E+01	7.74E+01	7.74E+01	7.74E+01	7.74E+01
	BD_compperwell	1.06E-01	1.06E-01	1.06E-01	1.06E-01	1.06E-01	1.06E-01
	PRV_upset_count	2.78E+03		3.31E+03	3.70E+02		2.98E+03
	PRV_upset_EF	7.00E-01	7.00E-01	7.00E-01	7.00E-01	7.00E-01	7.00E-01
	BD_vessel_wells	2.78E+03		3.31E+03	3.70E+02		2.98E+03
	BD_vessel_heatr	2.17E-01	2.17E-01	2.17E-01	2.17E-01	2.17E-01	2.17E-01
	BD_vessel_sep	6.72E-01	6.72E-01	6.72E-01	6.72E-01	6.72E-01	6.72E-01
	BD_vessel_dehy	3.75E-02	3.75E-02	3.75E-02	3.75E-02	3.75E-02	3.75E-02
	BD_vessel_EF	1.60E+00	1.60E+00	1.60E+00	1.60E+00	1.60E+00	1.60E+00
	EURv	2.99E+06	2.99E+06	2.99E+06	1.20E+07	1.20E+07	1.20E+07
	declinecurve_HF	1.40E-01	1.40E-01	1.40E-01	1.40E-01	1.40E-01	1.40E-01
	declinecurve_CON	5.00E-02	5.00E-02	5.00E-02	5.00E-02	5.00E-02	5.00E-02

Exhibit A-3. Production Parameters for Appalachian Basin (Eastern Overthrust Area) and Permian Basin

Category	Parameter Name	Appalachian Basin (Eastern Overthrust Area)			Permian Basin		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5
	NG_prod_v	2.86E+07	4.41E+08	8.23E+08	4.31E+06	2.54E+07	5.72E+07
	CH4_content	6.72E-01	7.48E-01	9.47E-01	5.22E-01	5.83E-01	6.55E-01
Produced water venting	1_PW_vol	3.35E-03	3.35E-03	3.35E-03	3.35E-03	3.35E-03	3.35E-03
	1_PW_EF	1.42E-02	1.42E-02	1.42E-02	1.42E-02	1.42E-02	1.42E-02
Well drilling	1_WELL_concrete	1.28E+04	1.60E+04	1.92E+04	1.28E+04	1.60E+04	1.92E+04
	1_WELL_steel	1.28E+04	1.60E+04	1.92E+04	1.28E+04	1.60E+04	1.92E+04
	1_EUR	1.20E+07	1.20E+07	1.20E+07	1.20E+07	1.20E+07	1.20E+07
Liquids unloading	1_LU	1.74E-04	1.83E-04	1.91E-04	9.00E-05		1.10E-04
Production flaring	1_FLARE_NGsent	2.74E+05	5.33E+07	1.49E+08	6.78E+04	5.24E+08	1.76E+09
Production acid gas removal (AGR)	1_AGR_CO2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.00E+01	2.00E+02
	1_AGR_CH4ef	3.73E-05	3.73E-05	3.73E-05	3.73E-05	3.73E-05	3.73E-05
Production combustion	1_COMB_fuel_1M	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.49E+05	1.80E+06
	1_COMB_fuel_5M	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	1_COMB_fuel_dl_1M	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	1_COMB_fuel_dl_5M	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Production compression	1_RECIP_cnt	0.00E+00	5.78E+01	1.14E+02	0.00E+00	4.08E+01	1.35E+02
	1_RECIP_CH4ef	0.00E+00	1.45E-01	1.82E-01	0.00E+00	1.37E-01	1.82E-01
	1_COMB_fuel_cd	0.00E+00	5.22E+05	1.37E+06	0.00E+00	7.07E+05	1.73E+06
	1_COMB_fuel_dl_cd	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Production fugitives	ELconn_cnt	5.30E+03	1.04E+05	3.78E+05	0.00E+00	1.99E+04	5.04E+04
	ELconn_hrs	8.60E+03	8.73E+03	8.76E+03	0.00E+00	5.73E+03	8.76E+03
	ELconn_EF	4.44E-05	5.09E-05	5.64E-05	0.00E+00	1.64E-04	2.58E-04
	ELflange_cnt	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	ELflange_hrs	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	ELflange_EF	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	ELoel_cnt	1.03E+02	7.67E+02	2.95E+03	0.00E+00	6.67E+02	1.64E+03
	ELoel_hrs	8.60E+03	8.73E+03	8.76E+03	0.00E+00	5.86E+03	8.76E+03
	ELoel_EF	9.03E-04	1.03E-03	1.15E-03	0.00E+00	3.52E-04	6.49E-04
	ELother_cnt	0.00E+00	1.13E+02	5.29E+02	0.00E+00	3.75E+00	1.20E+01
	ELother_hrs	0.00E+00	3.12E+03	6.57E+03	0.00E+00	2.21E+03	8.76E+03
	ELother_EF	0.00E+00	4.78E-02	8.31E-02	0.00E+00	3.20E-02	6.82E-02
	ELprv_cnt	2.00E+00	6.52E+01	2.09E+02	0.00E+00	3.50E+02	9.76E+02
	ELprv_hrs	8.60E+03	8.73E+03	8.76E+03	0.00E+00	5.91E+03	8.76E+03
	ELprv_EF	0.00E+00	5.46E-04	7.46E-04	0.00E+00	1.84E-03	2.93E-03
	ELpump_cnt	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+00	4.00E+00
	ELpump_hrs	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.19E+03	8.76E+03
	ELpump_EF	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.40E-02	5.61E-02

Category	Parameter Name	Appalachian Basin (Eastern Overthrust Area)			Permian Basin		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5
Production fugitives	ELvalve_cnt	1.15E+03	2.44E+04	8.82E+04	0.00E+00	6.66E+03	1.79E+04
	ELvalve_hrs	8.60E+03	8.73E+03	8.76E+03	0.00E+00	5.73E+03	8.76E+03
	ELvalve_EF	4.00E-04	4.58E-04	5.08E-04	0.00E+00	1.43E-03	2.79E-03
Production venting	HFcomp_nf	0.00E+00	4.02E+01	1.97E+02	0.00E+00	7.50E-02	3.00E-01
	HFcomp_f	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	HFwork_nf	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	HFwork_f	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	CONcomp_nf	0.00E+00	1.96E-01	9.82E-01	0.00E+00	1.42E+00	4.58E+00
	CONcomp_f	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	CONwork_nf	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	CONwork_f	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	PDhb_hr	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03
	PDhb_count	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.00E+00	2.40E+01
	PDhb_EF	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.31E-02	1.73E-01
	PDib_hr	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03
	PDib_count	0.00E+00	2.55E+03	9.31E+03	1.40E+01	8.74E+02	1.75E+03
	PDib_EF	0.00E+00	1.35E-01	2.44E-01	1.82E-02	1.05E-01	2.27E-01
	PDlb_HR	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03
	PDlb_count	0.00E+00	1.40E+00	7.00E+00	0.00E+00	2.38E+03	7.70E+03
	PDlb_EF	0.00E+00	5.94E-03	2.97E-02	0.00E+00	5.80E-03	1.47E-02
	Ppump_hr	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03
	Ppump_count	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
	Ppump_EF	0.00E+00	2.50E-01	1.25E+00	0.00E+00	1.17E+00	3.81E+00
	Dehy_sg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Dehy_des	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Dehy_lg	7.50E-04	2.15E-01	8.16E-01	0.00E+00	2.97E-03	1.19E-02
	BD_comp_wells	4.56E+02		7.04E+02	3.37E+02		8.42E+03
	BD_comp_EF	7.74E+01	7.74E+01	7.74E+01	7.74E+01	7.74E+01	7.74E+01
	BD_compperwell	1.06E-01	1.06E-01	1.06E-01	1.06E-01	1.06E-01	1.06E-01
	PRV_upset_count	4.56E+02		7.04E+02	3.37E+02		8.42E+03
	PRV_upset_EF	7.00E-01	7.00E-01	7.00E-01	7.00E-01	7.00E-01	7.00E-01
	BD_vessel_wells	4.56E+02		7.04E+02	3.37E+02		8.42E+03
	BD_vessel_heatr	2.17E-01	2.17E-01	2.17E-01	2.17E-01	2.17E-01	2.17E-01
	BD_vessel_sep	6.72E-01	6.72E-01	6.72E-01	6.72E-01	6.72E-01	6.72E-01
	BD_vessel_dehy	3.75E-02	3.75E-02	3.75E-02	3.75E-02	3.75E-02	3.75E-02
	BD_vessel_EF	1.60E+00	1.60E+00	1.60E+00	1.60E+00	1.60E+00	1.60E+00
	EURv	1.20E+07	1.20E+07	1.20E+07	1.20E+07	1.20E+07	1.20E+07
	declinecurve_HF	1.40E-01	1.40E-01	1.40E-01	1.40E-01	1.40E-01	1.40E-01
	declinecurve_CON	5.00E-02	5.00E-02	5.00E-02	5.00E-02	5.00E-02	5.00E-02

Exhibit A-4. Production Parameters for Williston Basin and Arkoma Basin

Category	Parameter Name	Williston Basin			Arkoma Basin		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5
	NG_prod_v	7.80E+06	2.19E+07	3.60E+07	7.81E+07	2.83E+08	4.88E+08
	CH4_content	3.21E-01	3.47E-01	3.72E-01	8.77E-01	8.85E-01	8.93E-01
Produced water venting	1_PW_vol	3.35E-03	3.35E-03	3.35E-03	3.35E-03	3.35E-03	3.35E-03
	1_PW_EF	1.42E-02	1.42E-02	1.42E-02	1.42E-02	1.42E-02	1.42E-02
Well drilling	1_WELL_concrete	1.28E+04	1.60E+04	1.92E+04	1.28E+04	1.60E+04	1.92E+04
	1_WELL_steel	1.28E+04	1.60E+04	1.92E+04	1.28E+04	1.60E+04	1.92E+04
	1_EUR	1.20E+07	1.20E+07	1.20E+07	1.20E+07	1.20E+07	1.20E+07
Liquids unloading	1_LU	0.00E+00	0.00E+00	0.00E+00	1.88E-03		1.17E-02
Production flaring	1_FLARE_NGsent	9.12E+08	2.90E+09	4.89E+09	0.00E+00	0.00E+00	0.00E+00
Production acid gas removal (AGR)	1_AGR_CO2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	1_AGR_CH4ef	3.73E-05	3.73E-05	3.73E-05	3.73E-05	3.73E-05	3.73E-05
Production combustion	1_COMB_fuel_1M	0.00E+00	3.60E+06	7.20E+06	0.00E+00	5.23E+04	1.05E+05
	1_COMB_fuel_5M	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	1_COMB_fuel_dl_1M	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	1_COMB_fuel_dl_5M	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Production compression	1_RECIP_cnt	0.00E+00	0.00E+00	0.00E+00	6.00E+01	2.20E+02	3.80E+02
	1_RECIP_CH4ef	0.00E+00	0.00E+00	0.00E+00	1.82E-01	1.82E-01	1.82E-01
	1_COMB_fuel_cd	0.00E+00	0.00E+00	0.00E+00	6.59E+05	1.38E+06	2.11E+06
	1_COMB_fuel_dl_cd	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Production fugitives	ELconn_cnt	0.00E+00	1.29E+05	2.57E+05	1.74E+05	3.69E+05	5.65E+05
	ELconn_hrs	0.00E+00	4.38E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03
	ELconn_EF	0.00E+00	9.61E-05	1.92E-04	3.11E-04	3.12E-04	3.13E-04
	ELflange_cnt	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	ELflange_hrs	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	ELflange_EF	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	ELoel_cnt	0.00E+00	5.73E+03	1.15E+04	7.39E+03	1.69E+04	2.65E+04
	ELoel_hrs	0.00E+00	4.38E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03
	ELoel_EF	0.00E+00	1.75E-04	3.50E-04	5.68E-04	5.70E-04	5.72E-04
	ELother_cnt	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	ELother_hrs	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	ELother_EF	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	ELprv_cnt	0.00E+00	1.89E+03	3.78E+03	2.69E+03	6.09E+03	9.48E+03
	ELprv_hrs	0.00E+00	4.38E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03
	ELprv_EF	0.00E+00	1.09E-03	2.18E-03	3.53E-03	3.55E-03	3.56E-03
	ELpump_cnt	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	ELpump_hrs	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	ELpump_EF	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	ELvalve_cnt	0.00E+00	3.86E+04	7.73E+04	5.49E+04	1.20E+05	1.85E+05

Category	Parameter Name	Williston Basin			Arkoma Basin		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5
Production fugitives	ELvalve_hrs	0.00E+00	4.38E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03
	ELvalve_EF	0.00E+00	6.84E-04	1.37E-03	2.22E-03	2.22E-03	2.23E-03
Production venting	HFcomp_nf	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	HFcomp_f	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	HFwork_nf	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	HFwork_f	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	CONcomp_nf	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.45E-01	1.49E+00
	CONcomp_f	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	CONwork_nf	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	CONwork_f	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	PDhb_hr	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03
	PDhb_count	0.00E+00	2.00E+02	4.00E+02	0.00E+00	0.00E+00	0.00E+00
	PDhb_EF	0.00E+00	2.11E-01	4.23E-01	0.00E+00	0.00E+00	0.00E+00
	PDib_hr	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03
	PDib_count	0.00E+00	5.00E-01	1.00E+00	3.77E+03	4.96E+03	6.16E+03
	PDib_EF	0.00E+00	7.65E-02	1.53E-01	5.56E-02	1.52E-01	2.49E-01
	PDlb_HR	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03
	PDlb_count	0.00E+00	5.00E-01	1.00E+00	6.20E+01	1.13E+03	2.20E+03
	PDlb_EF	0.00E+00	7.88E-03	1.58E-02	6.45E-03	1.60E-02	2.55E-02
	Ppump_hr	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03
	Ppump_count	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
	Ppump_EF	0.00E+00	1.88E+00	3.76E+00	0.00E+00	9.39E+01	1.88E+02
	Dehy_sg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Dehy_des	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Dehy_lg	0.00E+00	1.05E-02	2.10E-02	0.00E+00	0.00E+00	0.00E+00
	BD_comp_wells	2.78E+03		3.31E+03	2.69E+02		2.19E+03
	BD_comp_EF	7.74E+01	7.74E+01	7.74E+01	7.74E+01	7.74E+01	7.74E+01
	BD_compperwell	1.06E-01	1.06E-01	1.06E-01	1.06E-01	1.06E-01	1.06E-01
	PRV_upset_count	2.78E+03		3.31E+03	2.69E+02		2.19E+03
	PRV_upset_EF	7.00E-01	7.00E-01	7.00E-01	7.00E-01	7.00E-01	7.00E-01
	BD_vessel_wells	2.78E+03		3.31E+03	2.69E+02		2.19E+03
	BD_vessel_heatr	2.17E-01	2.17E-01	2.17E-01	2.17E-01	2.17E-01	2.17E-01
	BD_vessel_sep	6.72E-01	6.72E-01	6.72E-01	6.72E-01	6.72E-01	6.72E-01
	BD_vessel_dehy	3.75E-02	3.75E-02	3.75E-02	3.75E-02	3.75E-02	3.75E-02
	BD_vessel_EF	1.60E+00	1.60E+00	1.60E+00	1.60E+00	1.60E+00	1.60E+00
	EURv	1.20E+07	1.20E+07	1.20E+07	1.20E+07	1.20E+07	1.20E+07
	declinecurve_HF	1.40E-01	1.40E-01	1.40E-01	1.40E-01	1.40E-01	1.40E-01
	declinecurve_CON	5.00E-02	5.00E-02	5.00E-02	5.00E-02	5.00E-02	5.00E-02

A.2 GATHERING AND BOOSTING PARAMETERS FOR ONE FUTURE SCENARIOS

Exhibit A-5. Gathering and Boosting Parameters and their Description and Units

Category	Parameter Name	Parameter Description	Units
	2_NG_sent	Volume of natural gas gathered and boosted	Mcf
	2_mCH4	Mass fraction of methane in natural gas	dimensionless
Gathering and boosting correction factor	G_B_correction	Correction factor for G&B throughput, from GHGRP	dimensionless
Gathering and boosting acid gas removal (AGR)	2_AGR_CO2	Annual CO_2 emissions from acid gas removal units at natural gas gathering and boosting facilities	tonnes CO_2/yr
	2_AGR_CH4ef	Methane emission factor from acid gas removal at gathering and boosting facilities	kg CH_4/kg NG
Gathering and boosting combustion	2_COMB_fuel_1M	NG combustion in equipment with output of <1MMBtu/hr (does not include compressor drivers)	Mcf
	2_COMB_fuel_5M	NG combustion in equipment with output of <5MMBtu/hr (does not include compressor drivers)	Mcf
Gathering and boosting centrifugal compression venting	2_CENT_CH4	Methane emissions from gathering and boosting centrifugal compressors	tonnes
Gathering and boosting reciprocating compression	2_RECIP_CH4	Methane emissions from gathering and boosting reciprocating compressors	tonnes
	2_COMB_fuel_cd	NG combusted by compressor driver	Mcf
Gathering and boosting flaring	2_FLARE_CH4	Mass of CH_4 emitted by gathering and boosting flaring	tonnes
Gathering and boosting fugitives	2_GSconn_CH4	Annual CH_4 emissions from gas service connectors	tonnes CH_4/yr
	2_GSflange_CH4	Annual CH_4 emissions from gas service flanges	tonnes CH_4/yr
	2_GSoel_CH4	Annual CH_4 emissions from gas service open ended lines	tonnes CH_4/yr
	2_GSplastic_CH4	Annual CH_4 emissions from gas service plastic lines	tonnes CH_4/yr
	2_GSprv_CH4	Annual CH_4 emissions from gas service pressure relief valves	tonnes CH_4/yr
	2_GSpsteel_CH4	Annual CH_4 emissions from gas service protected steel lines	tonnes CH_4/yr
	2_GSupsteel_CH4	Annual CH_4 emissions from gas service unprotected steel lines	tonnes CH_4/yr

Category	Parameter Name	Parameter Description	Units
Gathering and boosting fugitives	2_GSvalve_CH4	Annual CH_4 emissions from gas service valves	tonnes CH_4/yr
	2_GPciron_CH4	Annual CH_4 emissions from pipeline cast iron	tonnes CH_4/yr
	2_GPplastic_CH4	Annual CH_4 emissions from pipeline plastics	tonnes CH_4/yr
	2_GPpsteel_CH4	Annual CH_4 emissions from pipeline protected steel	tonnes CH_4/yr
	2_GPupsteel_CH4	Annual CH_4 emissions from pipeline unprotected steel	tonnes CH_4/yr
Gathering and boosting venting	2_PDhb_cnt	Count of high-bleed pneumatic devices	count
	2_PDhb_hrs	Activity factor: operating hours for high bleed pneumatic devices	hours
	2_PDhb_EF	Emission factor for methane from high bleed pneumatic devices	kg NG/device-hr
	2_PDib_cnt	Count of intermittent-bleed pneumatic devices	count
	2_PDib_hrs	Activity factor: operating hours for intermittent bleed pneumatic devices	hours
	2_PDib_EF	Emission factor for methane from intermittent bleed pneumatic devices	kg NG/device-hr
	2_PDlb_cnt	Count of low-bleed pneumatic devices	count
	2_PDlb_hrs	Activity factor: operating hours for low bleed pneumatic devices	hours
	2_PDlb_EF	Emission factor for methane from low bleed pneumatic devices	kg NG/device-hr
	2_PPump_cnt	Count of pneumatic pumps	count
	2_PPump_hrs	Activity factor: operating hours for pneumatic pumps	hours
	2_PPump_EF	Emission factor for methane from pneumatic pumps	kg NG/device-hr
	2_DEHYsg_CH4	Annual CH_4 emissions from small dehydrator units.	tonnes CH_4
	2_DEHYdes_CH4	Annual CH_4 emissions from desiccant dehydrator units	tonnes CH_4
	2_DEHYlg_CH4	Annual CH_4 emissions from large dehydrator units	tonnes CH_4
	2_BDother_CH4	Annual CH_4 emissions from "other" blowdown events	tonnes CH_4
	2_BDcomp_CH4	Annual CH_4 emissions from compressor blowdown events	tonnes CH_4
	2_BDesd_CH4	Annual CH_4 emissions from emergency shutdown blowdown events	tonnes CH_4
	2_BDfacpip_CH4	Annual CH_4 emissions from facility piping blowdown events	tonnes CH_4
	2_BDpig_CH4	Annual CH_4 emissions from pig blowdown events	tonnes CH_4
	2_BDpipe_CH4	Annual CH_4 emissions from pipeline blowdown events	tonnes CH_4

Category	Parameter Name	Parameter Description	Units
Gathering and boosting venting	2_BDscrub_CH4	Annual CH_4 emissions from scrubber blowdown events	tonnes CH_4
	2_MISHAPS_EF	Gathering pipeline - mishap emission factor	kg CH_4/mile of gathering pipeline
	2_MISHAPS_region	Gathering pipeline - mishap activity factor: miles/well	Miles of gathering pipeline/well
	2_MISHAPS_AF	Gathering pipeline - Mishap activity factor: count of wells	wells

Exhibit A-6. Gathering and Boosting Parameters for Average and Gulf Coast Basin (LA TX)

Category	Parameter Name	ONE Future Average			Gulf Coast Basin (LA TX)		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5
	2_NG_sent	2.99E+08	4.10E+08	5.16E+08	5.63E+07	8.50E+07	1.14E+08
	2_mCH4	7.19E-01	7.65E-01	8.03E-01	7.13E-01	7.18E-01	7.24E-01
Gathering and boosting Correction Factor	G_B_correction	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Gathering and boosting acid gas removal (AGR)	2_AGR_CO2	5.19E+00	3.35E+01	8.24E+01	0.00E+00	3.24E+02	6.47E+02
	2_AGR_CH4ef	3.73E-05	3.73E-05	3.73E-05	3.73E-05	3.73E-05	3.73E-05
Gathering and boosting combustion	2_COMB_fuel_1M	1.47E+05	2.73E+05	4.07E+05	0.00E+00	3.36E+05	6.72E+05
	2_COMB_fuel_5M	1.41E+06	1.92E+06	2.41E+06	0.00E+00	2.35E+05	4.70E+05
Gathering and boosting centrifugal compression venting	2_CENT_CH4	0.00E+00	1.74E+02	3.84E+02	0.00E+00	0.00E+00	0.00E+00
Gathering and boosting reciprocating compression	2_RECIP_CH4	8.90E+00	1.48E+01	2.11E+01	6.73E+00	7.01E+00	7.28E+00
	2_COMB_fuel_cd	5.01E+06	8.81E+06	1.32E+07	1.69E+06	1.75E+06	1.81E+06
Gathering and boosting flaring	2_FLARE_CH4	1.82E+01	3.84E+01	6.45E+01	1.49E+01	1.10E+02	2.05E+02
Gathering and boosting fugitives	2_GSconn_CH4	2.09E+01	7.44E+01	1.35E+02	4.39E+00	1.09E+02	2.13E+02
	2_GSflange_CH4	0.00E+00	1.44E-01	3.27E-01	0.00E+00	0.00E+00	0.00E+00
	2_GSoel_CH4	1.48E+00	4.77E+00	8.57E+00	1.24E+00	4.83E+00	8.41E+00
	2_GSplastic_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_GSprv_CH4	4.62E+00	1.69E+01	3.09E+01	4.61E-01	2.41E+01	4.78E+01
	2_GSpsteel_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_GSupsteel_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_GSvalve_CH4	4.88E+01	1.74E+02	3.15E+02	8.98E+00	2.23E+02	4.37E+02
	2_GPciron_CH4	7.28E+00	3.28E+01	7.97E+01	0.00E+00	0.00E+00	0.00E+00
	2_GPplastic_CH4	3.99E+01	1.30E+02	2.39E+02	0.00E+00	5.05E+00	1.01E+01
	2_GPpsteel_CH4	1.36E+01	2.36E+01	3.63E+01	7.06E+00	3.09E+01	5.47E+01
	2_GPupsteel_CH4	1.41E+02	6.30E+02	1.51E+03	0.00E+00	0.00E+00	0.00E+00
Gathering and boosting venting	2_PDhb_cnt	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_PDhb_hrs	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Category	Parameter Name	ONE Future Average			Gulf Coast Basin (LA TX)		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5
Gathering and boosting venting	2_PDhb_EF	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_PDib_cnt	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
	2_PDib_hrs	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03
	2_PDib_EF	6.01E+01	1.92E+02	3.54E+02	2.64E+00	1.80E+01	3.33E+01
	2_PDlb_cnt	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_PDlb_hrs	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_PDlb_EF	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_PPump_cnt	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
	2_PPump_hrs	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03
	2_PPump_EF	6.71E+00	1.92E+01	3.44E+01	2.33E+00	4.88E+00	7.44E+00
	2_DEHYsg_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_DEHYdes_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_DEHYlg_CH4	5.61E+01	8.21E+01	1.11E+02	2.38E+00	2.85E+00	3.31E+00
	2_BDother_CH4	1.08E+02	1.74E+02	2.43E+02	0.00E+00	9.84E+01	1.97E+02
	2_BDcomp_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_BDesd_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_BDfacpip_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_BDpig_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_BDpipe_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_BDscrub_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_MISHAPS_EF	1.37E+01	1.37E+01	1.37E+01	1.37E+01	1.37E+01	1.37E+01
	2_MISHAPS_region	6.68E-01	6.68E-01	6.68E-01	6.68E-01	6.68E-01	6.68E-01
	2_MISHAPS_AF	8.05E+01	8.05E+01	8.05E+01	8.05E+01	8.05E+01	8.05E+01

Exhibit A-7. Gathering and Boosting Parameters for Appalachian Basin (Eastern Overthrust Area) and Permian Basin

Category	Parameter Name	Appalachian Basin (Eastern Overthrust Area)			Permian Basin		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5
	2_NG_sent	5.10E+07	2.91E+08	7.59E+08	6.31E+05	2.44E+06	4.77E+06
	2_mCH4	6.65E-01	7.49E-01	7.91E-01	5.83E-01	6.46E-01	6.78E-01
Gathering and boosting Correction Factor	G_B_correction	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Gathering and boosting acid gas removal (AGR)	2_AGR_CO2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_AGR_CH4ef	3.73E-05	3.73E-05	3.73E-05	3.73E-05	3.73E-05	3.73E-05
Gathering and boosting combustion	2_COMB_fuel_1M	0.00E+00	2.41E+05	7.06E+05	0.00E+00	0.00E+00	0.00E+00
	2_COMB_fuel_5M	4.70E+05	1.51E+06	3.46E+06	0.00E+00	4.27E+04	1.28E+05
Gathering and boosting centrifugal compression venting	2_CENT_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Category	Parameter Name	Appalachian Basin (Eastern Overthrust Area)			Permian Basin		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5
Gathering and boosting reciprocating compression	2_RECIP_CH4	3.97E+00	8.73E+00	2.42E+01	5.50E-01	1.76E+00	3.64E+00
	2_COMB_fuel_cd	5.22E+05	3.90E+06	9.58E+06	9.26E+04	1.92E+05	2.53E+05
Gathering and boosting flaring	2_FLARE_CH4	0.00E+00	2.69E+01	8.56E+01	0.00E+00	3.24E-02	9.71E-02
Gathering and boosting fugitives	2_GSconn_CH4	9.03E-01	2.01E+00	2.96E+00	0.00E+00	2.84E+00	8.53E+00
	2_GSflange_CH4	0.00E+00	1.96E-01	9.80E-01	0.00E+00	0.00E+00	0.00E+00
	2_GSoel_CH4	0.00E+00	2.92E-01	6.35E-01	0.00E+00	8.18E-02	2.45E-01
	2_GSplastic_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_GSprv_CH4	1.23E-01	3.05E-01	7.25E-01	0.00E+00	6.03E-01	1.81E+00
	2_GSpsteel_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_GSupsteel_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_GSvalve_CH4	2.07E+00	4.34E+00	6.29E+00	0.00E+00	7.73E+00	2.32E+01
	2_GPciron_CH4	0.00E+00	1.29E+02	5.72E+02	0.00E+00	0.00E+00	0.00E+00
	2_GPplastic_CH4	0.00E+00	4.33E+01	1.37E+02	0.00E+00	3.45E+00	1.04E+01
	2_GPpsteel_CH4	4.85E+00	4.49E+01	1.69E+02	0.00E+00	2.68E+01	8.05E+01
	2_GPupsteel_CH4	0.00E+00	5.57E+02	2.32E+03	0.00E+00	5.79E+01	1.74E+02
Gathering and boosting venting	2_PDhb_cnt	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_PDhb_hrs	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_PDhb_EF	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_PDib_cnt	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
	2_PDib_hrs	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03
	2_PDib_EF	0.00E+00	3.87E+01	1.23E+02	0.00E+00	4.45E+00	1.34E+01
	2_PDlb_cnt	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_PDlb_hrs	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_PDlb_EF	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_PPump_cnt	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
	2_PPump_hrs	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03
	2_PPump_EF	0.00E+00	2.78E+00	4.86E+00	0.00E+00	1.02E+00	3.06E+00
	2_DEHYsg_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_DEHYdes_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_DEHYlg_CH4	7.50E+01	1.55E+02	2.07E+02	0.00E+00	7.67E-02	2.30E-01
	2_BDother_CH4	8.02E+00	1.38E+02	4.16E+02	7.50E-01	3.87E+01	1.14E+02
	2_BDcomp_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_BDesd_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_BDfacpip_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_BDpig_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_BDpipe_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_BDscrub_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_MISHAPS_EF	1.37E+01	1.37E+01	1.37E+01	1.37E+01	1.37E+01	1.37E+01

Category	Parameter Name	Appalachian Basin (Eastern Overthrust Area)			Permian Basin		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5
Gathering and boosting venting	2_MISHAPS_region	6.68E-01	6.68E-01	6.68E-01	6.68E-01	6.68E-01	6.68E-01
	2_MISHAPS_AF	8.05E+01	8.05E+01	8.05E+01	8.05E+01	8.05E+01	8.05E+01

Exhibit A-8. Gathering and Boosting Parameters for Williston Basin and Arkoma Basin

Category	Parameter Name	Williston Basin			Arkoma Basin		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5
	2_NG_sent	8.71E+06	2.37E+07	3.87E+07	4.67E+07	2.44E+08	4.42E+08
	2_mCH4	3.02E-01	3.37E-01	3.71E-01	8.77E-01	8.85E-01	8.93E-01
Gathering and boosting Correction Factor	G_B_correction	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Gathering and boosting acid gas removal (AGR)	2_AGR_CO2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.45E+01	1.09E+02
	2_AGR_CH4ef	3.73E-05	3.73E-05	3.73E-05	3.73E-05	3.73E-05	3.73E-05
Gathering and boosting combustion	2_COMB_fuel_1M	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.54E+04	1.31E+05
	2_COMB_fuel_5M	0.00E+00	5.34E+05	1.07E+06	6.40E+05	1.58E+06	2.52E+06
Gathering and boosting centrifugal compression venting	2_CENT_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Gathering and boosting reciprocating compression	2_RECIP_CH4	2.70E+00	5.54E+00	8.37E+00	4.00E+00	2.38E+01	4.35E+01
	2_COMB_fuel_cd	4.67E+05	7.45E+05	1.02E+06	1.69E+06	1.51E+07	2.86E+07
Gathering and boosting flaring	2_FLARE_CH4	1.84E+00	1.40E+02	2.78E+02	0.00E+00	0.00E+00	0.00E+00
Gathering and boosting fugitives	2_GSconn_CH4	1.31E+00	1.07E+01	2.01E+01	3.47E+01	1.97E+02	3.60E+02
	2_GSflange_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_GSoel_CH4	4.00E-02	4.50E-01	8.60E-01	1.61E+00	1.26E+01	2.37E+01
	2_GSplastic_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_GSprv_CH4	3.33E-01	2.55E+00	4.76E+00	8.11E+00	4.54E+01	8.27E+01
	2_GSpsteel_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_GSupsteel_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_GSvalve_CH4	3.80E+00	2.73E+01	5.07E+01	8.00E+01	4.71E+02	8.62E+02
	2_GPciron_CH4	0.00E+00	5.00E-03	1.00E-02	0.00E+00	0.00E+00	0.00E+00
	2_GPplastic_CH4	0.00E+00	7.87E+01	1.57E+02	2.34E+00	3.39E+02	6.76E+02
	2_GPpsteel_CH4	1.00E-02	4.61E+00	9.20E+00	0.00E+00	1.76E+01	3.52E+01
	2_GPupsteel_CH4	0.00E+00	1.73E+02	3.46E+02	0.00E+00	4.17E+02	8.34E+02
Gathering and boosting venting	2_PDhb_cnt	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_PDhb_hrs	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_PDhb_EF	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_PDib_cnt	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
	2_PDib_hrs	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03
	2_PDib_EF	0.00E+00	0.00E+00	0.00E+00	3.40E+01	5.17E+02	1.00E+03
	2_PDlb_cnt	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Category	Parameter Name	Williston Basin			Arkoma Basin		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5
Gathering and boosting venting	2_PDlb_hrs	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_PDlb_EF	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_PPump_cnt	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
	2_PPump_hrs	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03	8.76E+03
	2_PPump_EF	0.00E+00	0.00E+00	0.00E+00	7.37E+00	5.19E+01	9.64E+01
	2_DEHYsg_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_DEHYdes_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_DEHYlg_CH4	0.00E+00	6.51E+00	1.30E+01	1.64E+01	2.54E+01	3.45E+01
	2_BDother_CH4	0.00E+00	1.27E+01	2.55E+01	4.29E+00	4.74E+01	9.05E+01
	2_BDcomp_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_BDesd_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_BDfacpip_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_BDpig_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_BDpipe_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_BDscrub_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2_MISHAPS_EF	1.37E+01	1.37E+01	1.37E+01	1.37E+01	1.37E+01	1.37E+01
	2_MISHAPS_region	6.68E-01	6.68E-01	6.68E-01	6.68E-01	6.68E-01	6.68E-01
	2_MISHAPS_AF	8.05E+01	8.05E+01	8.05E+01	8.05E+01	8.05E+01	8.05E+01

A.3 PROCESSING PARAMETERS FOR ONE FUTURE SCENARIOS

Exhibit A-9. Processing Parameters and their Description and Units

Category	Parameter Name	Parameter Description	Units
	3_NG_processed	Annual natural gas processed at a processing facility	Mcf
	3_NGL_processed	Annual natural gas liquids processed at a processing facility	bbl
	nat_mCO2	Mass fraction of CO_2 in natural gas	dimensionless
	nat_mCH4	Mass fraction of CH_4 in natural gas	dimensionless
Processing acid gas removal (AGR)	3_AGR_CO2	Annual CO_2 emissions from acid gas removal units at a natural gas processing facility	tonnes CO_2
	3_AGR_CH4ef	Methane emission factor from acid gas removal at processing	kg CH_4/kg NG
Processing combustion	3_NG_subpartC	Natural gas combusted at a processing facility	scf
Processing centrifugal compression	3_CENT_CH4	Methane emissions from processing centrifugal compressors	tonnes
	3_CENT_energy	Operating centrifugal compressor horsepower-hour at a processing facility	HPh

Category	Parameter Name	Parameter Description	Units
Processing centrifugal compression	Turbine_thermalefficiency	Thermal efficiency of gas-fired turbines used to drive centrifugal compressors	dimensionless
Processing reciprocating compression	3_RECIP_CH4	Methane emissions from processing reciprocating compressors	tonnes
	3_RECIP_energy	Operating reciprocating compressor horsepower-hour at a processing facility	HPh
	Recip_thermalefficiency	Thermal efficiency of reciprocating engines	dimensionless
Processing flaring	3_FLARE_vol	Natural gas sent to flares at a processing facility	scf
Processing fugitives	3_EL_CH4	Methane emissions from equipment leaks	tonnes
Processing venting	3_PD_AF	Count of high-bleed pneumatic devices	count
	3_PD_EF	Activity factor: operating hours for high bleed pneumatic devices	hours
	3_DEHYdes_CH4	CH_4 emitted from desiccant dehydrators	tonnes
	3_DEHYlg_CH4	CH_4 emitted from large glycol dehydrators	tonnes
	3_BDother_CH4	CH_4 emitted from "other" sources of venting	tonnes
	3_BDcomp_CH4	CH_4 emitted from compressor venting	tonnes
	3_BDesd_CH4	CH_4 emitted from emergency shutdown venting	tonnes
	3_BDfacpip_CH4	CH_4 emitted from facility piping venting	tonnes
	3_BDpig_CH4	CH_4 emitted from pigging venting	tonnes
	3_BDscrub_CH4	CH_4 emitted from scrubber venting	tonnes

Exhibit A-10. Processing Parameters for Average and Gulf Coast Basin (LA TX)

Category	Parameter Name	ONE Future Average			Gulf Coast Basin (LA TX)		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5
	3_NG_processed	2.70E+07	3.89E+07	4.90E+07	1.39E+07	3.58E+07	5.77E+07
	3_NGL_processed	4.25E+05	3.73E+06	7.69E+06	0.00E+00	1.33E+03	2.66E+03
	nat_mCO2	1.86E-02	3.30E-02	4.71E-02	6.12E-02	6.19E-02	6.26E-02
	nat_mCH4	5.85E-01	6.77E-01	7.56E-01	7.28E-01	7.36E-01	7.45E-01
Processing acid gas removal (AGR)	3_AGR_CO2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	3_AGR_CH4ef	3.73E-05	3.73E-05	3.73E-05	3.73E-05	3.73E-05	3.73E-05
Processing combustion	3_NG_subpartC	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Processing centrifugal compression	3_CENT_CH4	9.00E-03	1.05E+01	2.28E+01	0.00E+00	0.00E+00	0.00E+00
	3_CENT_energy	5.99E+06	7.89E+07	1.65E+08	0.00E+00	0.00E+00	0.00E+00
	Turbine_thermalefficiency	2.60E-01	2.60E-01	2.60E-01	2.60E-01	2.60E-01	2.60E-01
Processing reciprocating compression	3_RECIP_CH4	3.46E+01	8.17E+01	1.27E+02	1.05E+02	1.41E+02	1.78E+02
	3_RECIP_energy	5.55E+07	1.10E+08	1.73E+08	2.69E+07	7.45E+07	1.22E+08
	Recip_thermalefficiency	3.20E-01	0.00E+00	4.30E-01	3.20E-01		4.30E-01

Category	Parameter Name	ONE Future Average			Gulf Coast Basin (LA TX)		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5
Processing flaring	3_FLARE_vol	1.94E-01	3.44E-01	5.02E-01	3.15E-01	3.81E-01	4.48E-01
Processing fugitives	3_EL_CH4	4.89E-01	8.55E+00	1.80E+01	1.25E-02	1.27E-02	1.30E-02
Processing venting	3_PD_AF	0.00E+00	2.31E+00	5.00E+00	0.00E+00	0.00E+00	0.00E+00
	3_PD_EF	0.00E+00	2.02E+03	4.38E+03	0.00E+00	0.00E+00	0.00E+00
	3_DEHYdes_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	3_DEHYlg_CH4	8.44E-01	4.84E+00	1.03E+01	1.57E-01	1.48E+00	2.81E+00
Processing venting	3_BDother_CH4	0.00E+00	3.48E+00	7.06E+00	0.00E+00	0.00E+00	0.00E+00
	3_BDcomp_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	3_BDesd_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	3_BDfacpip_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	3_BDpig_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	3_BDscrub_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Exhibit A-11. Processing Parameters for Appalachian Basin (Eastern Overthrust Area) and Permian Basin

Category	Parameter Name	Appalachian Basin (Eastern Overthrust Area)			Permian Basin		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5
	3_NG_processed	5.83E+05	2.55E+07	5.03E+07	4.85E+05	9.44E+06	1.89E+07
	3_NGL_processed	6.07E+03	1.52E+06	3.03E+06	1.60E+04	1.95E+05	4.24E+05
	nat_mCO2	7.22E-03	7.37E-03	7.52E-03	2.52E-02	2.76E-02	3.09E-02
	nat_mCH4	7.22E-01	7.37E-01	7.52E-01	6.29E-01	6.91E-01	7.72E-01
Processing acid gas removal (AGR)	3_AGR_CO2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	3_AGR_CH4ef	3.73E-05	3.73E-05	3.73E-05	3.73E-05	3.73E-05	3.73E-05
Processing combustion	3_NG_subpartC	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Processing centrifugal compression	3_CENT_CH4	0.00E+00	4.50E-02	9.00E-02	0.00E+00	0.00E+00	0.00E+00
	3_CENT_energy	0.00E+00	1.59E+08	3.18E+08	0.00E+00	0.00E+00	0.00E+00
	Turbine_thermalefficiency	2.60E-01	2.60E-01	2.60E-01	2.60E-01	2.60E-01	2.60E-01
Processing reciprocating compression	3_RECIP_CH4	0.00E+00	2.76E+00	5.51E+00	0.00E+00	0.00E+00	0.00E+00
	3_RECIP_energy						
	Recip_thermalefficiency	3.20E-01		4.30E-01	3.20E-01		4.30E-01
Processing flaring	3_FLARE_vol	0.00E+00	6.38E-02	1.28E-01	2.95E-01	9.29E-01	2.43E+00
Processing fugitives	3_EL_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.72E+00	1.01E+01
Processing venting	3_PD_AF	0.00E+00	5.00E+00	1.00E+01	0.00E+00	0.00E+00	0.00E+00
	3_PD_EF	0.00E+00	4.38E+03	8.76E+03	0.00E+00	0.00E+00	0.00E+00
	3_DEHYdes_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	3_DEHYlg_CH4	0.00E+00	0.00E+00	0.00E+00	7.71E-01	1.32E+01	2.71E+01
	3_BDother_CH4	0.00E+00	5.93E+00	1.19E+01	0.00E+00	0.00E+00	0.00E+00

Category	Parameter Name	Appalachian Basin (Eastern Overthrust Area)			Permian Basin		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5
Processing venting	3_BDcomp_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	3_BDesd_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	3_BDfacpip_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	3_BDpig_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	3_BDscrub_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Exhibit A-12. Processing Parameters for Williston Basin and Arkoma Basin

Category	Parameter Name	Williston Basin			Arkoma Basin		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5
	3_NG_processed	3.92E+07	3.92E+07	3.92E+07	1.42E+07	1.42E+07	1.42E+07
	3_NGL_processed	1.62E+07	1.62E+07	1.62E+07	0.00E+00	0.00E+00	0.00E+00
	nat_mCO2	1.48E-02	1.48E-02	1.48E-02	3.56E-02	3.56E-02	3.56E-02
	nat_mCH4	3.80E-01	3.80E-01	3.80E-01	8.89E-01	8.89E-01	8.89E-01
Processing acid gas removal (AGR)	3_AGR_CO2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	3_AGR_CH4ef	3.73E-05	3.73E-05	3.73E-05	3.73E-05	3.73E-05	3.73E-05
Processing combustion	3_NG_subpartC	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Processing centrifugal compression	3_CENT_CH4	5.68E+01	5.68E+01	5.68E+01	0.00E+00	0.00E+00	0.00E+00
	3_CENT_energy	3.03E+07	3.03E+07	3.03E+07	0.00E+00	0.00E+00	0.00E+00
	Turbine_thermalefficiency	2.60E-01	2.60E-01	2.60E-01	2.60E-01	2.60E-01	2.60E-01
Processing reciprocating compression	3_RECIP_CH4	1.31E+02	1.31E+02	1.31E+02	3.78E+01	3.78E+01	3.78E+01
	3_RECIP_energy	2.92E+08	2.92E+08	2.92E+08	1.16E+08	1.16E+08	1.16E+08
	Recip_thermalefficiency	3.20E-01		4.30E-01	3.20E-01		4.30E-01
Processing flaring	3_FLARE_vol	5.97E-01	5.97E-01	5.97E-01	0.00E+00	0.00E+00	0.00E+00
Processing fugitives	3_EL_CH4	4.00E+01	4.00E+01	4.00E+01	0.00E+00	0.00E+00	0.00E+00
Processing venting	3_PD_AF	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	3_PD_EF	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	3_DEHYdes_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	3_DEHYlg_CH4	0.00E+00	0.00E+00	0.00E+00	6.27E+00	6.27E+00	6.27E+00
Processing venting	3_BDother_CH4	0.00E+00	0.00E+00	0.00E+00	1.14E+01	1.14E+01	1.14E+01
	3_BDcomp_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	3_BDesd_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	3_BDfacpip_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	3_BDpig_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	3_BDscrub_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

A.4 TRANSMISSION, STORAGE, AND PIPELINE PARAMETERS FOR ONE FUTURE SCENARIOS

Exhibit A-13. Transmission, Storage, and Pipeline Parameters for all ONE Future Scenarios

Category	Parameter Name	Parameter Description	All Scenarios			Units
			P2.5	Expected	P97.5	
Transmission						
	4_NG_trans	Annual natural gas volume through a transmission facility	3.08E+08	3.42E+08	3.78E+08	Mcf
	nat_mCO2	Mass fraction of CO_2 in natural gas	2.10E-02	2.10E-02	2.10E-02	dimensionless
	nat_mCH4	Mass fraction of CH_4 in natural gas	8.91E-01	8.91E-01	8.91E-01	dimensionless
Transmission centrifugal compression	4_CENT_CH4	Methane emissions from transmission centrifugal compressors	1.34E+02	1.63E+02	1.96E+02	tonnes
	4_CENT_energy	Operating centrifugal compressor horsepower at a transmission facility	9.78E+07	1.13E+08	1.30E+08	hp
	Turbine_thermalefficiency	Thermal efficiency of gas-fired turbines	2.00E-01	2.70E-01	3.50E-01	dimensionless
Transmission reciprocating compression	4_RECIP_CH4	Methane emissions from transmission reciprocating compressors	3.42E+02	4.15E+02	4.84E+02	tonnes
	4_RECIP_energy	Operating reciprocating compressor horsepower at a transmission facility	3.27E+07	3.99E+07	4.72E+07	hp
	Recip_thermalefficiency	Thermal efficiency of reciprocating engines	2.50E-01	3.45E-01	4.00E-01	dimensionless
Transmission flaring	4_FLARE_CH4_1	Methane emissions from flare stacks at a natural gas transmission facility	2.20E+00	2.70E+00	3.22E+00	tonnes
Transmission fugitives	4_TS_CH4_leak	Leaks from transmission storage	1.92E+01	3.32E+01	4.91E+01	tonnes
	4_LEAKS_CH4	Emission factor for high-bleed pneumatic devices	1.32E+01	1.56E+01	1.84E+01	kg/controller-yr
Transmission facility venting	4_PDhb_count	Number of high-bleed pneumatic devices	3.50E-01	6.88E-01	1.10E+00	count
	4_PDhb_EF	Emission factor for high-bleed pneumatic devices	2.92E+02	4.03E+02	5.27E+02	kg/controller-yr
	4_PDib_count	Number of intermittent-bleed pneumatic devices	7.53E+00	1.05E+01	1.43E+01	count
	4_PDib_EF	Emission factor for intermittent-bleed pneumatic devices	8.68E+01	1.08E+02	1.31E+02	kg/controller-yr

Category	Parameter Name	Parameter Description	All Scenarios			Units
			P2.5	Expected	P97.5	
Transmission facility venting	4_PDlb_count	Number of low-bleed pneumatic devices	8.76E-01	1.43E+00	2.16E+00	count
	4_PDlb_EF	Emission factor for low-bleed pneumatic devices	3.35E+01	4.51E+01	5.59E+01	kg/controller-yr
	4_BDother_CH4	Emission mass for other blowdowns	3.11E+01	3.66E+01	4.26E+01	tonnes CH_4/yr
	4_BDcomp_CH4	Emission mass for compressor blowdowns	2.73E+01	3.53E+01	4.45E+01	tonnes CH_4/yr
	4_BDesd_CH4	Emission mass for ESD blowdowns	6.93E+00	1.20E+01	1.89E+01	tonnes CH_4/yr
	4_BDfacpip_CH4	Emission mass for facility piping blowdowns	3.61E+00	1.94E+01	4.15E+01	tonnes CH_4/yr
	4_BDpig_CH4	Emission mass for pig blowdowns	2.18E-01	1.14E+00	2.57E+00	tonnes CH_4/yr
	4_BDpipe_CH4	Emission mass for pipeline venting blowdowns	0.00E+00	0.00E+00	0.00E+00	tonnes CH_4/yr
	4_BDscrub_CH4	Emission mass for scrubbers/strainers blowdowns	1.92E-01	4.23E-01	7.74E-01	tonnes CH_4/yr
	4_DEHY_EF	Emission factor for dehydrator vents	1.81E+00	1.81E+00	1.81E+00	kg CH_4/MMcf
	4_DEHY_thru	throughput volume for dehydrator vents	1.19E+06	1.19E+06	1.19E+06	MMcf
	4_NG_trans_DEHY_v	Annual production DEHY volume	2.82E+10	2.82E+10	2.82E+10	Mcf
Storage						
	5_storcap	Storage facility capacity	4.39E+07	5.67E+07	7.04E+07	Mcf
	nat_mCH4	Mass fraction of CH_4 in natural gas	8.91E-01	8.91E-01	8.91E-01	dimensionless
Storage centrifugal compression	5_CENT_CH4_vent	Methane emissions from storage centrifugal compressors	0.00E+00	1.65E+01	4.30E+01	tonnes
	5_CENT_energy	Operating centrifugal compressor horsepower at a storage facility	0.00E+00	4.88E+06	1.15E+07	HPh
	Turbine_thermalefficiency	Thermal efficiency of gas-fired turbines	2.00E-01	2.70E-01	3.50E-01	dimensionless
Storage reciprocating compression	5_RECIP_CH4vent	Methane emissions from storage reciprocating compressors	3.62E+01	4.41E+01	5.28E+01	tonnes
	5_RECIP_energy	Operating reciprocating compressor horsepower at a storage facility	6.37E+07	8.05E+07	9.84E+07	HPh
	Recip_thermalefficiency	Thermal efficiency of reciprocating engine used to drive reciprocating compressors	2.50E-01	3.45E-01	4.00E-01	dimensionless
Storage flaring	5_FLARE_CH4	Methane emissions from flare stacks at natural gas storage facilities	0.00E+00	0.00E+00	0.00E+00	tonnes

Category	Parameter Name	Parameter Description	All Scenarios			Units
			P2.5	Expected	P97.5	
Storage fugitives	5_ELstation_CH4	Methane leaks from storage stations	0.00E+00	0.00E+00	0.00E+00	tonnes
	5_ELwell_CH4	Methane leaks from storage wells	0.00E+00	0.00E+00	0.00E+00	tonnes
Storage venting	5_PDhb_hrs	Operating hours for high bleed devices	0.00E+00	1.16E+03	2.50E+03	hours
	5_PDhb_count	Number of high bleed devices	0.00E+00	2.21E+00	7.70E+00	count
	5_PDhb_EF	Emission factor for high bleed devices	0.00E+00	2.27E+00	4.93E+00	scf/hr-device
	5_PDib_hrs	Operating hours for intermittent bleed devices	5.33E+03	6.90E+03	8.34E+03	hours
	5_PDib_count	Number of intermittent bleed devices	1.79E+01	3.47E+01	5.47E+01	count
	5_PDib_EF	Emission factor for intermittent bleed devices	1.40E+00	1.81E+00	2.19E+00	scf/hr-device
	5_PDlb_hrs	Operating hours for low bleed devices	0.00E+00	1.25E+03	2.67E+03	hours
	5_PDlb_count	Number of low bleed devices	0.00E+00	1.83E+00	4.39E+00	count
	5_PDlb_EF	Emission factor for low bleed devices	0.00E+00	1.91E-01	4.07E-01	scf/hr-device
	5_DEHY_EF	Emission factor for dehydrator venting	0.00E+00	0.00E+00	0.00E+00	kg CH_4/MMcf dehydrated
	5_DEHY_AF	Activity factor for dehydrator venting	0.00E+00	0.00E+00	0.00E+00	MMcf dehydrated
	5_STATION_EF	Emission factor for storage station venting	8.40E+04	8.40E+04	8.40E+04	kg/station
	5_STATION_AF	Activity factor for storage station venting	1.00E+00	1.00E+00	1.00E+00	stations
	5_storcap_DEHY_v	Annualized storage capacity, volume, for dehydrators	9.24E+06	9.24E+06	9.24E+06	MMcf
Pipeline						
	6_overview_mi	Pipeline length	4.74E+03	7.56E+03	1.00E+04	miles
	6_transfer	Annual throughput of pipeline, volume	8.49E+08	1.39E+09	2.06E+09	Mcf
	nat_mCH4	Mass fraction of CH_4 in natural gas	8.91E-01	8.91E-01	8.91E-01	dimensionless
Transmission pipeline fugitives	6_PIPEFUG_EF	Fugitive emission factor for transmission pipelines	1.12E+03	1.12E+03	1.12E+03	kg CH_4/mile
Transmission pipeline venting	6_OTHER_CH4	Annual emissions from all other pipeline segments with a physical volume greater than or equal to 50 cubic feet	3.14E+02	1.43E+03	3.28E+03	tonnes
	6_ESD_CH4	Annual emissions from emergency shutdowns	1.52E-02	4.95E+01	1.71E+02	tonnes
	6_REPAIR_CH4	Annual emissions from equipment replacement or repair	1.84E+02	3.31E+02	5.09E+02	tonnes

Category	Parameter Name	Parameter Description	All Scenarios			Units
			P2.5	Expected	P97.5	
Transmission pipeline venting	6_CONSTRUCT_CH4	Annual emissions from new construction or modification of pipelines including commissioning and change of service	4.29E+02	9.66E+02	1.73E+03	tonnes
	6_CAUTION_CH4	Annual emissions from operational precaution during activities	2.53E+01	9.01E+01	1.82E+02	tonnes
	6_INTEGRITY_CH4	Annual emissions from pipeline integrity work	2.89E+01	5.47E+01	9.29E+01	tonnes
	6_MAINT_CH4	Annual emissions from traditional operations or pipeline maintenance	5.33E+02	1.46E+03	4.57E+03	tonnes

A.5 DISTRIBUTION PARAMETERS FOR ONE FUTURE SCENARIOS

Exhibit A-14. Distribution Parameters for ONE Future Average

Category	Parameter Name	Parameter Description	ONE Future Average			Units
			P2.5	Expected	P97.5	
	7_NG_deliv	Annual natural gas delivered by distribution systems, volume	1.73E+08	2.28E+08	2.87E+08	Mcf
	nat_mCH4	Mass fraction of CH_4 in natural gas	8.91E-01	8.91E-01	8.91E-01	dimensionless
Distribution combustion	7_COMB_CO2_5M	CO_2 emissions from distribution combustion in equipment with 5 MMBtu/hr capacity	8.27E+03	1.25E+04	1.69E+04	tonnes
	7_COMB_CO2_1M	CO_2 emissions from distribution combustion in equipment with 1 MMBtu/hr capacity	0.00E+00	0.00E+00	0.00E+00	tonnes
Distribution combustion compressor drives	7_COMB_CO2_cd	CO_2 emissions from distribution combustion by compressor drivers	0.00E+00	8.56E+03	2.24E+04	tonnes
Distribution fugitives	7_TD_CH4	Leaks from transmission-distribution transfer stations	1.28E+01	3.83E+01	6.89E+01	tonnes
	7_MAINS_CH4	Leaks from above grade metering-regulating stations that are not above grade T-D transfer stations	6.15E+03	9.06E+03	1.20E+04	tonnes
	7_BELOW_CH4	Leaks from below grade T-D station and distribution mains & services	8.36E-01	3.29E+00	6.28E+00	tonnes
	7_METERres_AF	Activity factor for leaks from residential customer meters	1.47E-04	1.80E-04	2.16E-04	meters/kg NG
	7_METERres_EF	Emission factor for leaks from residential customer meters	1.49E+00	1.49E+00	1.49E+00	kg CH_4/meter
Distribution fugitives	7_METERcom_AF	Activity factor for leaks from commercial and industrial customer meters	1.82E-05	2.05E-05	2.33E-05	meters/kg NG
	7_METERcom_EF	Emission factor for leaks from commercial and industrial customer meters	9.73E+00	9.73E+00	9.73E+00	g CH_4/meter
Distribution venting	7_PRV_AF	Activity factor for PRV releases	3.47E-06	4.32E-06	5.61E-06	miles/kg NG
	7_PRV_EF	Emission factor for PRV releases	9.63E-01	9.63E-01	9.63E-01	kg CH_4/mile
	7_PIPEBD_AF	Activity factor for pipeline blowdown releases	6.43E-06	8.01E-06	1.02E-05	miles/kg NG
	7_PIPEBD_EF	Emission factor for pipeline blowdown releases	1.96E+00	1.96E+00	1.96E+00	kg CH_4/mile
	7_DIG_AF	Activity factor for mishaps - dig ins releases	8.30E-06	8.30E-06	8.30E-06	miles/kg NG
	7_DIG_EF	Emission factor for mishaps - dig ins releases	3.06E+01	3.06E+01	3.06E+01	kg CH_4/mile

Exhibit A-15. Distribution Parameters for Massachusetts, New York, and Ohio

Category	Parameter Name	Massachusetts			New York			Ohio		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5	P2.5	Expected	P97.5
	7_NG_deliv	2.46E+07	6.79E+07	1.11E+08	1.53E+08	1.72E+08	1.85E+08	2.82E+08	2.82E+08	2.82E+08
	nat_mCH4	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01
Distribution combustion	7_COMB_CO2_5M	4.90E+03	1.37E+04	2.26E+04	2.98E+03	4.61E+03	7.00E+03	1.49E+04	1.49E+04	1.49E+04
	7_COMB_CO2_1M	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Distribution combustion compressor drives	7_COMB_CO2_cd	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.14E+04	9.41E+04	0.00E+00	0.00E+00	0.00E+00
Distribution fugitives	7_TD_CH4	0.00E+00	4.70E-02	9.40E-02	0.00E+00	3.54E+00	1.05E+01	2.28E+01	2.28E+01	2.28E+01
	7_MAINS_CH4	1.60E+03	8.26E+03	1.49E+04	7.56E+03	9.15E+03	1.11E+04	2.52E+04	2.52E+04	2.52E+04
	7_BELOW_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.83E-01	1.31E+00	0.00E+00	0.00E+00	0.00E+00
	7_METERres_AF	1.49E-04	1.74E-04	1.99E-04	6.27E-05	9.27E-05	1.37E-04	1.78E-04	1.78E-04	1.78E-04
	7_METERres_EF	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00
	7_METERcom_AF	2.94E-05	3.58E-05	4.21E-05	1.34E-05	1.61E-05	1.86E-05	1.66E-05	1.66E-05	1.66E-05
	7_METERcom_EF	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00
Distribution venting	7_PRV_AF	3.52E-06	6.01E-06	8.50E-06	1.21E-06	2.27E-06	3.11E-06	3.79E-06	3.79E-06	3.79E-06
	7_PRV_EF	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01
	7_PIPEBD_AF	6.91E-06	1.04E-05	1.38E-05	2.62E-06	4.31E-06	5.80E-06	6.98E-06	6.98E-06	6.98E-06
	7_PIPEBD_EF	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00
	7_DIG_AF	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06
	7_DIG_EF	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01

Exhibit A-16. Distribution Parameters for Florida, Missouri, and Arkansas

Category	Parameter Name	Florida			Missouri			Arkansas		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5	P2.5	Expected	P97.5
	7_NG_deliv	1.23E+07	1.23E+07	1.23E+07	2.81E+06	2.81E+06	2.81E+06	6.57E+06	6.57E+06	6.57E+06
	nat_mCH4	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01
Distribution combustion	7_COMB_CO2_5M	1.23E+03	1.23E+03	1.23E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	7_COMB_CO2_1M	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Distribution combustion compressor drives	7_COMB_CO2_cd	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Distribution fugitives	7_TD_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	7_MAINS_CH4	6.69E+02	6.69E+02	6.69E+02	2.06E+02	2.06E+02	2.06E+02	3.58E+02	3.58E+02	3.58E+02
	7_BELOW_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	7_METERres_AF	4.44E-04	4.44E-04	4.44E-04	3.26E-04	3.26E-04	3.26E-04	3.47E-04	3.47E-04	3.47E-04
	7_METERres_EF	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00
	7_METERcom_AF	3.46E-05	3.46E-05	3.46E-05	7.06E-05	7.06E-05	7.06E-05	4.60E-05	4.60E-05	4.60E-05
	7_METERcom_EF	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00
Distribution venting	7_PRV_AF	1.59E-05	1.59E-05	1.59E-05	2.12E-05	2.12E-05	2.12E-05	1.37E-05	1.37E-05	1.37E-05
	7_PRV_EF	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01
	7_PIPEBD_AF	2.30E-05	2.30E-05	2.30E-05	3.39E-05	3.39E-05	3.39E-05	1.68E-05	1.68E-05	1.68E-05
	7_PIPEBD_EF	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00
	7_DIG_AF	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06
	7_DIG_EF	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01

Exhibit A-17. Distribution Parameters for Maryland, Tennessee, and Utah

Category	Parameter Name	Maryland			Tennessee			Utah		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5	P2.5	Expected	P97.5
	7_NG_deliv	1.08E+06	1.08E+06	1.08E+06	1.36E+07	1.36E+07	1.36E+07	1.80E+08	1.80E+08	1.80E+08
	nat_mCH4	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01
Distribution combustion	7_COMB_CO2_5M	0.00E+00	0.00E+00	0.00E+00	1.23E+03	1.23E+03	1.23E+03	8.58E+03	8.58E+03	8.58E+03
	7_COMB_CO2_1M	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Distribution combustion compressor drives	7_COMB_CO2_cd	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Distribution fugitives	7_TD_CH4	0.00E+00	0.00E+00	0.00E+00	6.10E-01	6.10E-01	6.10E-01	2.30E-01	2.30E-01	2.30E-01
	7_MAINS_CH4	2.10E+01	2.10E+01	2.10E+01	3.14E+02	3.14E+02	3.14E+02	3.56E+03	3.56E+03	3.56E+03
	7_BELOW_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	7_METERres_AF	1.18E-04	1.18E-04	1.18E-04	2.25E-04	2.25E-04	2.25E-04	2.91E-04	2.91E-04	2.91E-04
	7_METERres_EF	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00
	7_METERcom_AF	2.80E-05	2.80E-05	2.80E-05	3.37E-05	3.37E-05	3.37E-05	2.16E-05	2.16E-05	2.16E-05
	7_METERcom_EF	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00
Distribution venting	7_PRV_AF	5.24E-06	5.24E-06	5.24E-06	6.51E-06	6.51E-06	6.51E-06	5.47E-06	5.47E-06	5.47E-06
	7_PRV_EF	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01
	7_PIPEBD_AF	8.68E-06	8.68E-06	8.68E-06	1.27E-05	1.27E-05	1.27E-05	9.34E-06	9.34E-06	9.34E-06
	7_PIPEBD_EF	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00
	7_DIG_AF	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06
	7_DIG_EF	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01

Exhibit A-18. Distribution Parameters for Colorado, Illinois, and New Jersey

Category	Parameter Name	Colorado			Illinois			New Jersey		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5	P2.5	Expected	P97.5
	7_NG_deliv	2.33E+06	2.33E+06	2.33E+06	4.39E+08	4.39E+08	4.39E+08	4.84E+07	4.84E+07	4.84E+07
	nat_mCH4	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01
Distribution combustion	7_COMB_CO2_5M	0.00E+00	0.00E+00	0.00E+00	2.89E+04	2.89E+04	2.89E+04	3.33E+03	3.33E+03	3.33E+03
	7_COMB_CO2_1M	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Distribution combustion compressor drives	7_COMB_CO2_cd	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Distribution fugitives	7_TD_CH4	0.00E+00	0.00E+00	0.00E+00	1.56E+02	1.56E+02	1.56E+02	5.50E-01	5.50E-01	5.50E-01
	7_MAINS_CH4	2.38E+02	2.38E+02	2.38E+02	4.84E+03	4.84E+03	4.84E+03	3.02E+03	3.02E+03	3.02E+03
	7_BELOW_CH4	0.00E+00	0.00E+00	0.00E+00	1.45E+01	1.45E+01	1.45E+01	0.00E+00	0.00E+00	0.00E+00
	7_METERres_AF	4.94E-04	4.94E-04	4.94E-04	2.09E-04	2.09E-04	2.09E-04	1.16E-04	1.16E-04	1.16E-04
	7_METERres_EF	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00
	7_METERcom_AF	2.01E-05	2.01E-05	2.01E-05	2.09E-05	2.09E-05	2.09E-05	2.57E-05	2.57E-05	2.57E-05
	7_METERcom_EF	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00
Distribution venting	7_PRV_AF	2.97E-05	2.97E-05	2.97E-05	4.08E-06	4.08E-06	4.08E-06	3.59E-06	3.59E-06	3.59E-06
	7_PRV_EF	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01
	7_PIPEBD_AF	4.70E-05	4.70E-05	4.70E-05	7.79E-06	7.79E-06	7.79E-06	6.09E-06	6.09E-06	6.09E-06
	7_PIPEBD_EF	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00
	7_DIG_AF	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06
	7_DIG_EF	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01

Exhibit A-19. Distribution Parameters for Oklahoma, Maine, and Rhode Island

Category	Parameter Name	Oklahoma			Maine			Rhode Island		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5	P2.5	Expected	P97.5
	7_NG_deliv	1.33E+06	1.33E+06	1.33E+06	3.26E+06	3.26E+06	3.26E+06	3.84E+07	3.84E+07	3.84E+07
	nat_mCH4	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01
Distribution combustion	7_COMB_CO2_5M	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.30E+03	6.30E+03	6.30E+03
	7_COMB_CO2_1M	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Distribution combustion compressor drives	7_COMB_CO2_cd	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Distribution fugitives	7_TD_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	7_MAINS_CH4	1.19E+02	1.19E+02	1.19E+02	3.53E+01	3.53E+01	3.53E+01	5.93E+03	5.93E+03	5.93E+03
	7_BELOW_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	7_METERres_AF	4.89E-04	4.89E-04	4.89E-04	4.71E-05	4.71E-05	4.71E-05	1.63E-04	1.63E-04	1.63E-04
	7_METERres_EF	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00
	7_METERcom_AF	7.35E-05	7.35E-05	7.35E-05	1.26E-05	1.26E-05	1.26E-05	3.49E-05	3.49E-05	3.49E-05
	7_METERcom_EF	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00
Distribution venting	7_PRV_AF	3.10E-05	3.10E-05	3.10E-05	3.02E-06	3.02E-06	3.02E-06	4.51E-06	4.51E-06	4.51E-06
	7_PRV_EF	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01
	7_PIPEBD_AF	3.56E-05	3.56E-05	3.56E-05	4.07E-06	4.07E-06	4.07E-06	8.02E-06	8.02E-06	8.02E-06
	7_PIPEBD_EF	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00
	7_DIG_AF	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06
	7_DIG_EF	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01

Exhibit A-20. Distribution Parameters for Virginia, Georgia, and West Virginia

Category	Parameter Name	Virginia			Georgia			West Virginia		
		P2.5	Expected	P97.5	P2.5	Expected	P97.5	P2.5	Expected	P97.5
	7_NG_deliv	1.01E+08	1.01E+08	1.01E+08	1.97E+08	1.97E+08	1.97E+08	3.44E+07	3.44E+07	3.44E+07
	nat_mCH4	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01	8.91E-01
Distribution combustion	7_COMB_CO2_5M	3.33E+03	3.33E+03	3.33E+03	5.95E+03	5.95E+03	5.95E+03	1.05E+03	1.05E+03	1.05E+03
	7_COMB_CO2_1M	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Distribution combustion compressor drives	7_COMB_CO2_cd	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Distribution fugitives	7_TD_CH4	5.60E-01	5.60E-01	5.60E-01	3.10E+00	3.10E+00	3.10E+00	2.08E+01	2.08E+01	2.08E+01
	7_MAINS_CH4	2.03E+03	2.03E+03	2.03E+03	5.94E+03	5.94E+03	5.94E+03	2.85E+03	2.85E+03	2.85E+03
	7_BELOW_CH4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	7_METERres_AF	5.65E-05	5.65E-05	5.65E-05	3.21E-04	3.21E-04	3.21E-04	1.28E-04	1.28E-04	1.28E-04
	7_METERres_EF	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00	1.49E+00
	7_METERcom_AF	1.31E-05	1.31E-05	1.31E-05	2.55E-05	2.55E-05	2.55E-05	1.49E-05	1.49E-05	1.49E-05
	7_METERcom_EF	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00	9.73E+00
Distribution venting	7_PRV_AF	2.90E-06	2.90E-06	2.90E-06	8.85E-06	8.85E-06	8.85E-06	5.05E-06	5.05E-06	5.05E-06
	7_PRV_EF	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01	9.63E-01
	7_PIPEBD_AF	5.88E-06	5.88E-06	5.88E-06	1.78E-05	1.78E-05	1.78E-05	7.52E-06	7.52E-06	7.52E-06
	7_PIPEBD_EF	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00	1.96E+00
	7_DIG_AF	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06	8.30E-06
	7_DIG_EF	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01	3.06E+01

APPENDIX B: NATURAL GAS COMPOSITION AND VENTING AND FLARING GHG EMISSIONS

TABLE OF CONTENTS

LIST OF EXHIBITS

ACRONYMS AND ABBREVIATIONS

CH_4	Methane
CO_2	Carbon dioxide
CO	Carbon monoxide
GHG	Greenhouse gas
GWP	Global Warming Potential
LA	Louisiana
N_2O	Nitrous Oxide
TX	Texas

B-1. NATURAL GAS COMPOSITION AND VENTING AND FLARING GHG EMISSIONS

Greenhouse gas (GHG) emissions from a scenario depends on the composition of the natural gas pre-processing and post-processing. **Exhibit B-1** and **Exhibit B-2** show the post-processing and pre-processing mass fractions of different components for ONE Future scenarios, respectively. **Exhibit B-3** shows the carbon content and higher heating value for all the relevant natural gas components.

Exhibit B-1. Pre-Processing Natural Gas Composition for Source-Based Scenarios and ONE Future Average

Component	Gulf Coast Basin (LA TX)	Appalachian Basin (Eastern Overthrust Area)	Permian Basin	Williston Basin	Arkoma Basin	ONE Future Average
Hydrogen sulfide	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Carbon dioxide	5.68E-03	9.22E-04	2.24E-02	5.68E-03	6.37E-04	1.69E-02
Methane	8.35E-01	8.36E-01	6.88E-01	8.35E-01	9.20E-01	8.08E-01
Benzene	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ethylbenzene	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Toluene	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Xylene	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nitrogen	1.40E-02	3.02E-02	7.23E-02	1.40E-02	3.35E-02	1.52E-02
Ethane	7.22E-02	8.04E-02	1.17E-01	7.22E-02	3.13E-02	5.76E-02
2,2,4-Trimethylpentane	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cyclohexane	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cyclopentane	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Iso-butane	1.15E-02	5.23E-03	1.02E-02	1.15E-02	6.48E-04	8.19E-03
Iso-pentane	5.87E-03	2.88E-03	6.75E-03	5.87E-03	6.55E-04	5.40E-03
Methyl cyclohexane	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
n-butane	1.17E-02	9.57E-03	1.97E-02	1.17E-02	1.38E-03	9.56E-03
n-hexane	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
n-pentane	4.68E-03	3.27E-03	5.88E-03	4.68E-03	5.80E-04	4.09E-03
Propane	3.32E-02	2.99E-02	5.52E-02	3.32E-02	6.40E-03	3.04E-02
Heptane	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hexane	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Undefined volatile organic compounds	7.87E-03	9.90E-03	7.87E-03	7.87E-03	8.51E-03	7.11E-03

Exhibit B-2. Post-Processing Natural Gas Composition for all ONE Future Scenarios

Component	Post-Processing Composition
Hydrogen sulfide	0.00E+00
Carbon dioxide	1.80E-02
Methane	8.62E-01
Benzene	1.80E-04
Ethylbenzene	1.20E-05
Toluene	7.00E-05
Xylene	1.90E-05
Nitrogen	3.30E-02
Ethane	6.40E-02
2,2,4-Trimethylpentane	1.10E-04
Cyclohexane	0.00E+00
Cyclopentane	0.00E+00
Iso-butane	0.00E+00
Iso-pentane	0.00E+00
Methyl cyclohexane	0.00E+00
n-butane	5.50E-03
n-hexane	3.20E-04
n-pentane	2.20E-03
Propane	1.50E-02
Heptane	0.00E+00
Hexane	4.30E-05
Undefined volatile organic compounds	0.00E+00

Exhibit B-3. Carbon Content and Higher Heating Values of all Natural Gas Components

Component	Carbon Content	Higher Heating Value
Hydrogen sulfide	N/A	1.65E+04
Carbon dioxide	N/A	0.00E+00
Methane	N/A	5.27E+04
Benzene	9.23E-01	4.01E+04
Ethylbenzene	9.05E-01	4.01E+04
Toluene	9.12E-01	4.01E+04
Xylene	9.05E-01	4.01E+04
Nitrogen	N/A	0.00E+00
Ethane	7.99E-01	4.92E+04
2,2,4-Trimethylpentane	8.41E-01	4.01E+04
Cyclohexane	8.56E-01	4.46E+04
Cyclopentane	8.56E-01	4.49E+04
Iso-butane	8.27E-01	4.68E+04
Iso-pentane	8.32E-01	4.64E+04
Methyl cyclohexane	8.56E-01	4.11E+04
n-butane	8.27E-01	4.70E+04
n-hexane	8.36E-01	4.62E+04
n-pentane	8.32E-01	4.65E+04
Propane	8.17E-01	4.77E+04
Heptane	8.39E-01	4.22E+04
Hexane	8.36E-01	4.61E+04
Undefined volatile organic compounds	7.55E-01	4.64E+04

The GHG emissions from gas composition are calculated as follows:

Carbon Dioxide:

$$\begin{aligned} &Mass\ of\ CO_2\ emitted\ per\ unit\ mass\ of\ natural\ gas\ flared\ and\ vented \\ &= Flaring\ Rate \times Flaring\ Efficiency \\ &\times \left(\left(Mass\ Fraction\ of\ CH_4 \times \frac{44}{16}\right)\right. \\ &+ \left(\sum (Carbon\ Content \times Mass\ Fraction)_{for\ all\ other\ components} \times \frac{44}{12}\right)\Bigg) \\ &+ Mass\ Fraction\ of\ CO_2 - \left(\frac{44}{28} \times CO\ Emission\ Factor\right) \end{aligned}$$

Methane:

$$\begin{aligned} &Mass\ of\ CH_4\ emitted\ per\ mass\ of\ natural\ gas\ flared\ and\ vented \\ &= Flaring\ Rate \times (1 - Flaring\ Efficiency) \times Mass\ Fraction\ of\ CH_4 \\ &+ (1 - Flaring\ Rate) \times Mass\ Fraction\ of\ CH_4 \end{aligned}$$

Nitrous Oxide:

$$\begin{aligned} &Mass\ of\ N_2O\ emitted\ per\ mass\ of\ natural\ gas\ flared\ and\ vented \\ &= Flaring\ Rate \times Flaring\ Efficiency \times N_2O\ Emission\ Factor \\ &\times Higher\ Heating\ Value\ of\ Natural\ Gas \end{aligned}$$

Where, the flaring efficiency is 98%, CO emission factor is 1.68E-07, N_2O emission factor is 9.05E-11, and the higher heating value (HHV) of a natural gas mixture is the total of mass fraction of each gas component multiplied by their respective higher heating values. **Exhibit B-4** and **Exhibit B-5** show the flared and vented GHG emissions for all the pre-processing and post-processing gas compositions shown in **Exhibit B-1** and **Exhibit B-2**, respectively**.** These results are on a per mass of natural gas basis, hence a flaring rate of 1 is used.

Exhibit B-4. GHG Emissions from Flared Natural Gas

Component	Pre-Processing Flared Emissions						Post-Processing Flared Emissions for All Scenarios
	Gulf Coast Basin (LA TX)	Appalachian Basin (Eastern Overthrust Area)	Permian Basin	Williston Basin	Arkoma Basin	ONE Future Average	
Carbon dioxide	2.67E+00	2.65E+00	2.51E+00	2.67E+00	2.61E+00	2.54E+00	2.58E+00
Methane	1.67E-02	1.67E-02	1.38E-02	1.67E-02	1.84E-02	1.62E-02	1.72E-02
Nitrous oxide	4.53E-06	4.51E-06	4.17E-06	4.53E-06	4.51E-06	4.30E-06	4.40E-06

Exhibit B-5. GHG Emissions from Vented Natural Gas

Component	Pre-Processing Vented Emissions						Post-Processing Vented Emissions for All Scenarios
	Gulf Coast Basin (LA TX)	Appalachian Basin (Eastern Overthrust Area)	Permian Basin	Williston Basin	Arkoma Basin	ONE Future Average	
Carbon dioxide	5.68E-03	9.22E-04	2.24E-02	5.68E-03	6.37E-04	1.69E-02	1.80E-02
Methane	8.35E-01	8.36E-01	6.88E-01	8.35E-01	9.20E-01	8.08E-01	8.62E-01
Nitrous oxide	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

This page intentionally left blank.

APPENDIX C: K-NEAREST NEIGHBOR ANALYSIS

TABLE OF CONTENTS

LIST OF EXHIBITS

ACRONYMS AND ABBREVIATIONS

kNN	Kernel-nearest neighbor

C-1. K-NEAREST NEIGHBOR BACKGROUND

Kernel-nearest neighbor (kNN) algorithm predicts unknown values using the most similar known values. It can be used for both classification and regression. The algorithm first calculates the distance between the unknown point and all the known points then selects the *k* closest points (based on distance). The average of these data points gives the final prediction for the unknown point. This work uses the Euclidean distances between the data points to identify the nearest neighbors and the elbow method to select the optimum *k* value. **Exhibit C-1** shows the formula to calculate the Euclidean distance between two points *x* and *y*.

Exhibit C- 1: Euclidean Distance Formula

$$Distance = \sqrt{\sum_{i=1}^{k}(x_i - y_i)^2}$$

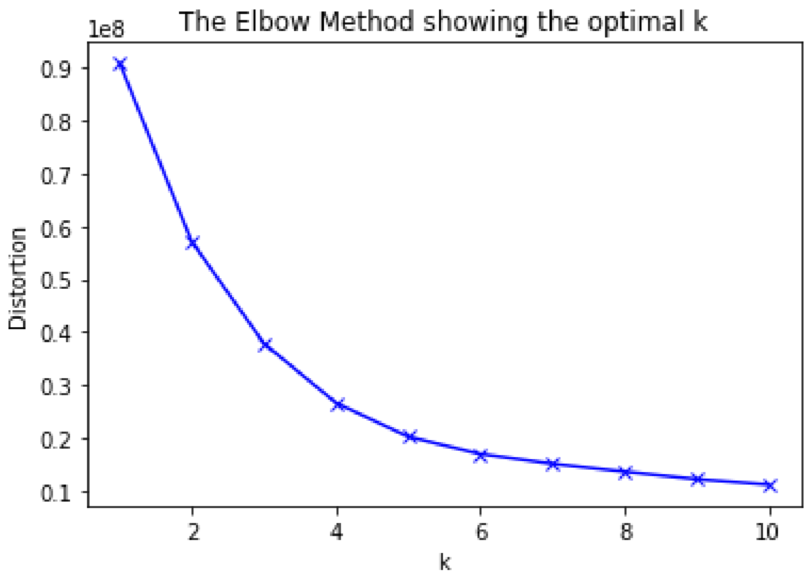
The elbow method plots the distortions using different values of *k*; the elbow bend on the resultant line chart represents the optimum value of *k*.

C-2. TRANSMISSION THROUGHPUT PREDICTIONS

This work consists of a dataset with 243 transmission facilities, 101 of which have a value for the throughput of natural gas whereas the remaining 142 facilities do not. However, the energy parameters for centrifugal and reciprocating compressors are known for all data points. These parameters were used to calculate the distances to estimate the throughput values for the remaining 142 facilities. This work used Python to perform this analysis.

The raw data was split into two dataframes, one that has all the facilities for which the throughput values are known along with the centrifugal and reciprocating compressors' energy parameters (training dataset) and the other that has the remaining facilities that do not provide the throughput values but only the centrifugal and reciprocating compressors' energy parameters (learning dataset). The *sklearn* Python package was used to perform the analysis. It performs the distance calculations automatically. It was used in a loop to calculate the nearest distances for all the unknown points, with different values of *k* ranging from 1 to 10. The average Euclidean distance for each cluster (distortion) was plotted against the respective *k* value. Based on **Exhibit C- 2**, which shows the resulting elbow curve, 4 was selected as the optimum *k* value.

Exhibit C- 2: Elbow Curve for k Value Ranging from 1 to 10



The same package was then used to perform the complete analysis using *k = 4*, which predicted the throughput values for the remaining 142 transmission facilities.

This page intentionally left blank.

APPENDIX D: SUPPORTING INFORMATION FOR MAC ANALYSIS

TABLE OF CONTENTS

LIST OF EXHIBITS

ACRONYMS AND ABBREVIATIONS

AGA	American Gas Association
Bcf	Billion cubic feet
CH_4	Methane
EPA	Environmental Protection Agency
ESD	Emergency shutdown
ICF	Inner City Fund
kg	Kilogram
LA	Louisiana
LDAR	Leak detection and repair
MAC	Marginal abatement cost
Mcf	Thousand cubic feet
NETL	National Energy Technology Laboratory
ONE Future	Our Nation's Energy Future
STAR	Natural Gas STAR Program
TX	Texas

D-1. INTRODUCTION

This appendix defines the parameters used by the National Energy Technology Laboratory's (NETL) Marginal Abatement Cost (MAC) analysis of the Our Nation's Energy Future (ONE Future) natural gas infrastructure.

D-2. REPLACING HIGH/INTERMITTENT BLEED PNEUMATICS WITH AIR SYSTEMS

ONE Future considered capital and operating cost expenditures of $59,918 and $17,770, respectively, to replace high or intermittent bleed pneumatics with air-based compressors based on specific information from the Environmental Protection Agency's (EPA) Natural Gas STAR Program ("STAR") (EPA 2018). As per STAR documentation, capital expenditures represent the cost per facility containing two compressors (one standby), two volume tanks, and one dryer. However, EPA's documentation does not explicitly state a replacement ratio of pneumatic devices with air compressors. Thus, the team's analysis assumed that an air compressor could replace three pneumatic devices (Zavala-Araiza et al. 2017), and a facility contains three pneumatic devices. The air compressors were assumed to have a service life of five years based on EPA's documentation. The operating costs quoted in EPA's documentation includes the cost of powering the air compressors over 1 year ($13,140), the replacement cost of the membrane in an air dryer ($2,894), and the servicing cost of a compressor ($1,736). This analysis considered annual operational costs only associated with instrument maintenance in a facility ($1,736 + $2,894 = $4,630).

D-3. REPLACING HIGH BLEED DEVICES WITH LOW BLEED DEVICES

ONE Future considered capital and operating cost expenditures of $3,000 and $0, respectively, to replace high bleed devices with low bleed ones based on STAR recommendations and updates received from industry partners (EPA 2018). The replaced low bleed pneumatic devices were assumed to have a service life of five years.

D-4. REDESIGN BLOWDOWN SYSTEMS AND ALTER ESD PRACTICES

The capital cost ($15,000/compressor station) to install emergency shutdown (ESD) valves was adopted from the ONE Future MAC report (EPA 2018), (ICF 2016). Capital expenditures include the cost of replacing 10 ESD valves in a compressor station with a total of 8 compressors. A service life of five years was assumed for ESD valves. This mitigation measure does not require an annual operational cost.

D-5. PIPELINE MODIFICATIONS

EPA recommends installing an inline or a portable compressor on the smallest section of the pipeline as a strategy to relieve pressure from pipelines. ONE Future's MAC analysis (ICF 2016) considered an operational cost of $31,000 as a leasing cost for a compressor from STAR. EPA does not explicitly state the number of compressors spanning the pipeline, but provided an example considering a compressor per 10-mile stretch. Since installing compressors every 10 miles was deemed expensive ($30,155/year/compressor), one compressor every 20 miles was considered in this analysis, as advised by ICF International (ICF 2016).

D-6. Wet Seal Degassing Recovery System for Centrifugal Compressors

The capital cost for incorporating wet seal degassing systems in centrifugal compressors was obtained from STAR documentation (EPA 2018). The cost of wet seal systems shown in Section 7 of the report represents the cost of four compressors at a station, including the cost of seal oil gas demisters.

D-7. Replacement of Reciprocating Compressor Rod Packing Systems

Capital expenditures for this mitigation strategy were adopted from ONE Future's MAC analysis (ICF 2016).

D-8. Replacement of Cast Iron Distribution Pipeline

American Gas Association (AGA) estimates a replacement cost of $3.3 million per mile of cast iron pipe (AGA 2013). The average life of the replaced pipeline was assumed to be 150 years.

D-9. LDAR: Well Pads, Gas Processing, and Transmission Stages

ONE Future's MAC report (ICF 2016) provided the annual cost of leak detection and repair (LDAR) activities in well pads, gas processing, and transmission stages. The annual LDAR estimates include the cost of annual site inspections, initial setup, and labor costs for repairs. This analysis did not consider LDAR activities in well pads due to lack of well count data.

D-10. MAC Parameters and Results for ONE Future

Exhibit D-1 and **Exhibit D-2** show the all the parameters used to perform the MAC analysis for ONE Future assets. The capital and operating costs shown in **Exhibit D-1** represent the original costs listed in the sources as described in **Section D-2** through **Section D-9**.

Exhibit D-1. Parameters without Escalation for all Methane Mitigation Strategies

Emission Reduction Opportunities for This Analysis	Mapping with ONE Future's MAC Emissions Mitigation Strategies	Unit	Capital Cost, 2006$/ unit*	Opera-ting Cost, 2006$ /unit-year*	Service Life, Years*	% Reduc-tion (Emissions)*
Production						
High bleed pneumatics	Replace with instrument air systems - high bleed	High bleed device	59,918	4,630	5	100%
High bleed pneumatics	Replace high bleed devices with low bleed devices	High bleed device	3,000	0	5	78%
Intermittent bleed pneumatics	Replace with instrument air systems - intermittent bleed	Intermittent bleed device	59,918	4,630	5	100%
Gathering and Boosting						
High bleed pneumatics	Replace with instrument air systems - high bleed	High bleed device	59,918	4,630	5	100%
High bleed pneumatics	Replace high bleed devices with low bleed devices	High bleed device	3,000	0	5	78%
Intermittent bleed pneumatics	Replace with instrument air systems - intermittent bleed	Intermittent bleed device	59,918	4,630	5	100%
Transmission Compression						
Centrifugal compressors	Wet seal degassing recovery system for centrifugal compressors	Centrifugal compressor	70,000	0	5	95%
Reciprocating compressors	Replacement of reciprocating compressor rod packing systems	Reciprocating compressor	6,600	0	10	31%
Emergency shutdowns	Redesign blowdown systems and alter ESD practices	ESD Valve	15,000	0	5	95%
Pipeline modifications	Pipeline pump-down before maintenance	Compressor	0	30,155	N/A	80%
Transmission Storage						
High bleed pneumatics	Replace with instrument air systems - high bleed	High bleed device	59,918	4630	5	100%
High bleed pneumatics	Replace high bleed devices with low bleed devices	High bleed device	3,000	0	5	78%
Intermittent bleed pneumatics	Replace with instrument air systems - intermittent	Intermittent bleed device	59,918	4630	5	100%
Distribution						
Distribution mains – cast iron	Replacement of cast iron distribution pipelines	Pipeline mile	3,300,000 **	0	150	98%
LDAR (Leak Detection and Repair)						
Gas processing fugitives	Processing LDAR	Processing facility	12,501	0	1	40%
Transmission fugitives	Transmission LDAR	Transmission compression facility	10,001	0	1	40%

Exhibit D-2. Device Count and Corresponding Emission Factors for ONE Future Assets

Emission Mitigation Strategies	Emission Factor per Device or Station, kg/unit/year*	Device Count or Pipeline Length, number or miles**
Production		
Gulf Coast (LA TX)		
Replace with Instrument Air Systems – High Bleed Devices	4,371	2
Replace High Bleed Devices with Low Bleed Devices	4,371	2
Replace with Instrument Air Systems – Intermittent Bleed devices	1,535	2,957
Appalachian Basin (Eastern Overthrust Area)		
Replace with Instrument Air Systems – High Bleed Devices	4,371	0
Replace High Bleed Devices with Low Bleed Devices	4,371	0
Replace with Instrument Air Systems – Intermittent Bleed devices	1,535	12,758
Permian Basin		
Replace with Instrument Air Systems – High Bleed Devices	4,371	24
Replace High Bleed Devices with Low Bleed Devices	4,371	24
Replace with Instrument Air Systems – Intermittent Bleed devices	1,535	3,497
Williston Basin		
Replace with Instrument Air Systems – High Bleed Devices	4,371	400
Replace High Bleed Devices with Low Bleed Devices	4,371	400
Replace with Instrument Air Systems – Intermittent Bleed devices	1,535	1
Arkoma Basin		
Replace with Instrument Air Systems – High Bleed Devices	4,371	0
Replace High Bleed Devices with Low Bleed Devices	4,371	0
Replace with Instrument Air Systems – Intermittent Bleed devices	1,535	9,942
Gathering and Boosting		
Gulf Coast (LA TX)		
Replace with Instrument Air Systems – High Bleed Devices	4,371	4
Replace High Bleed Devices with Low Bleed Devices	4,371	4
Replace with Instrument Air Systems – Intermittent Bleed devices	1,535	837
Appalachian Basin (Eastern Overthrust Area)		
Replace with Instrument Air Systems – High Bleed Devices	4,371	63
Replace High Bleed Devices with Low Bleed Devices	4,371	63
Replace with Instrument Air Systems – Intermittent Bleed devices	1,535	1,019
Permian Basin		
Replace with Instrument Air Systems – High Bleed Devices	4,371	7
Replace High Bleed Devices with Low Bleed Devices	4,371	7
Replace with Instrument Air Systems – Intermittent Bleed devices	1,535	66

Emission Mitigation Strategies	Emission Factor per Device or Station, kg/unit/year*	Device Count or Pipeline Length, number or miles**
Williston Basin		
Replace with Instrument Air Systems – High Bleed Devices	4,371	0
Replace High Bleed Devices with Low Bleed Devices	4,371	0
Replace with Instrument Air Systems – Intermittent Bleed devices	1,535	0
Arkoma Basin		
Replace with Instrument Air Systems – High Bleed Devices	4,371	0
Replace High Bleed Devices with Low Bleed Devices	4,371	0
Replace with Instrument Air Systems – Intermittent Bleed devices	1,535	13
Transmission		
Wet Seal Degassing Recovery System for Centrifugal Compressors	17,714	242
Replacement of Reciprocating Compressor Rod Packing Systems	30,739	1,029
Redesign Blowdown Systems and Alter ESD Practices	70,815	243
Pipeline Pump-Down Before Maintenance	1,256	1,618
Storage		
Replace with Instrument Air Systems – High Bleed Devices	2,359	67
Replace High Bleed Devices with Low Bleed Devices	2,359	67
Replace with Instrument Air Systems – Intermittent Bleed devices	415	962
Distribution		
Replacement of Cast Iron Distribution Pipelines, Massachusetts	1157	1,931
Replacement of Cast Iron Distribution Pipelines, New York	1157	2,022
Replacement of Cast Iron Distribution Pipelines, Ohio	1157	31
Replacement of Cast Iron Distribution Pipelines, Tennessee	1157	0.50
Replacement of Cast Iron Distribution Pipelines, Illinois	1157	44
Replacement of Cast Iron Distribution Pipelines, New Jersey	1157	486.60
Replacement of Cast Iron Distribution Pipelines, Rode Island	1157	730
Replacement of Cast Iron Distribution Pipelines, Virginia	1157	9.60
LDAR		
Processing LDAR	13,600	10
Transmission LDAR	22,224	243

* From *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (EPA 2017).

** From data provided by ONE Future.

The costs were escalated to represent 2017 dollars using factors from the Chemical Engineering Plant Cost Index (Chemical Engineering n.d.), shown in **Exhibit D-3.** These factors were estimated based on the appropriate equipment index in 2006 and 2017.

Exhibit D-3. Cost Escalation Factors

Technology Type	Index Used	2006 Index	2017 Index	Escalation Factor
Capital Costs				
Replace with Instrument Air Systems - High Bleed	PUMPS COMPR	785.73	983.50	1.25
Replace high bleed devices with low bleed devices, per device	PUMPS COMPR	785.73	983.50	1.25
Replace with Instrument Air Systems - Intermittent	PUMPS COMPR	785.73	983.50	1.25
Wet Seal Degassing Recovery System for Centrifugal Compressors	EQUIP INDEX	588.04	684.44	1.16
Replacement of Reciprocating Compressor Rod Packing Systems	PUMPS COMPR	785.73	983.50	1.25
Redesign Blowdown Systems and Alter ESD Practices	PIPE VLVS/FTGS	708.01	878.11	1.24
Pipeline Pump-Down Before Maintenance				
Replacement of Cast Iron Distribution Pipelines, Distribution, MA	PIPE VLVS/FTGS	708.01	878.11	1.24
Replacement of Cast Iron Distribution Pipelines, Distribution, NY	PIPE VLVS/FTGS	708.01	878.11	1.24
Replacement of Cast Iron Distribution Pipelines, Distribution, OH	PIPE VLVS/FTGS	708.01	878.11	1.24
Replacement of Cast Iron Distribution Pipelines, Distribution, TN	PIPE VLVS/FTGS	708.01	878.11	1.24
Replacement of Cast Iron Distribution Pipelines, Distribution, IL	PIPE VLVS/FTGS	708.01	878.11	1.24
Replacement of Cast Iron Distribution Pipelines, Distribution, NJ	PIPE VLVS/FTGS	708.01	878.11	1.24
Replacement of Cast Iron Distribution Pipelines, Distribution, RI	PIPE VLVS/FTGS	708.01	878.11	1.24
Replacement of Cast Iron Distribution Pipelines, Distribution, VA	PIPE VLVS/FTGS	708.01	878.11	1.24
Processing LDAR	PROCESS INSTRU	420.13	405.67	0.97
Transmission LDAR	PROCESS INSTRU	420.13	405.67	0.97
Operating Costs				
Replace with Instrument Air Systems - High Bleed	EQUIP INDEX	588.04	684.44	1.16
Replace with Instrument Air Systems – Intermittent	EQUIP INDEX	588.04	684.44	1.16
Pipeline Pump-Down Before Maintenance	PUMPS COMPR	785.73	983.50	1.25

Exhibit D-4 and **Exhibit D-5** show parameters and results tables for ONE Future's 2016 MAC analysis (ICF 2016) and the MAC analysis conducted as part of this work. These tables include data for expenditures, service life, emission reduction effectiveness, emission reductions, and emission reduction costs. Expenditures are derived from STAR data (EPA 2018) and are escalated using the Chemical Engineering Plant Cost Index (Chemical Engineering n.d.). Service life is inferred from STAR data (EPA 2018) and is also reflected in ONE Future's MAC analysis (ICF 2016). Emission reduction effectiveness is provided in ONE Future's MAC analysis (ICF 2016). For NETL's MAC analysis (shown in **Exhibit D-5**), emission reductions are calculated by dividing ONE Future's emissions by the emission reduction effectiveness; costs are calculated by factoring escalated expenditures by ONE Future device counts, amortizing by service life, and dividing by emission reductions.

Exhibit D-4. Parameters and Results for the MAC Analysis Performed by ICF in 2016

MAC Author	Mitigation Strategy	Expenditures		Service Life (years)	Emission Reduction Effectiveness	Bcf CH_4 reduced						2006$/Mcf reduced				
		Capital (2006$)	Operating (2006$)			Production	Gathering & Boosting	Processing	Transmission	Storage	Total	Production	Gathering & Boosting	Processing	Transmission	Storage
ICF 2016	Early Replacement of High-Bleed Devices with Low-Bleed Devices	3,000	0	5	78%	6.58			0.610	0.12	7.3	4.26			7.94	7.94
	Install Plunger Lift Systems in Gas Wells	20,000	2,400	5	95%	2.29					2.3	3.10				
	Install Vapor Recovery Units	50,636	9,166	5	95%	1.57					1.6	(0.50)				
	LDAR Processing	12,501	0	1	40%			11.09			11.1			2.75		
	LDAR Transmission	10,001	0	1	40%				7.70	4.40	12.1				5.24	5.24
	LDAR Wells	(1,574)		1	40%	5.02				0.34	5.4	(0.87)				2.06
	Pipeline Pump-Down Before Maintenance	0	30,155	5	80%				2.81		2.8				1.80	
	Redesign Blowdown Systems and Alter ESD Practices	15,000	0	5	95%				6.38	1.22	7.6				1.29	1.29
	Replace Kimray Pumps with Electric Pumps	10,000	2,000	5	100%	4.27		0.13			4.4	(1.63)		1.04		
	Replace Pneumatic Chemical Injection Pumps with Solar Electric Pumps	5,000	75	5	100%	2.68					2.7	2.90				
	Replace with Instrument Air Systems - High Bleed	60,000	17,770	5	100%				6.40	1.20					1.12	1.12
	Replace with Instrument Air Systems - Intermittent	60,000	17,770	5	100%				7.40	0.80					0.37	0.37
	Replacement of Reciprocating Compressor Rod Packing Systems	6,600	0	10	31%	0.58		0.32	1.85	0.36	3.1	4.28		6.94	7.96	7.96
	Wet Seal Degassing Recovery System for Centrifugal Compressors	70,000	0	5	95%			7.55	7.39	0.76	15.7			0.37	0.42	0.42
	TOTAL					23.0	0	19.1	40.6	9.2	91.8					

Exhibit D-5. Parameters and Results for the MAC Analysis Performed by NETL in 2020

MAC Author	Mitigation Strategy	Expenditures		Service	Emission Reduction Effectiveness	Bcf CH_4 reduced							2017$/Mcf reduced					
		Capital (2017$)	Operating (2017$)			Production	Gathering & Boosting	Processing	Transmission	Storage	Distribution	Total	Production	Gathering & Boosting	Processing	Transmission	Storage	Distribution
NETL 2020	Early Replacement of High-Bleed Devices with Low-Bleed Devices	3,800	0	5	78%	0.08	0.01			0.007		0.10	1.10	4.20			7.78	
	LDAR Processing	12,000	0	1	40%			0.003				0.003			42.27			
	LDAR Transmission	10,000	0	1	40%				0.11			0.11				20.70		
	Pipeline Pump-Down Before Maintenance	0	38,000	5	80%				0.09			0.09				35.78		
	Redesign Blowdown Systems and Alter ESD Practices	18,600	0	5	95%				0.86			0.86				1.05		
	Replace with Instrument Air Systems - High Bleed	75,000	5,400	5	100%	0.10	0.02			0.008		0.12	26.53	29.62			54.88	
	Replace with Instrument Air Systems - Intermittent	75,000	5,400	5	100%	2.35	0.16			0.02		2.53	81.27	84.36			311.85	
	Replacement of Reciprocating Compressor Rod Packing Systems	8,300	0	10	31%				0.51			0.51				1.67		
	Wet Seal Degassing Recovery System for Centrifugal Compressors	105,000	0	5	95%				0.21			0.21				23.72		
	Replacement of Cast Iron Distribution Pipelines	4,100,000	0								0.31	0.31						460.62
	TOTAL					2.52	0.19	0.003	3.40	0.04	0.31	4.84						

D-11. REFERENCES

AGA. 2013. Managing the Reduction of the Nation's Cast Iron Inventory. https://www.aga.org/sites/default/files/managing_the_nations_cast_iron_inventory.pdf. American Gas Association. Accessed March 19, 2020.

Chemical Engineering. n.d. The Chemical Engineering Plant Cost Index. http://www.chemengonline.com/pci-home. Accessed May 21, 2020.

EPA. 2017. Annex 3.6: Methodology for Estimating CH4 and CO2 Emissions from Natural Gas Systems. U.S. Environmental Protection Agency. Accessed March 19, 2020.

EPA. 2018. Natural Gas STAR Program. Recommended Technologies to Reduce Methane Emissions. U.S. Environmental Protection Agency. https://www.epa.gov/natural-gas-star-program/recommended-technologies-reduce-methane-emissions. Accessed March 18, 2020.

ICF. 2016. Economic Analysis of Methane Emission Reduction Potential from Natural Gas Systems. ICF International. May 2016. https://onefuture.us/wp-content/uploads/2018/07/ICF-Study.pdf. Fairfax, VA.

Zavala-Araiza, Daniel, Ramón A. Alvarez, David R. Lyon, David T. Allen, Anthony J. Marchese, Daniel J. Zimmerle, and Steven P. Hamburg. 2017. Super-Emitters in Natural Gas Infrastructure Are Caused by Abnormal Process Conditions. *Nature Communications* 8(1):14012.

This page intentionally left blank.

APPENDIX E: LIFE CYCLE GREENHOUSE GAS EMISSIONS FOR NATURAL GAS THROUGH END USE

TABLE OF CONTENTS

LIST OF EXHIBITS

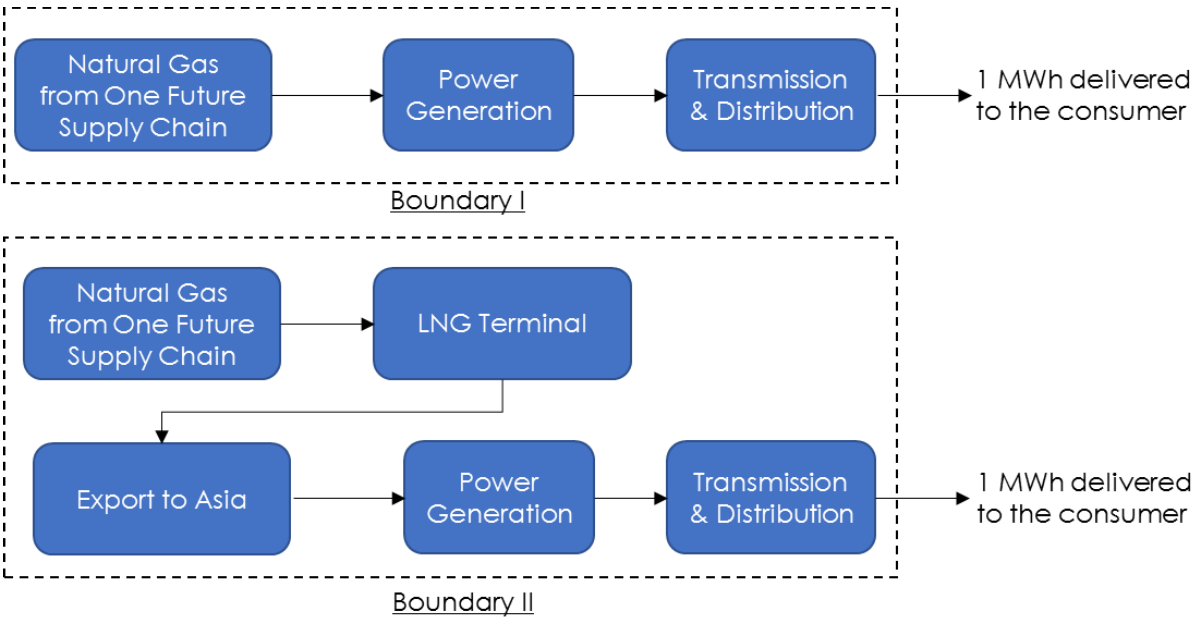
ACRONYMS AND ABBREVIATIONS

CHP	Combined heat and power
CO_2	Carbon dioxide
g	Grams
GHG	Greenhouse gas
hr	Hour
kg	Kilogram
km	Kilometer
lb	Pound
LNG	Liquefied natural gas
MJ	Megajoule
MMBtu	Million British thermal unit
MW	Megawatt
MWh	Megawatt hour
NETL	National Energy Technology Laboratory
NGCC	Natural gas combined cycle
ONE Future	Our Nation's Energy Future
SF_6	Sulfur hexafluoride
U.S.	United States

E-1. SYSTEM BOUNDARY

Exhibit E-1 displays the system boundary considered in modeling the natural gas end use scenarios. Two boundaries are used. Boundary I represents natural gas-fired power scenarios in the United States (U.S.). Boundary II represents scenarios where natural gas is exported from the U.S. for combustion in foreign power plants.

Exhibit E-1: High-Level Expanded System Boundaries of Natural Gas-Fired Power Scenarios



E-2. SCENARIO DEFINITIONS

Three natural gas end use scenarios were modeled in this analysis:

1. Electricity from advanced natural gas power plants
2. Electricity from fleet natural gas power plants
3. Electricity from liquefied natural gas (LNG) exported to Shanghai, China

E-2.1. ADVANCED NATURAL GAS POWER PLANTS

The advanced natural gas power plant modeled in this analysis is a thermoelectric power plant equipped with natural gas combined cycle (NGCC) technology without carbon capture as characterized by prior work at the National Energy Technology Laboratory (NETL). The natural gas feed rate to the NGCC power plant is 93,272 kilogram (kg)/hour (hr) with a net efficiency of 53.6%. The power plant is rated with a net power output of 727 megawatts (MW). The stack (direct) emissions from this scenario are modeled based on the emissions profile reported in NETL's baseline study for an NGCC plant, specifically 119 pounds (lb) carbon dioxide (CO_2)/million British thermal units (MMBtu) of feed (NETL 2019).

E-2.2. FLEET NATURAL GAS POWER PLANTS

A key distinction between the natural gas fleet and advanced natural gas plant (NGCC) is that the former uses a single cycle combustion technology while the latter uses a combined cycle combustion technology. In this analysis, four scenarios are modeled: peaking, load following, baseload, and total fleet, as fleet natural gas power plants. The net efficiency to model these scenarios are derived from EIA-923 and EIA-860 (EIA's annual surveys that collect information about electric power plants Form: EIA-860, Annual Electric Generator Report, and Form EIA-923, Power Plant Operations Report), using 2017 data for consistency with the study year. The plants in these datasets were filtered on the following criteria:

1. Baseload plants with capacity factor >= 0.6, load following with capacity factor >0.2 and <0.6, peaking plants with capacity factor <0.2, and total fleet with capacity factor between 0 to 1.
2. Plants whose primary fuel type is natural gas, and natural gas constitutes 90% or more of its annual net generation across all fuel types
3. Electricity generating units with a positive annual net generation
4. No erroneous plant identification (e.g. 99999) or plants with efficiencies greater than 1
5. No combined heat and power (CHP) plants

The net efficiencies of fleet power plants are shown in **Exhibit E-2.**

Exhibit E-2: Net Electricity Generation Efficiencies for Fleet Power Plants

Fleet Type	Power Plant Net Efficiency, %
Peaking	32.17%
Load Following	44.52%
Baseload	48.11%
Total Fleet	43.77%

E-2.3. LNG SUPPLY CHAIN

These scenarios consider exporting the natural gas extracted in the United States from Our Nation's Energy Future (ONE Future) companies to China or Europe, as LNG for electricity generation. The following assumptions are made based on a prior NETL study on LNG (Roman-White et al. 2019) to compute the life cycle greenhouse gas (GHG) emissions from this scenario:

1. Prior to the export, the natural gas extracted from ONE Future supply chain is assumed to be sent to an LNG terminal through pipelines, spanning 971 kilometers (km) (Littlefield et al. 2019)
2. LNG tankers from the terminal are shipped to China via one of the five different sea routes. An average of these shipping routes was used to evaluate the distance that will be traveled. LNG is shipped to Europe via one direct route.

3. A natural gas power plant exists at the LNG import destination.
4. The natural gas power plant at the import destination is located close to the import port, eliminating the need for natural gas pipeline transport.
5. The natural gas power plant at the import destination is modeled similarly as in the 2019 NETL LNG study with a net efficiency of 46.4%.

E-3. POWER PLANT HEAT RATES

Computing the emissions from natural gas end use scenarios require the scaling of upstream natural gas emissions (from production through transmission and distribution) to 1 MWh of electricity delivered to consumers. The scaling factor is a function of net power plant efficiency and the loss of electricity during electricity transmission and distribution. The rate of natural gas consumption (in megajoules [MJ]) at a natural gas power plant is calculated by converting MWh to MJ (where 1 MWh = 3,600 MJ) and dividing by net powerplant efficiency. Error! Reference s ource not found. displays the heat rates used in this analysis.

Exhibit E-3: Power Plant Heat Rates

Scenario	Power Plant Net Efficiency, %	Heat Rate, MJ Natural Gas/MWh Busbar
Electricity from an NGCC power plant	53.6	6,716
Electricity from fleet, peaking power plant	32.2	11,180
Electricity from fleet, load following power plant	44.5	8,090
Electricity from fleet, baseload power plant	48.1	7,484
Electricity from fleet, total fleet	43.8	8,219
Electricity from exported LNG	46.4	7,759

The emission profiles for the peaking, load following, baseload and total fleet power plants are calculated using the NETL life cycle inventory data for Natural Gas Energy Conversion U.S. Fleet Average (NETL 2012). The efficiency is adjusted in each case to properly scale the feed rate into the power plant and resultant combustion emissions to represent the 2017 data.

E-4. ELECTRICITY TRANSMISSION AND DISTRIBUTION

In all end use cases, it is assumed that the electricity is distributed using the existing transmission and distribution infrastructure. Consistent with the prior analyses (Littlefield et al. 2019), a 7 percent loss of electrical energy is considered during transmission and distribution. Additionally, sulfur hexafluoride (SF_6) emissions from the transmission and distribution equipment are included at the rate of 0.075 grams (g) of SF_6/megawatt hour (MWh) delivered (NETL 2013).

E-5. REFERENCES

Littlefield, James, Selina Roman-White, Daniel J. Augustine, Ambica Pegallapati, George G. Zaimes, Srijana Rai, Gregory Cooney, and Timothy J. Skone. 2019. Life Cycle Analysis of Natural Gas Extraction and Power Generation. DOE/NETL-2019/2039. U.S. Department of Energy, National Energy Technology Laboratory. https://www.netl.doe.gov/energy-analysis/details?id=3198. Pittsburgh, PA.

NETL. 2012. NETL Unit Process Library. Natural Gas Energy Conversion U.S. Fleet Average. U.S. Department of Energy, National Energy Technology Laboratory. https://netl.doe.gov/node/2573. Accessed March 19, 2020.

NETL. 2013. NETL Unit Process Library. Electricity Transmission. U.S. Department of Energy, National Energy Technology Laboratory. https://netl.doe.gov/node/2573. Accessed March 19, 2020.

NETL. 2019. Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity. U.S. Department of Energy, National Energy Technology Laboratory. Pittsburgh, PA. Accessed March 19, 2020.

Roman-White, Selina, Srijana Rai, James Littlefield, Gregory Cooney, and Timothy J. Skone. 2019. Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States: 2019 Update. DOE/NETL-2019/2041. U.S. Department of Energy, National Energy Technology Laboratory. https://www.netl.doe.gov/energy-analysis/details?id=4440. Pittsburgh, PA.

This page intentionally left blank.

APPENDIX F: ONE FUTURE AVERAGE EXCLUDING NON-GHGRP DATA POINTS

TABLE OF CONTENTS

LIST OF EXHIBITS

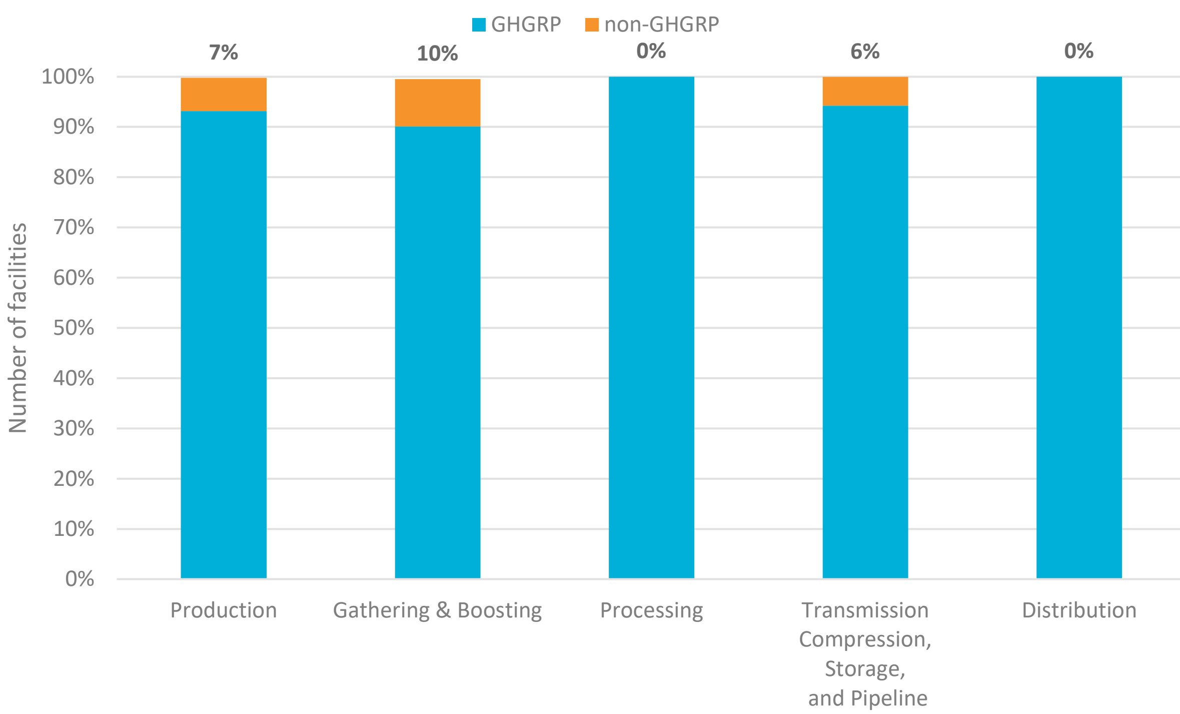
ACRONYMS AND ABBREVIATIONS

CH_4	Methane
g	gram
GHG	Greenhouse gas
GHGRP	Greenhouse Gas Reporting Program
MJ	Megajoule

F-1. ONE FUTURE AVERAGE EXCLUDING NON-GHGRP DATA POINTS

The representation of facilities not meeting the Greenhouse Gas Reporting Program (GHGRP) threshold in ONE Future data is very low. These facilities are called non-GHGRP facilities in this report. There are 2 non-GHGRP facilities in the production and gathering and boosting stages each, 17 in transmission compression, storage, and pipeline all together, and 0 in processing and distribution. **Exhibit F-1** shows the percent share of non-GHGRP facilities in the total number of reported facilities within each stage of the supply chain.

Exhibit F-1: Representation of Non-GHGRP Facilities in ONE Future



The purpose of the above figure is to show the shares, on a facility count basis, of GHGRP and non-GHGRP facilities in each stage. However, facility count is not the determinant of the relative life cycle greenhouse gas (GHG) contributions of these two facility types. Emissions are a function of multiple variables that represent an interplay between facility emissions and throughput. If the non-GHGRP facilities are removed, the life cycle GHG emissions do not change significantly. The removal of the non-GHGRP facilities increases the CH_4 emissions from ONE Future's average by 0.001 g CH_4/MJ and increases the CH_4 emission rate from 0.76% to 0.77% (with a 95% confidence interval of 0.49–1.08%). ONE Future has improved the representativeness of their supply chain by providing non-GHGRP data; however, as shown here, the provided non-GHGRP data are not a significant contribution to the total life cycle results of ONE Future supply chain.

APPENDIX G: ONE FUTURE SCENARIO CH_4 EMISSION RESULTS

TABLE OF CONTENTS

LIST OF EXHIBITS

ACRONYMS AND ABBREVIATIONS

CH_4 Methane
LA Louisiana
TX Texas

G-1. ONE FUTURE SCENARIO RESULTS: CH_4 EMISSIONS

Exhibit G-1. ONE Future CH_4 Emission Results for Gulf Coast Basin (LA TX) Scenario

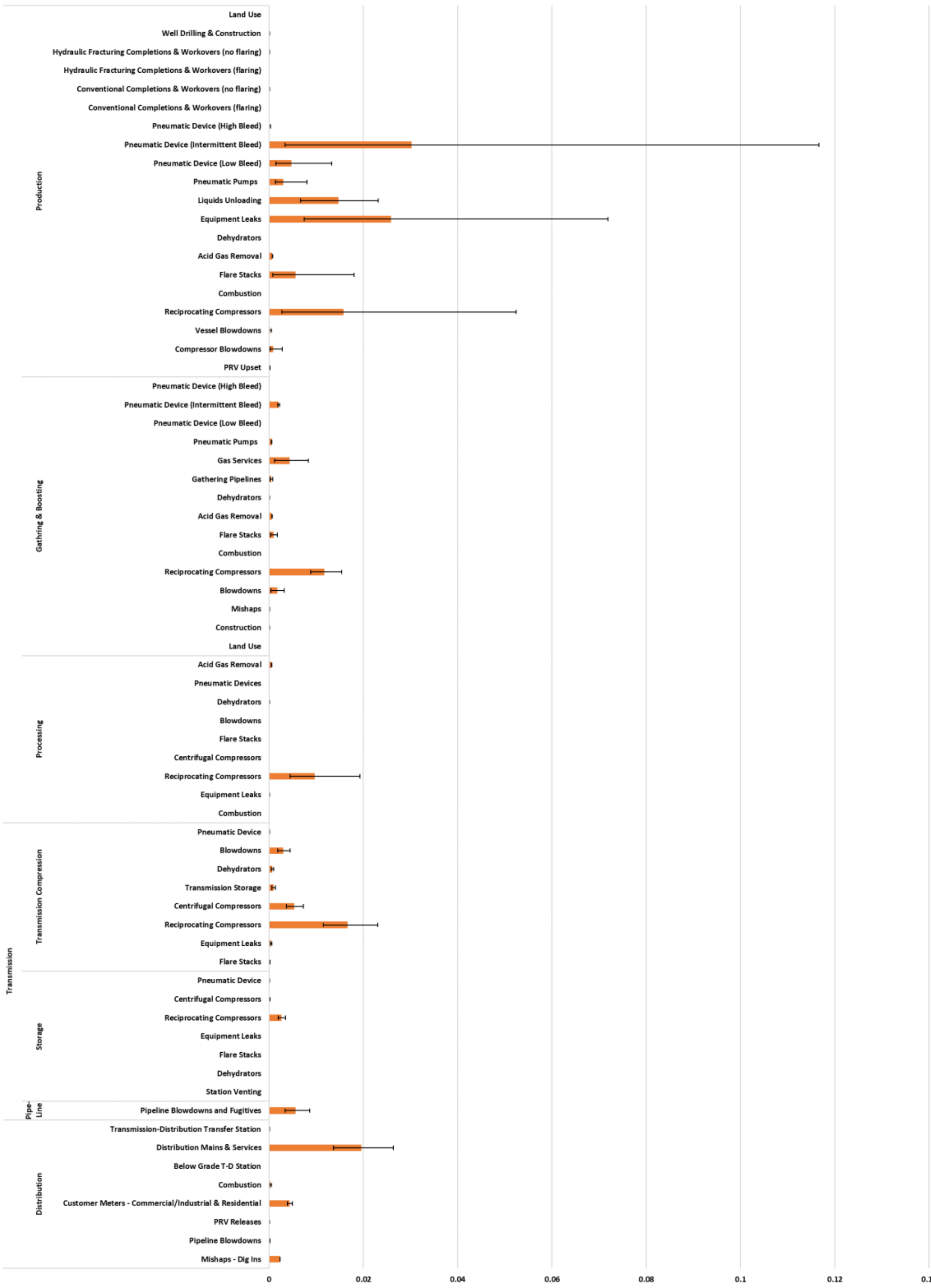


Exhibit G-2. ONE Future CH_4 Emission Results for Appalachian Basin (Eastern Overthrust Area) Scenario

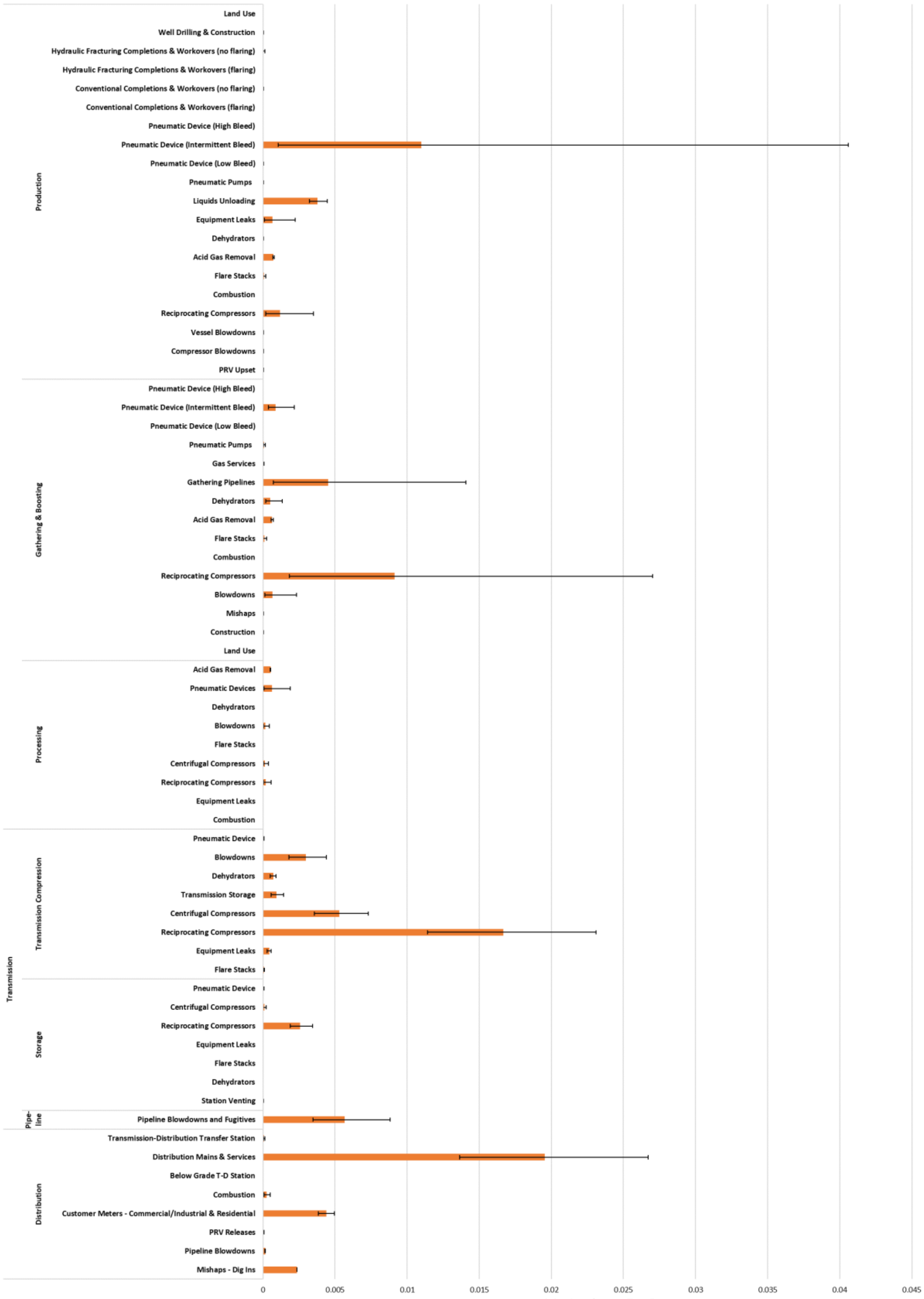


Exhibit G-3. ONE Future CH_4 Emission Results for Permian Basin Scenario

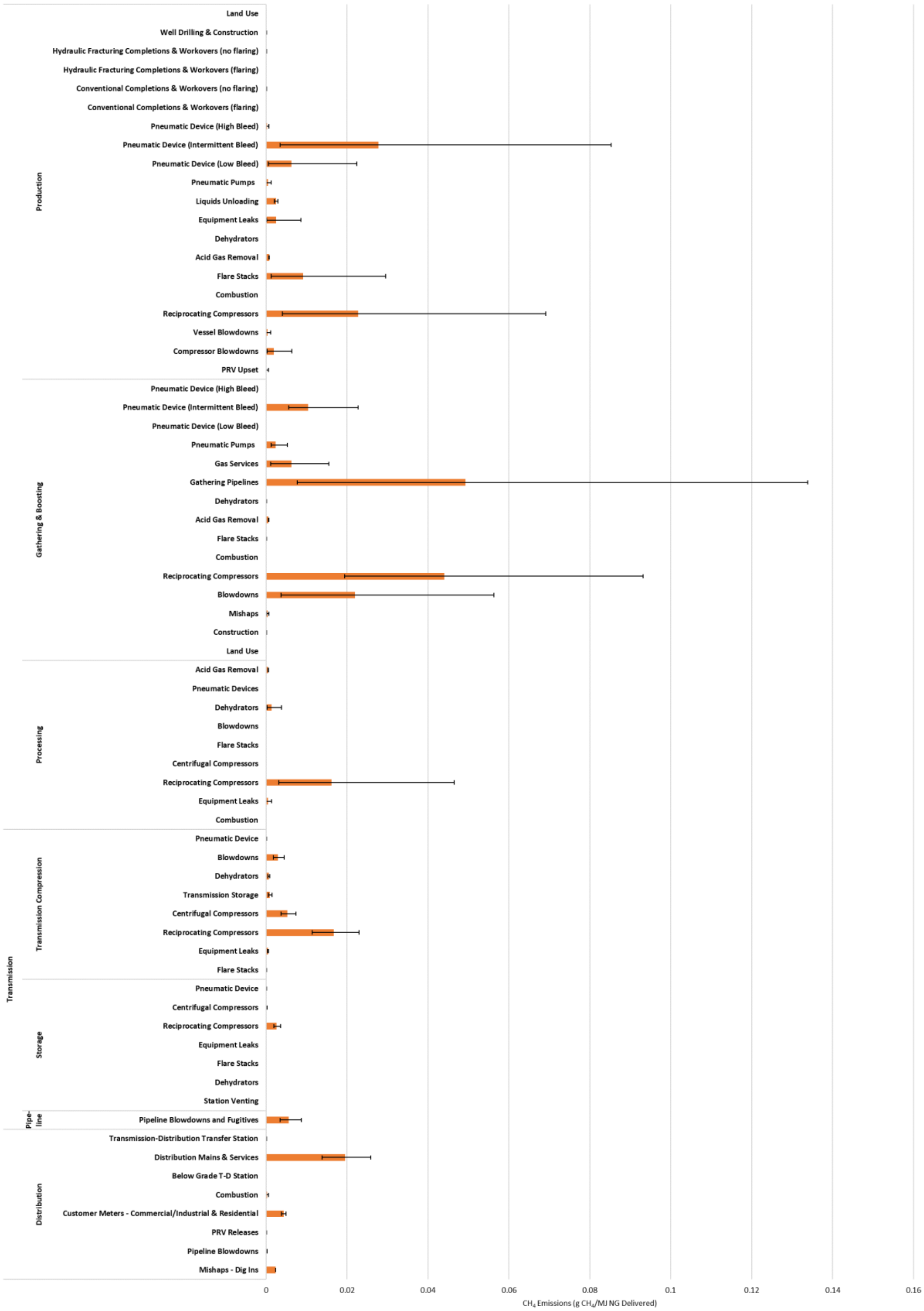


Exhibit G-4. ONE Future CH_4 Emission Results for Williston Basin Scenario

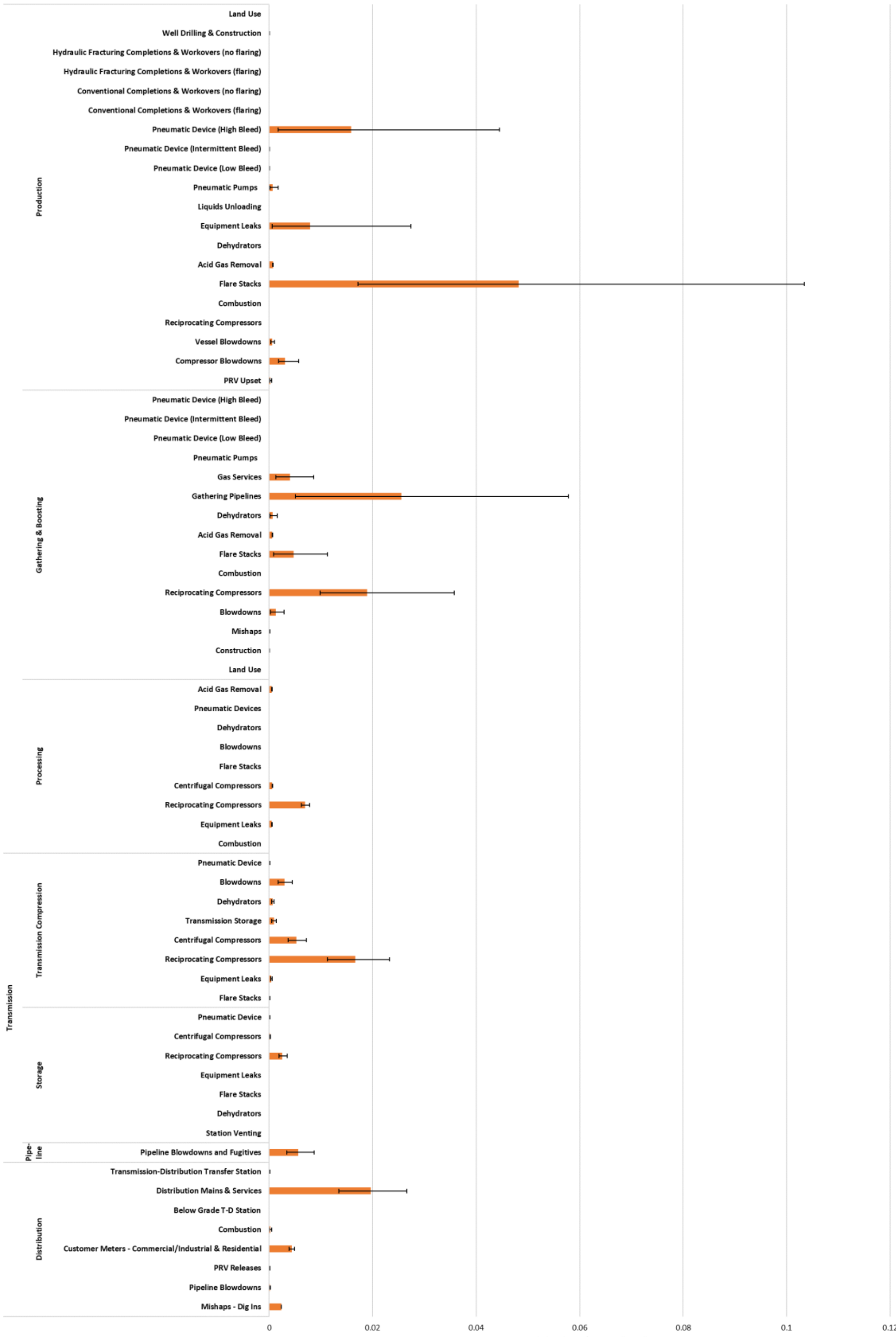


Exhibit G-5. ONE Future CH_4 Emission Results for Arkoma Basin Scenario

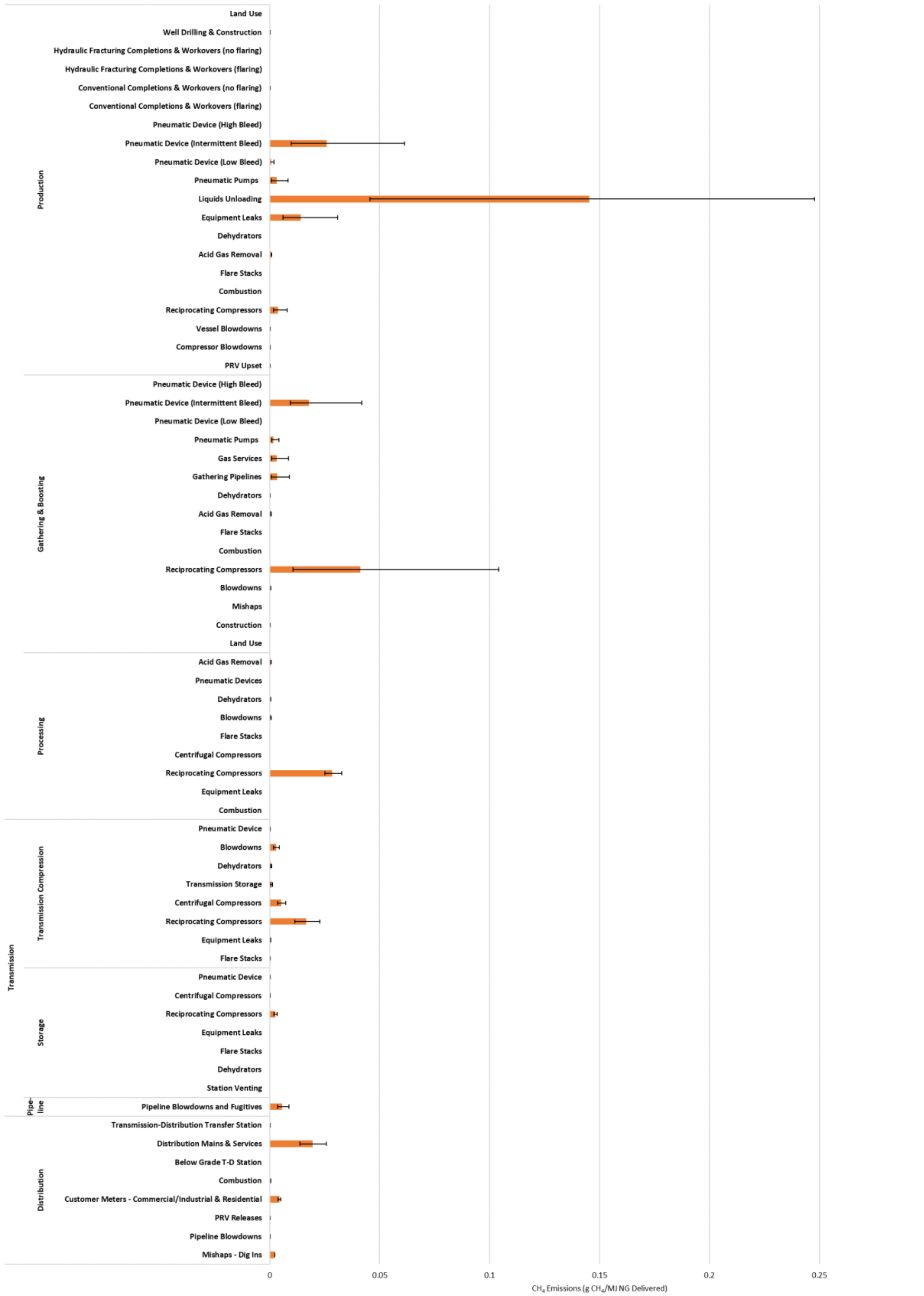


Exhibit G-6. ONE Future CH_4 Emission Results for Massachusetts Scenario

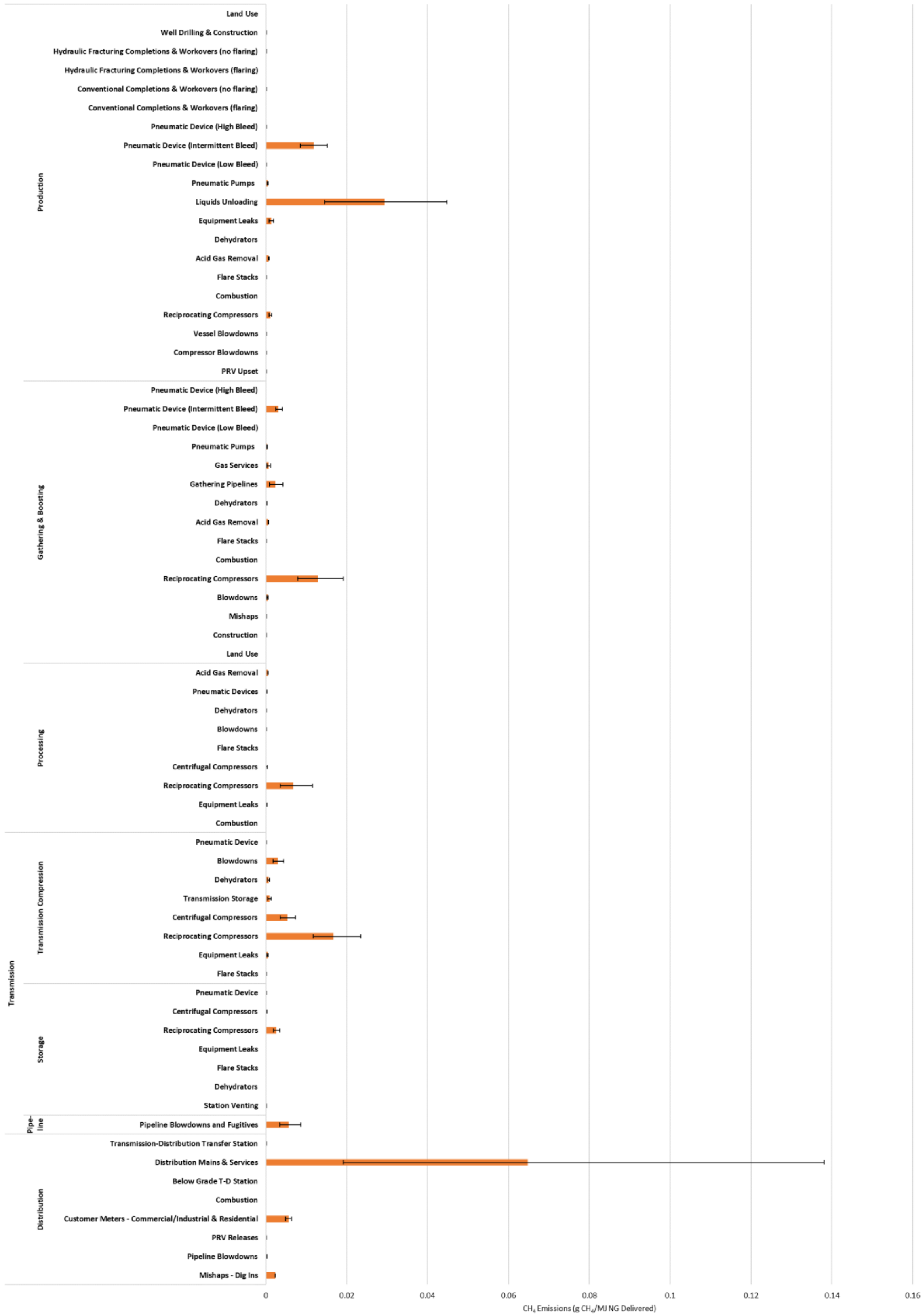


Exhibit G-7. ONE Future CH_4 Emission Results for New York Scenario

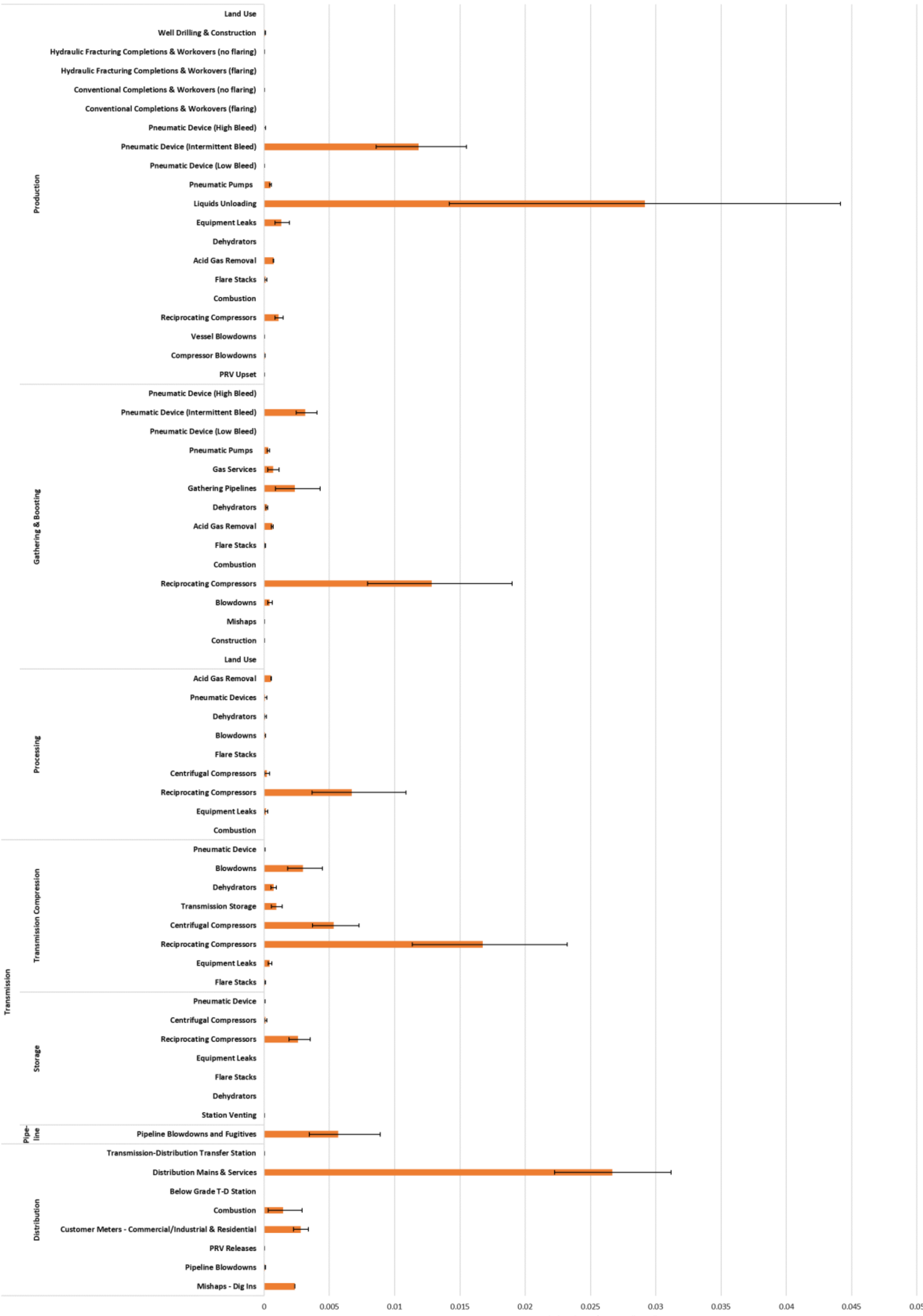


Exhibit G-8. ONE Future CH_4 Emission Results for Ohio Scenario

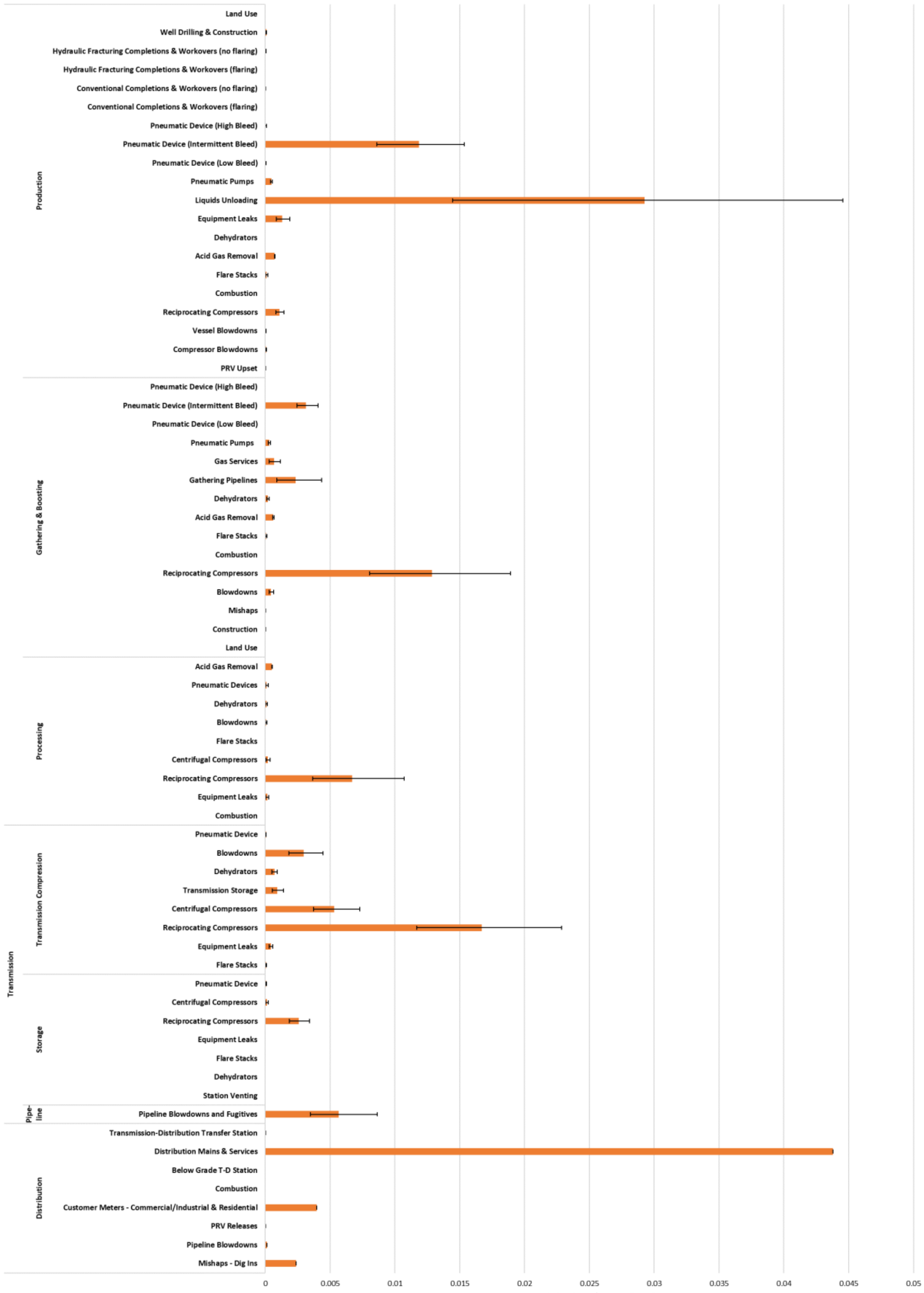


Exhibit G-9. ONE Future CH_4 Emission Results for Florida Scenario

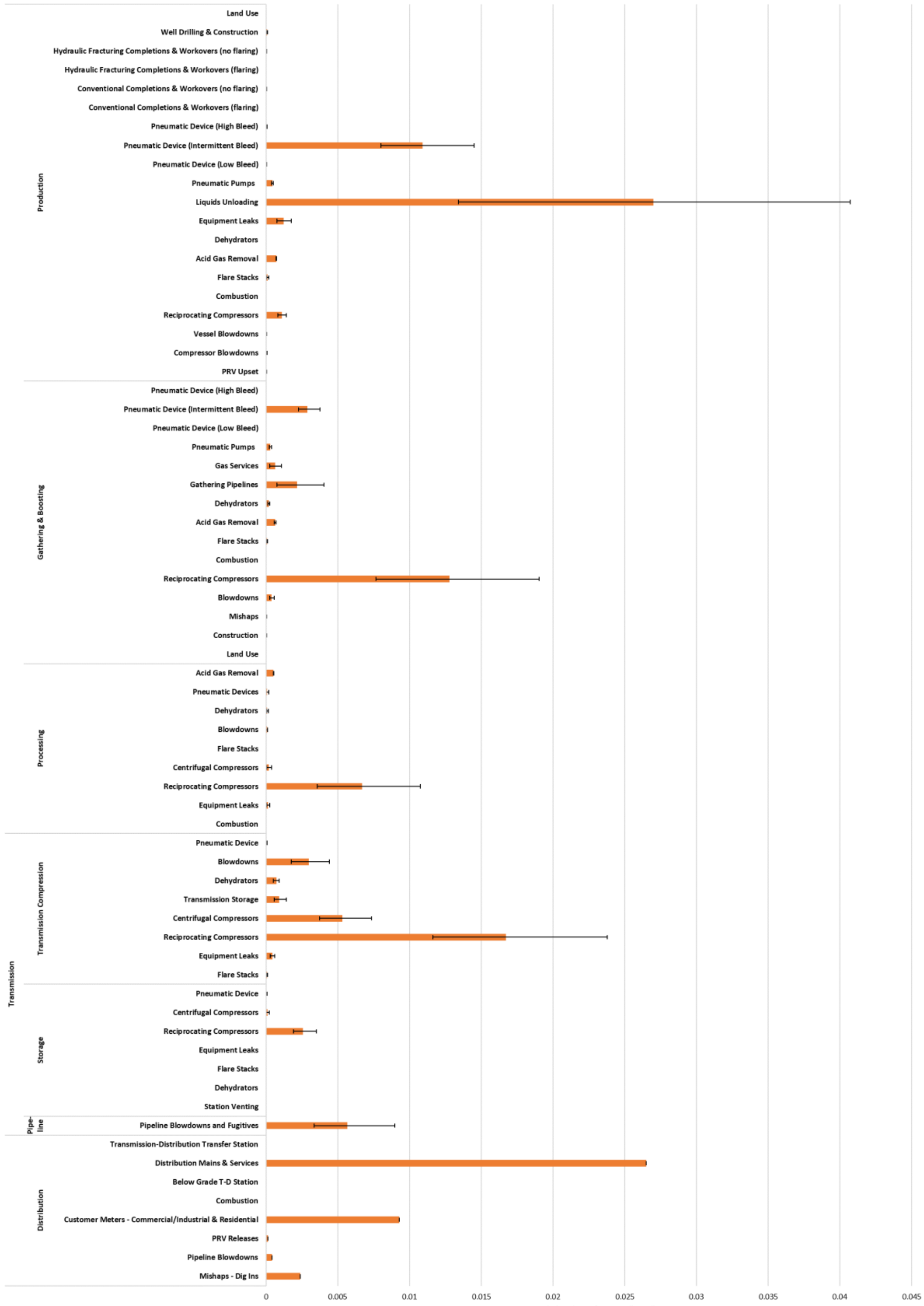


Exhibit G-10. ONE Future CH_4 Emission Results for Missouri Scenario

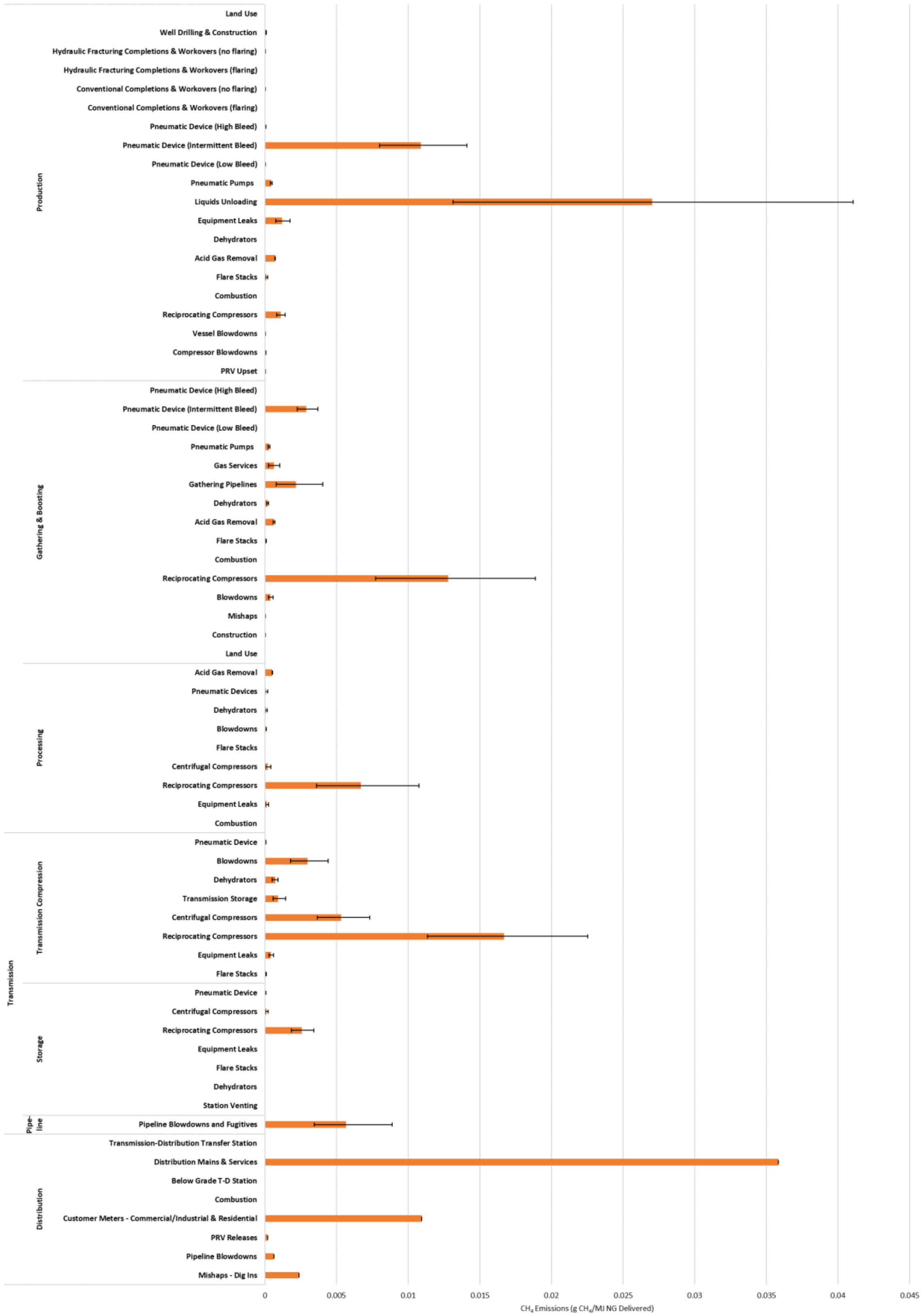


Exhibit G-11. ONE Future CH_4 Emission Results for Arkansas Scenario

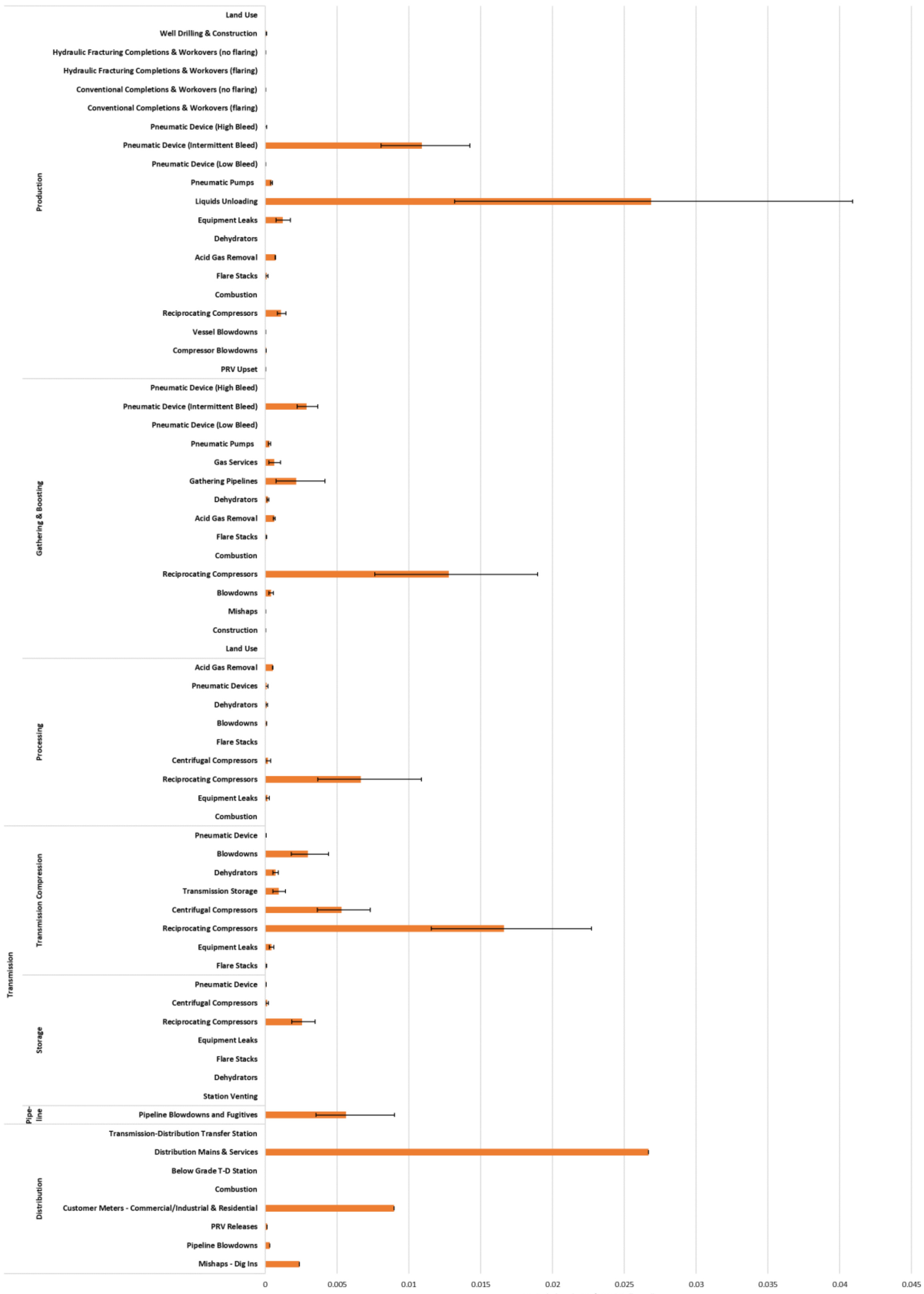


Exhibit G-12. ONE Future CH_4 Emission Results for Maryland Scenario

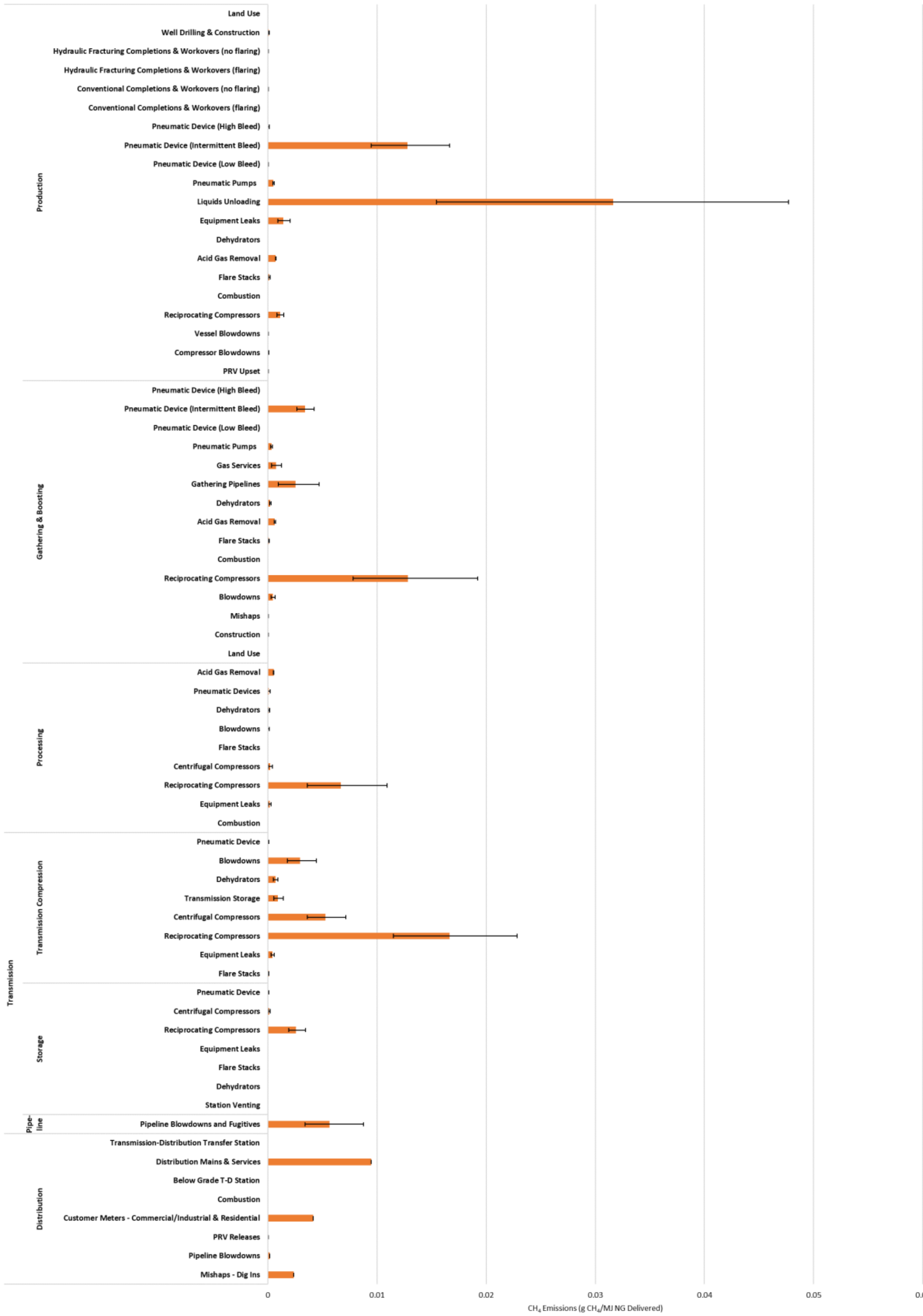


Exhibit G-13. ONE Future CH_4 Emission Results for Tennessee Scenario

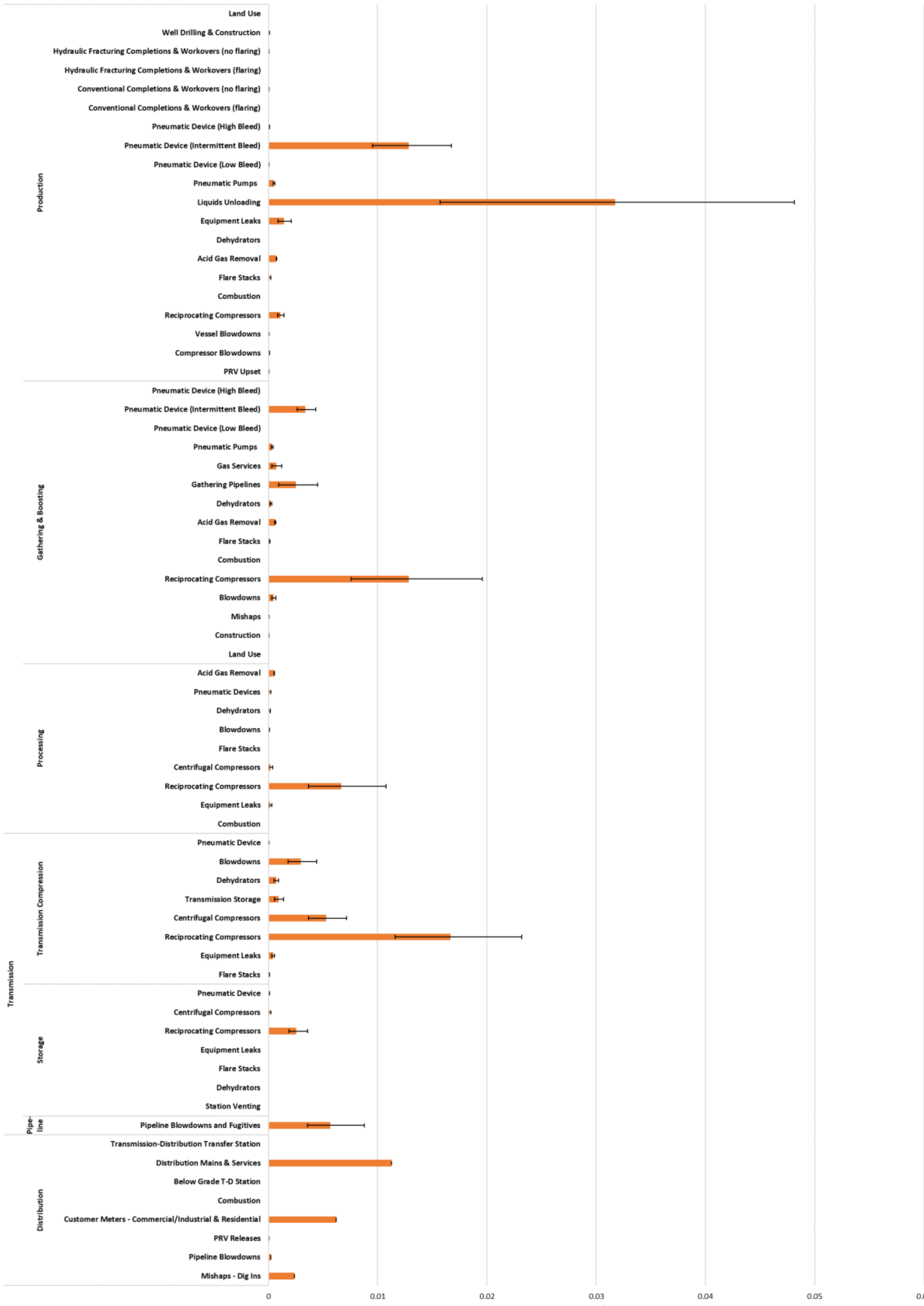


Exhibit G-14. ONE Future CH_4 Emission Results for Utah Scenario

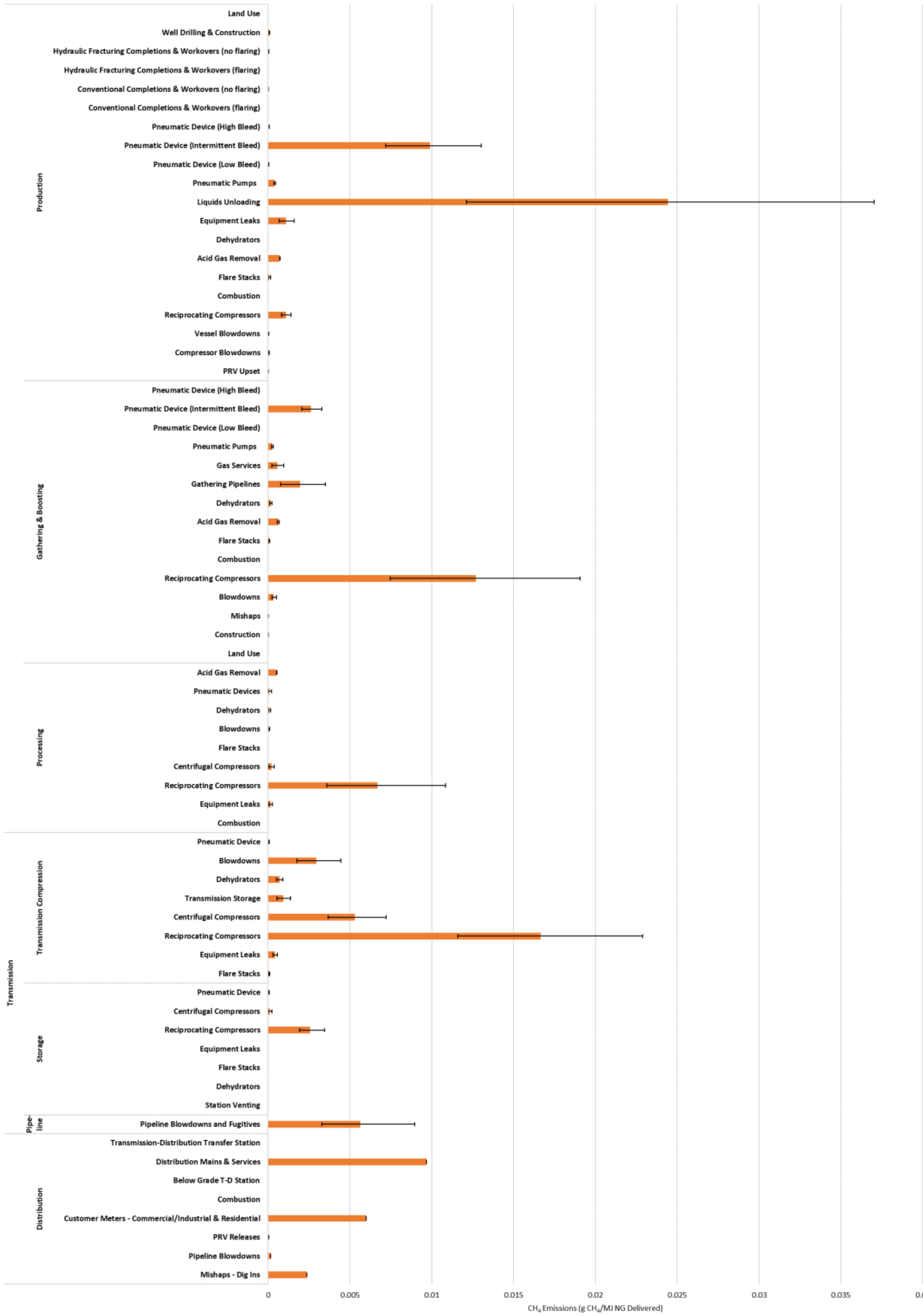


Exhibit G-15. ONE Future CH_4 Emission Results for Colorado Scenario

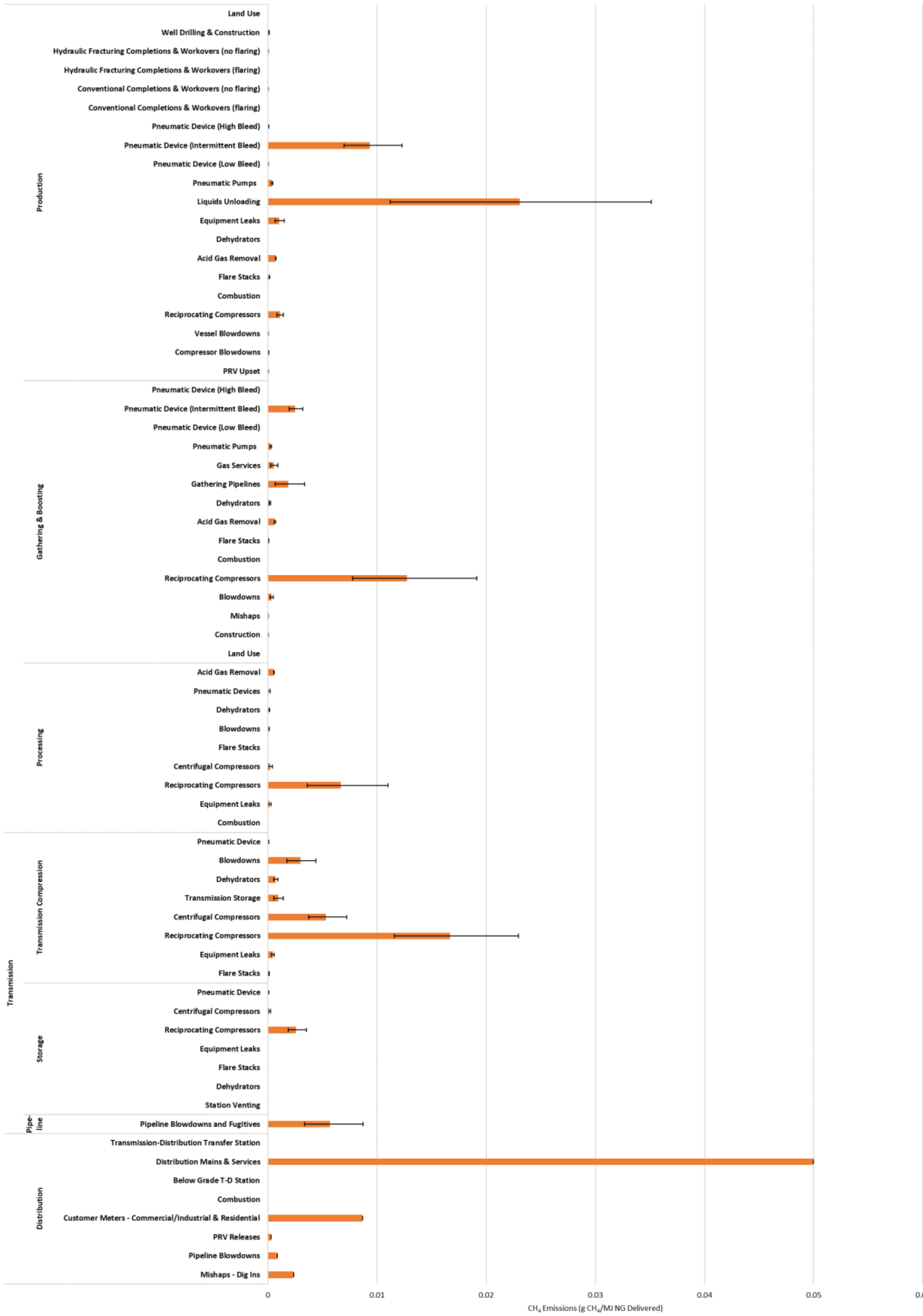


Exhibit G-16. ONE Future CH_4 Emission Results for Illinois Scenario

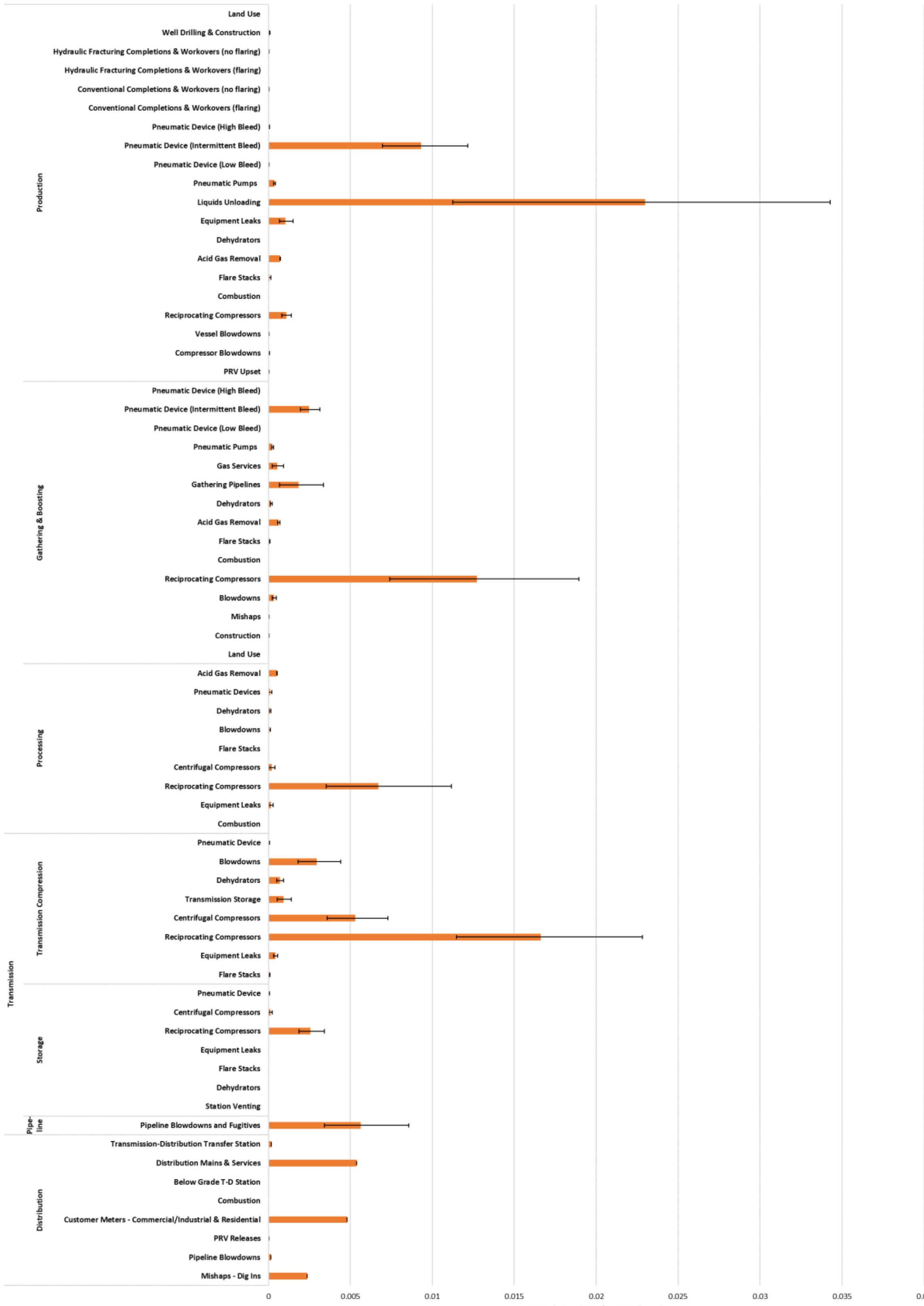


Exhibit G-17. ONE Future CH_4 Emission Results for New Jersey Scenario

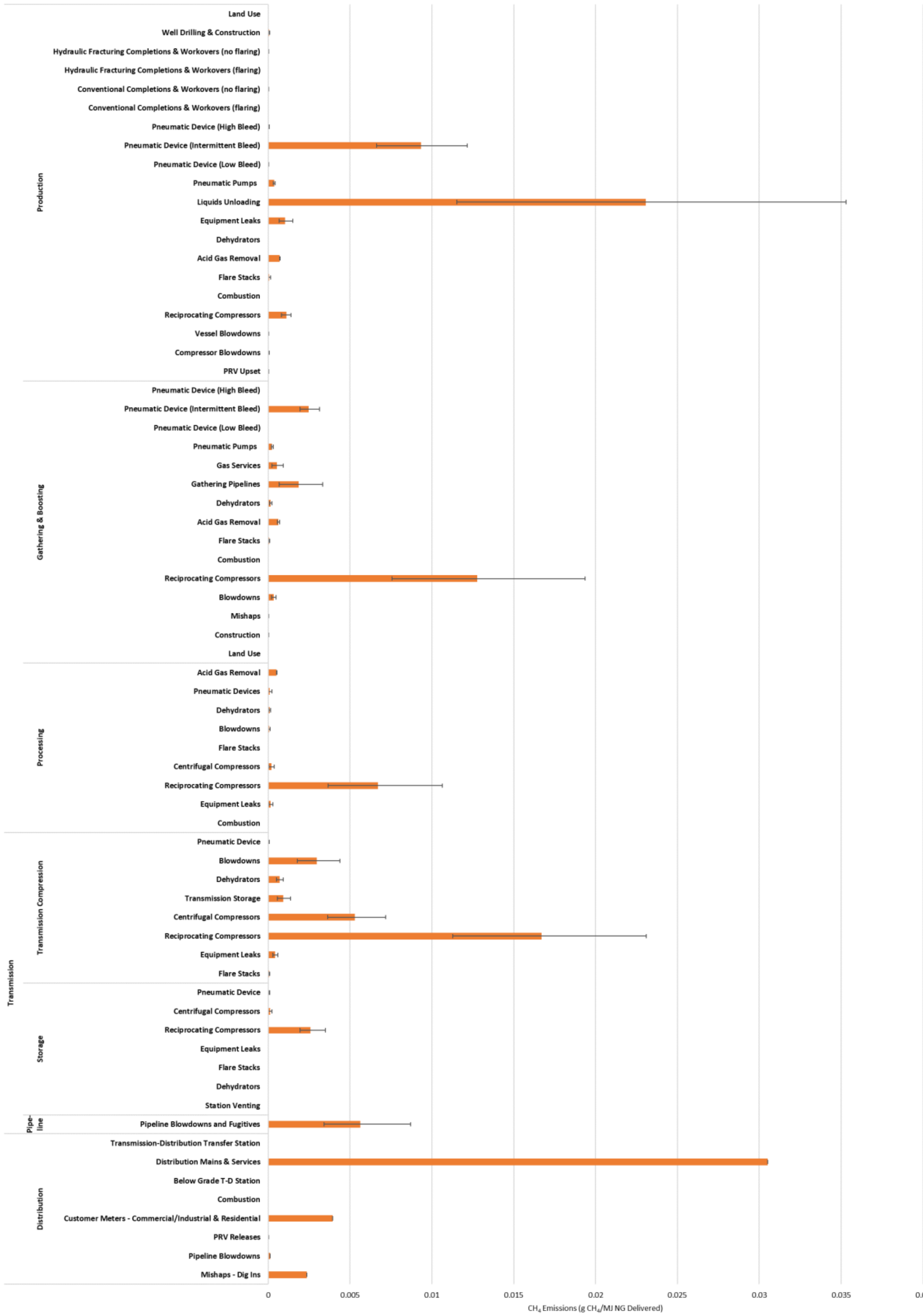


Exhibit G-18. ONE Future CH_4 Emission Results for Oklahoma Scenario

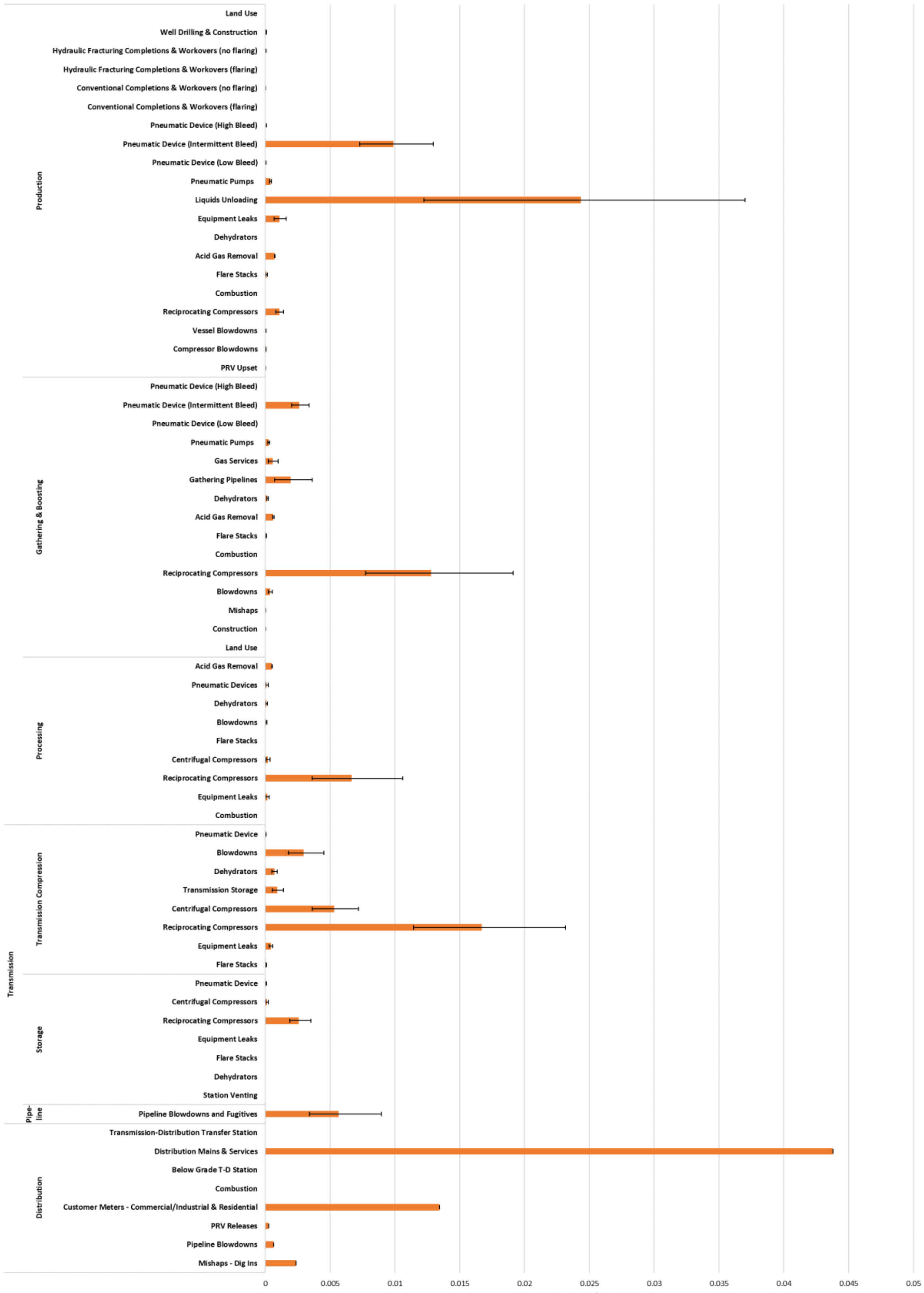


Exhibit G-19. ONE Future CH_4 Emission Results for Maine Scenario

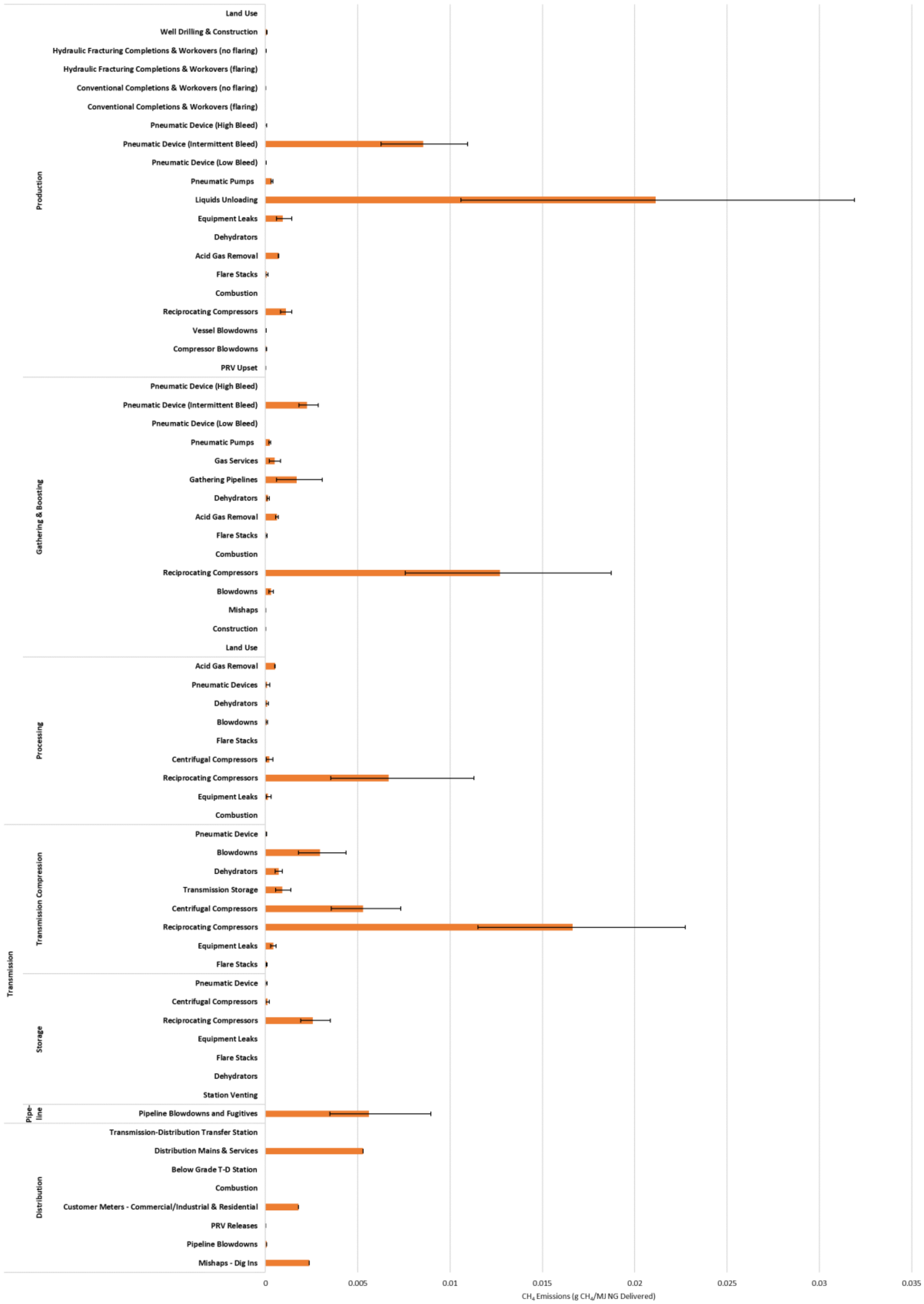


Exhibit G-20. ONE Future CH_4 Emission Results for Rhode Island Scenario

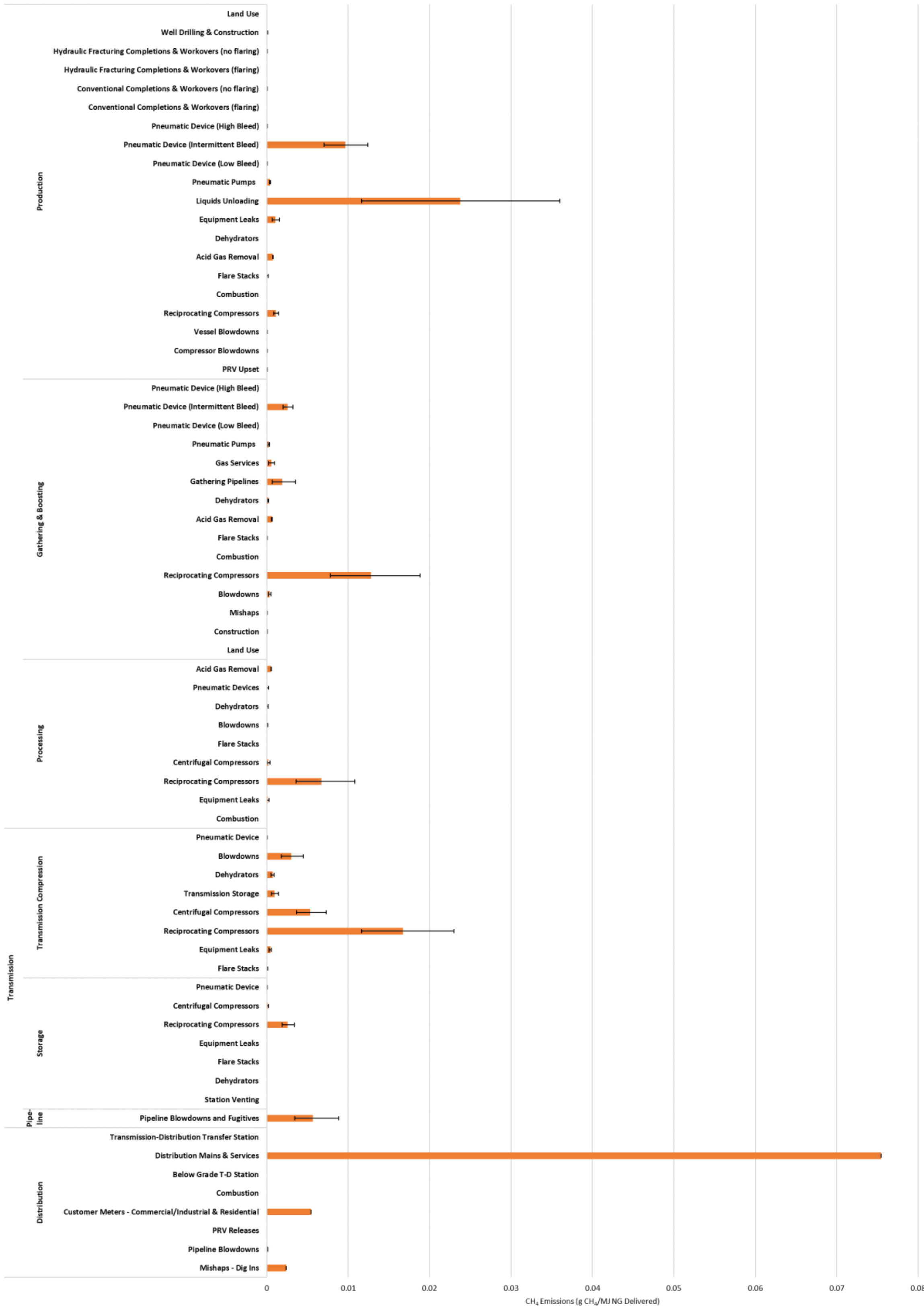


Exhibit G-21. ONE Future CH_4 Emission Results for Virginia Scenario

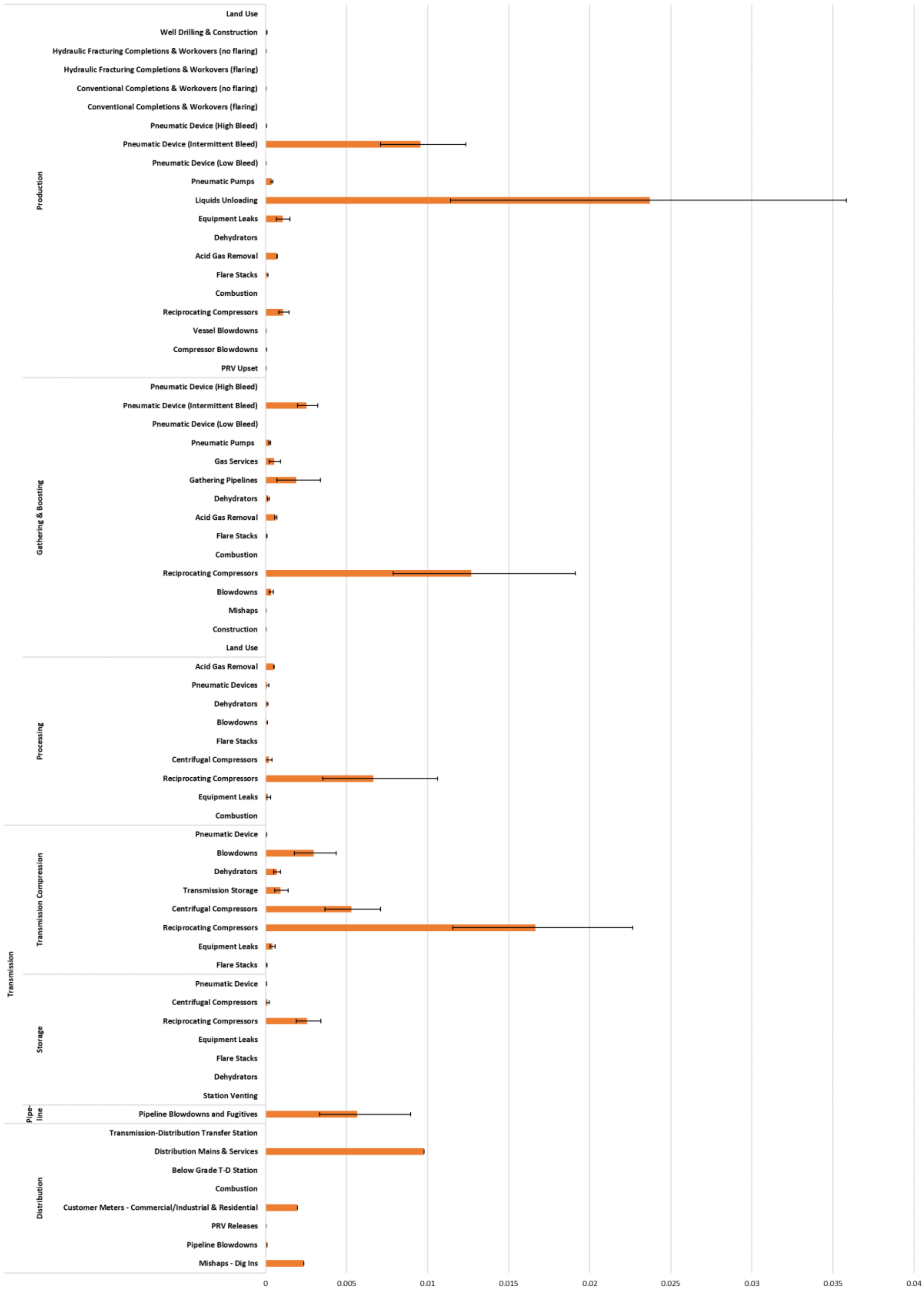


Exhibit G-22. ONE Future CH_4 Emission Results for Georgia Scenario

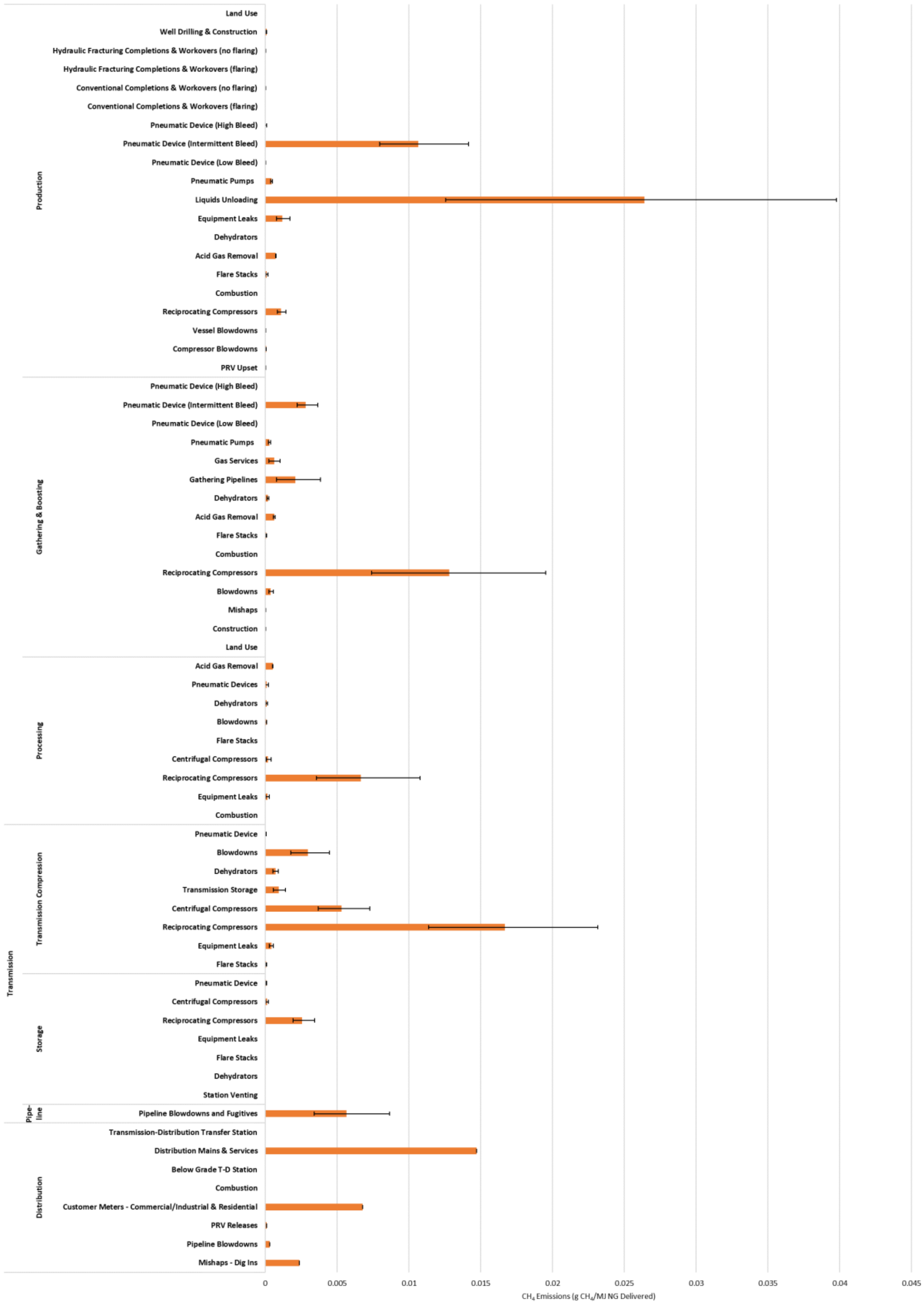


Exhibit G-23. ONE Future CH_4 Emission Results for West Virginia Scenario

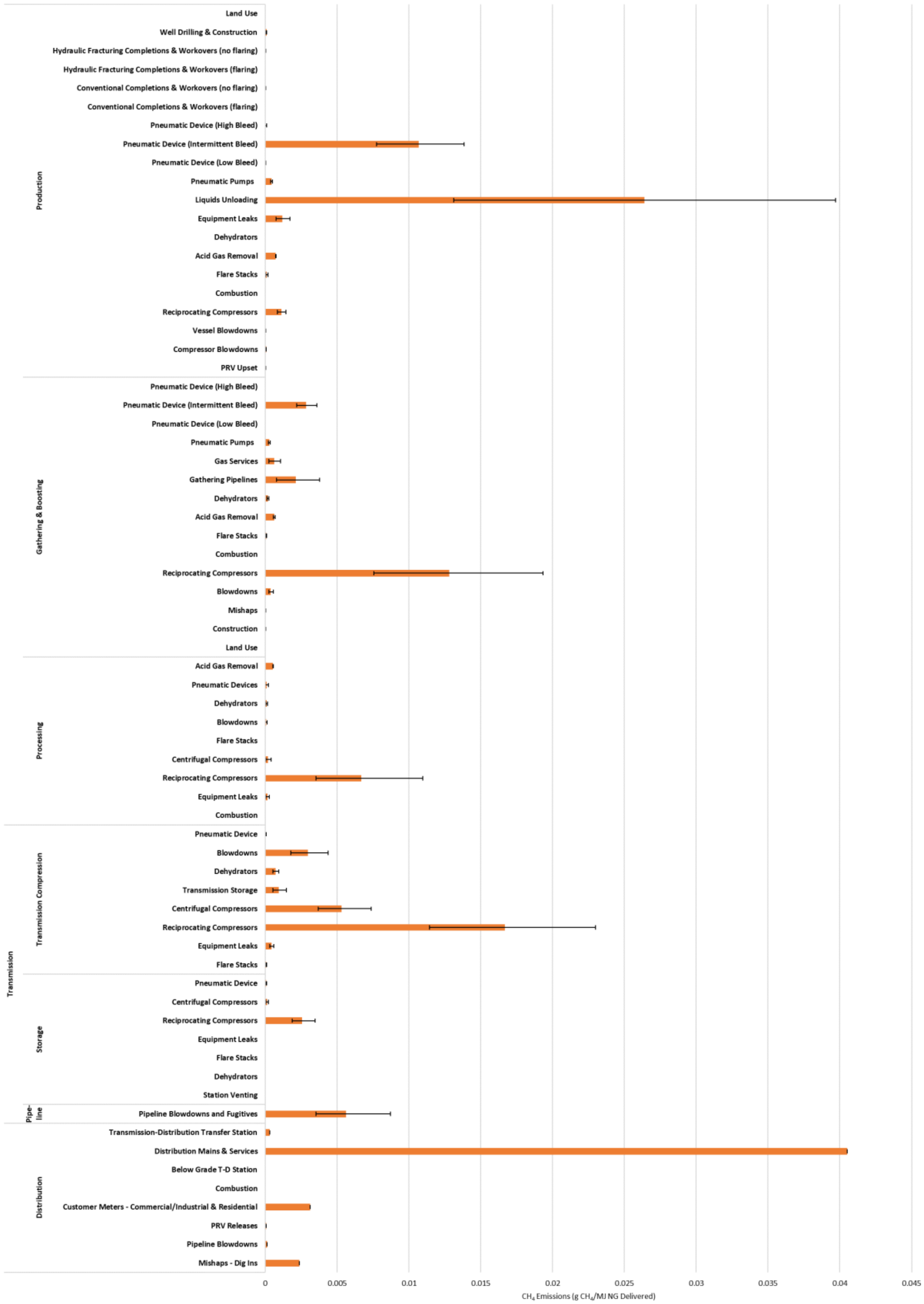


Exhibit G-24. CH_4 Emission Rates for All ONE Future Scenarios

Scenario	CH4 Emission Rate		
	P2.5	Expected	P97.5
Gulf Coast Basin (LA TX)	0.50%	1.13%	2.55%
Appalachian Basin (Eastern Overthrust Area)	0.31%	0.56%	1.08%
Permian Basin	0.57%	1.66%	3.96%
Williston Basin	0.53%	1.17%	2.28%
Arkoma Basin	0.90%	2.02%	3.69%
Massachusetts	0.54%	1.04%	1.76%
New York	0.54%	0.81%	1.13%
Ohio	0.67%	0.91%	1.19%
Florida	0.59%	0.82%	1.10%
Missouri	0.65%	0.89%	1.15%
Arkansas	0.59%	0.82%	1.09%
Maryland	0.49%	0.74%	1.03%
Tennessee	0.51%	0.76%	1.06%
Utah	0.46%	0.68%	0.94%
Colorado	0.70%	0.92%	1.17%
Illinois	0.42%	0.63%	0.88%
New Jersey	0.56%	0.77%	1.03%
Oklahoma	0.70%	0.92%	1.18%
Maine	0.39%	0.60%	0.84%
Rhode Island	0.83%	1.05%	1.30%
Virginia	0.43%	65.00%	0.90%
Georgia	0.50%	0.73%	1.00%
West Virginia	0.63%	0.86%	1.13%
Average	**0.49%**	**0.76%**	**1.08%**

This page intentionally left blank.

APPENDIX H: ONE FUTURE SCENARIO GWP RESULTS

TABLE OF CONTENTS

LIST OF EXHIBITS

ACRONYMS AND ABBREVIATIONS

GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
LA	Louisiana
TX	Texas
yr	Year

H-1. ONE FUTURE SCENARIO RESULTS: GWP (100-YR)

Exhibit H-1. ONE Future 100-yr GWP Results for Gulf Coast Basin (LA TX) Scenario

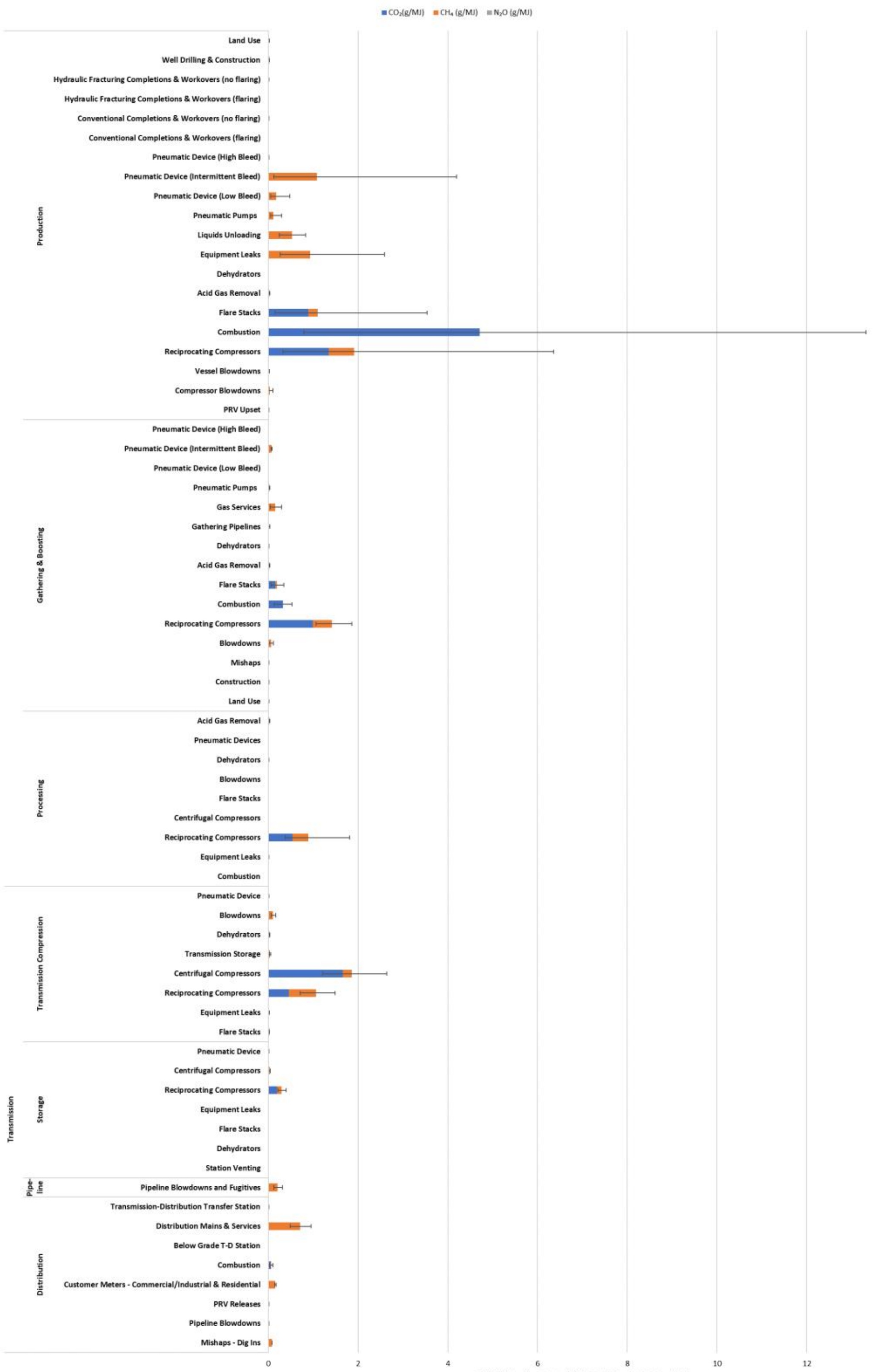


Exhibit H-2. ONE Future 100-yr GWP Results for Appalachian Basin (Eastern Overthrust Area) Scenario

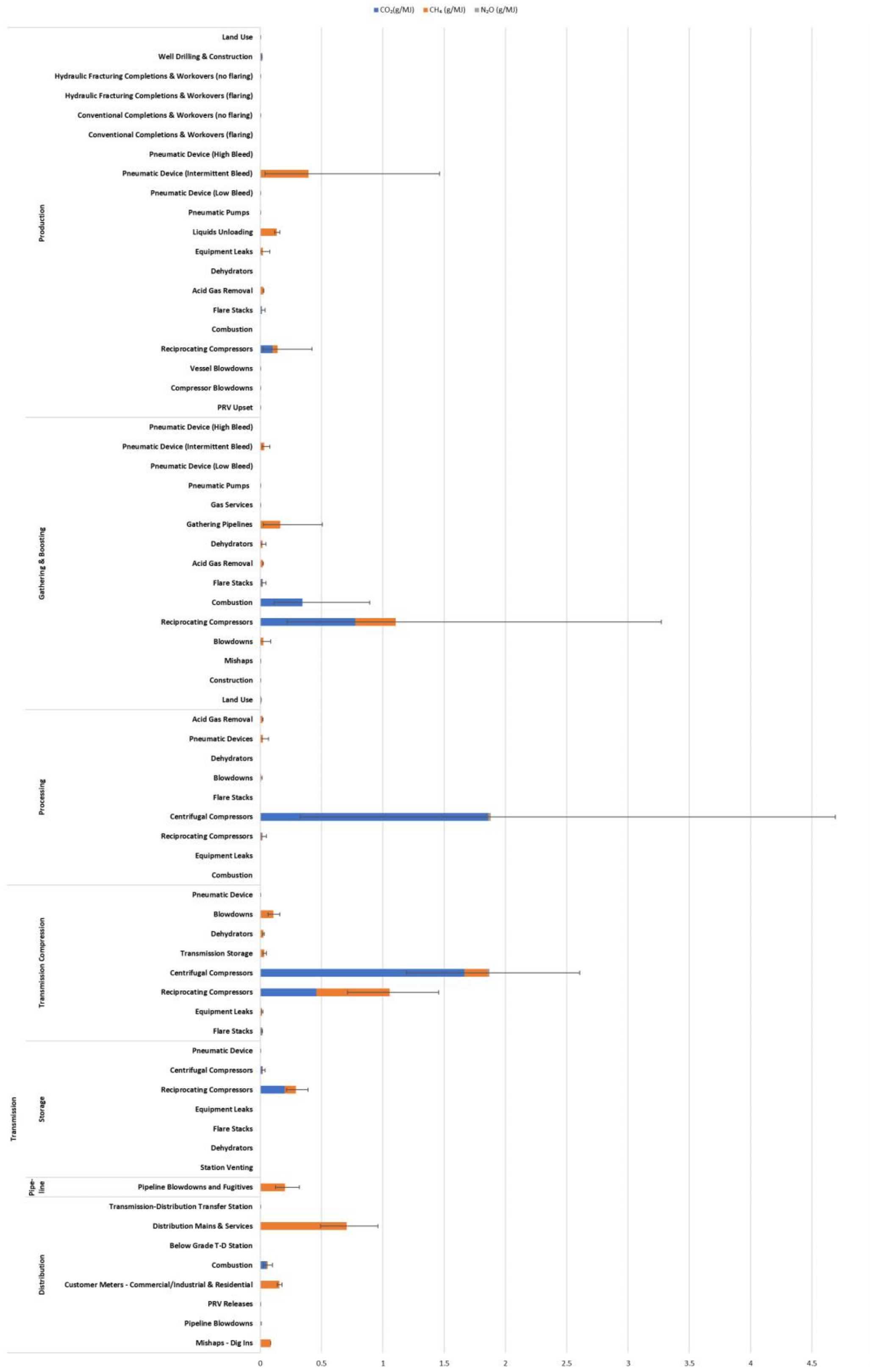


Exhibit H-3. ONE Future 100-yr GWP Results for Permian Basin Scenario

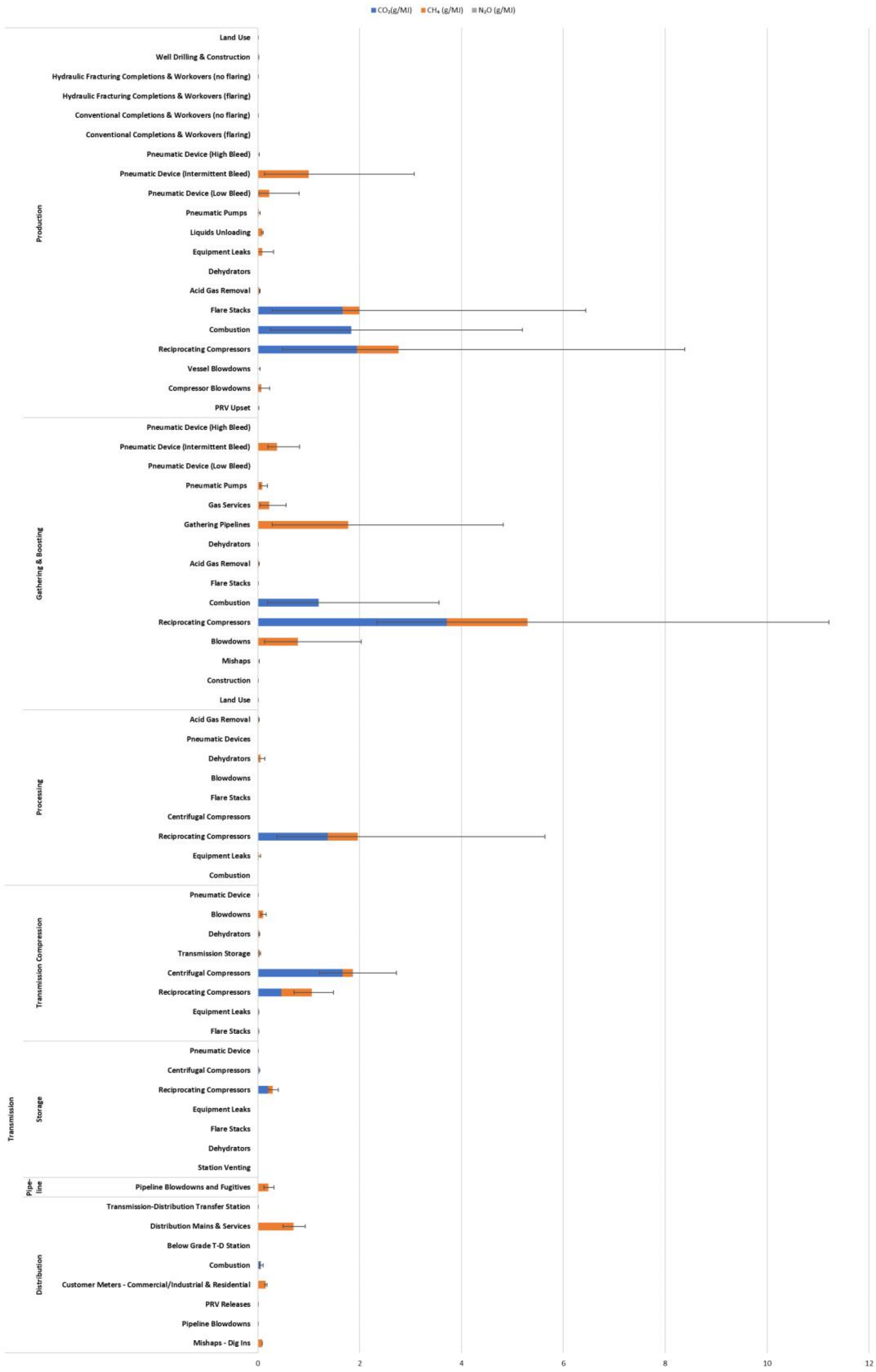


Exhibit H-4. ONE Future 100-yr GWP Results for Williston Basin Scenario

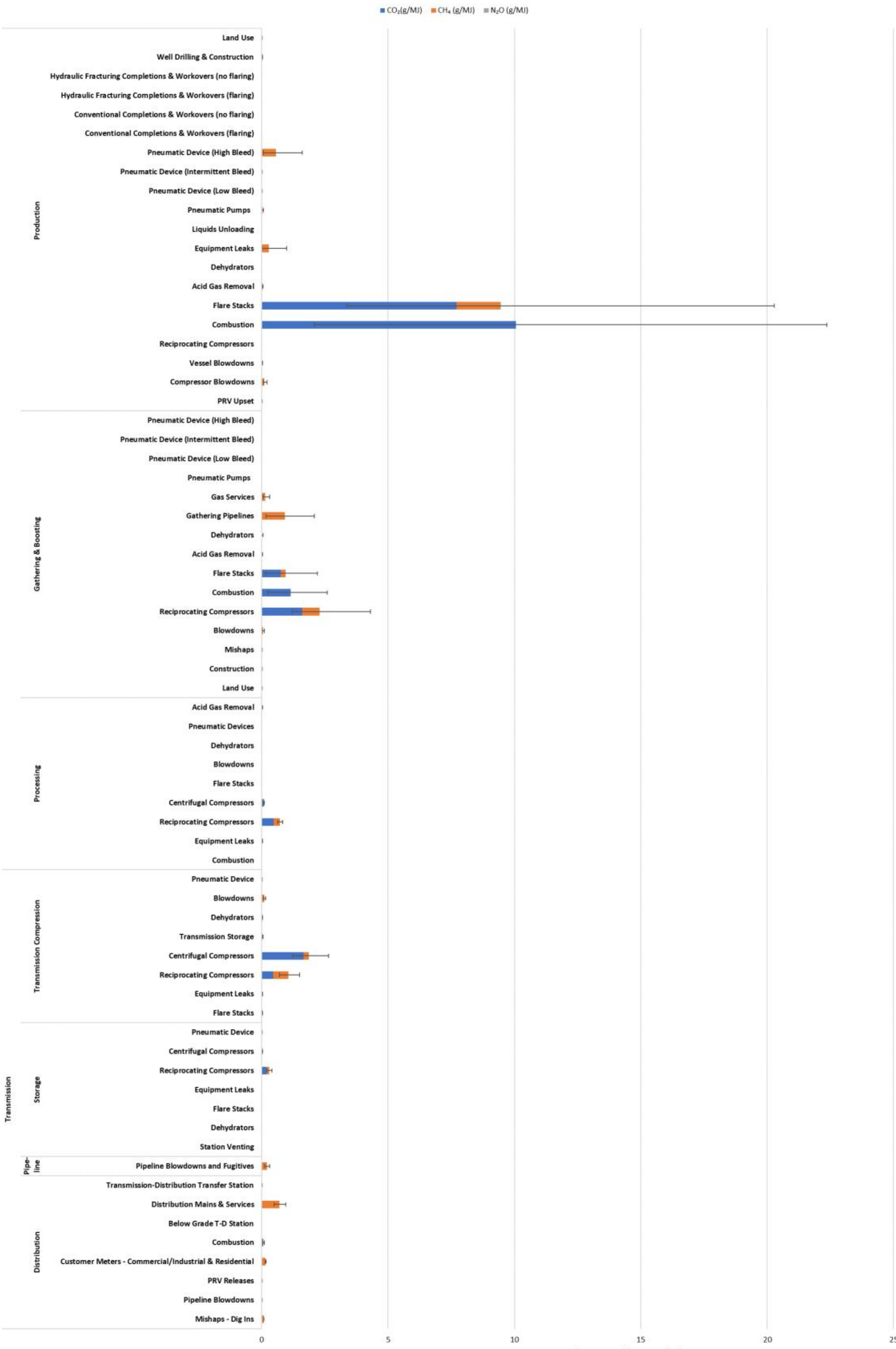


Exhibit H-5. ONE Future 100-yr GWP Results for Arkoma Scenario

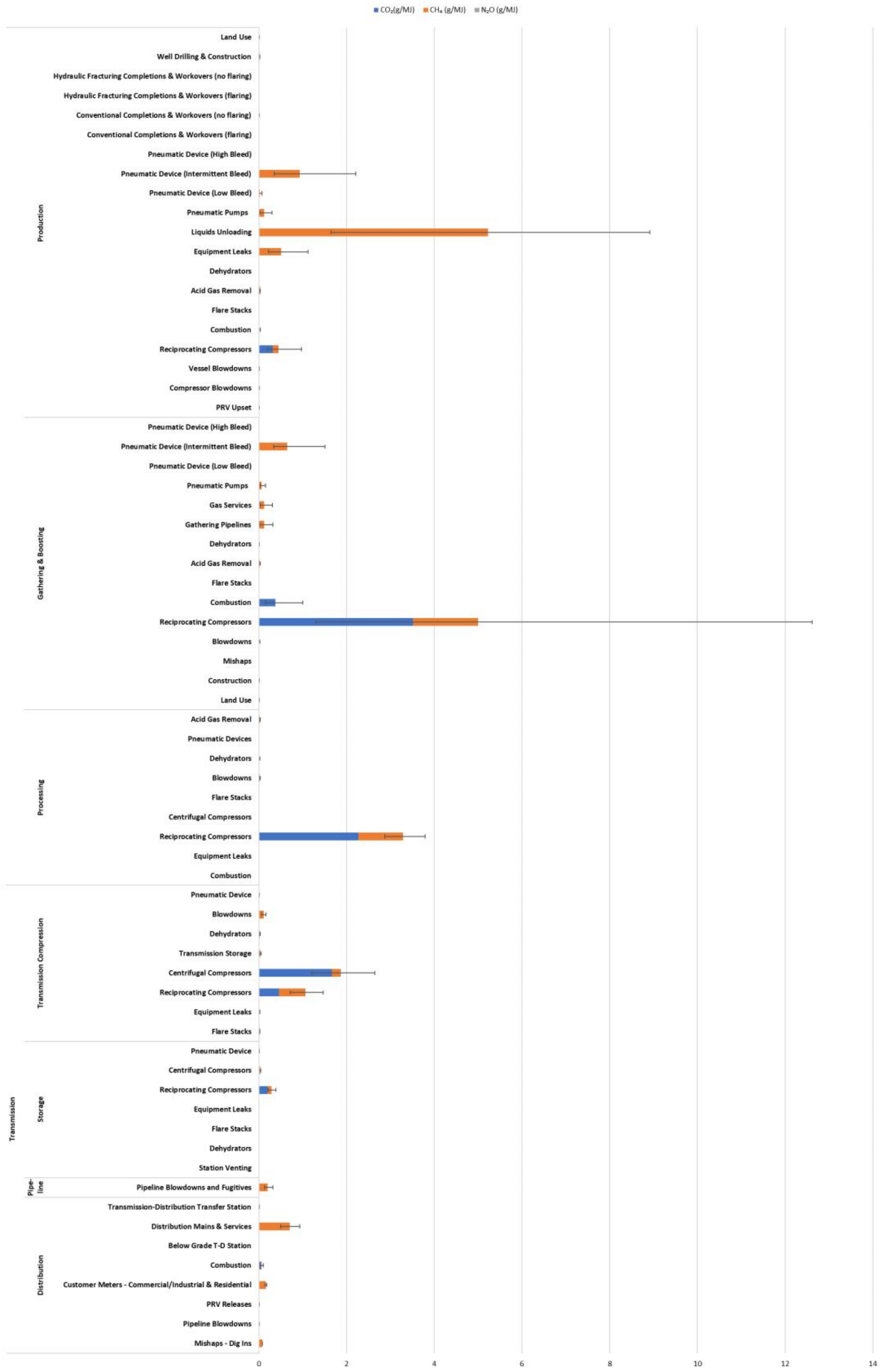


Exhibit H-6. ONE Future 100-yr GWP Results for Massachusetts Scenario

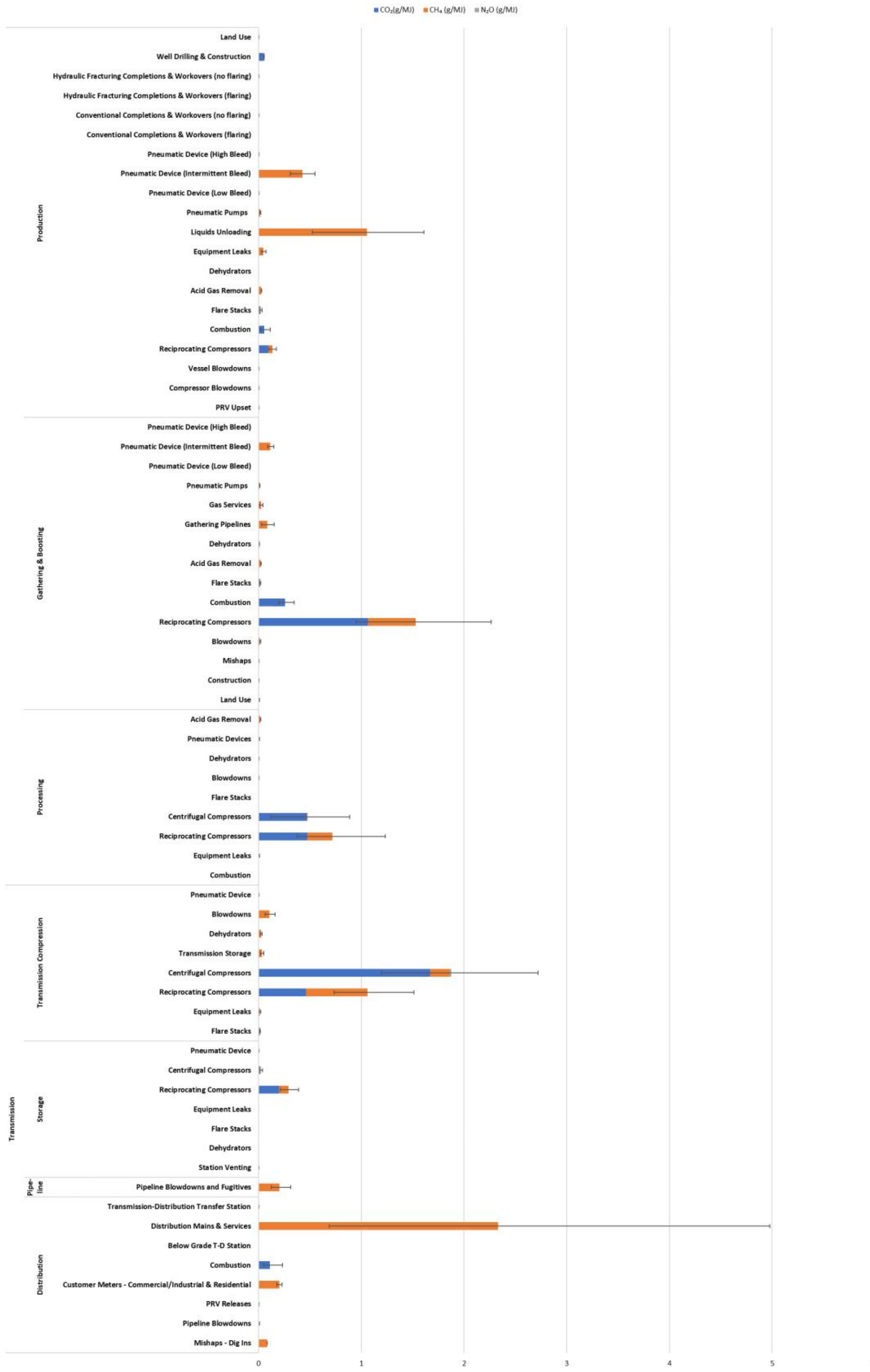


Exhibit H-7. ONE Future 100-yr GWP Results for New York Scenario

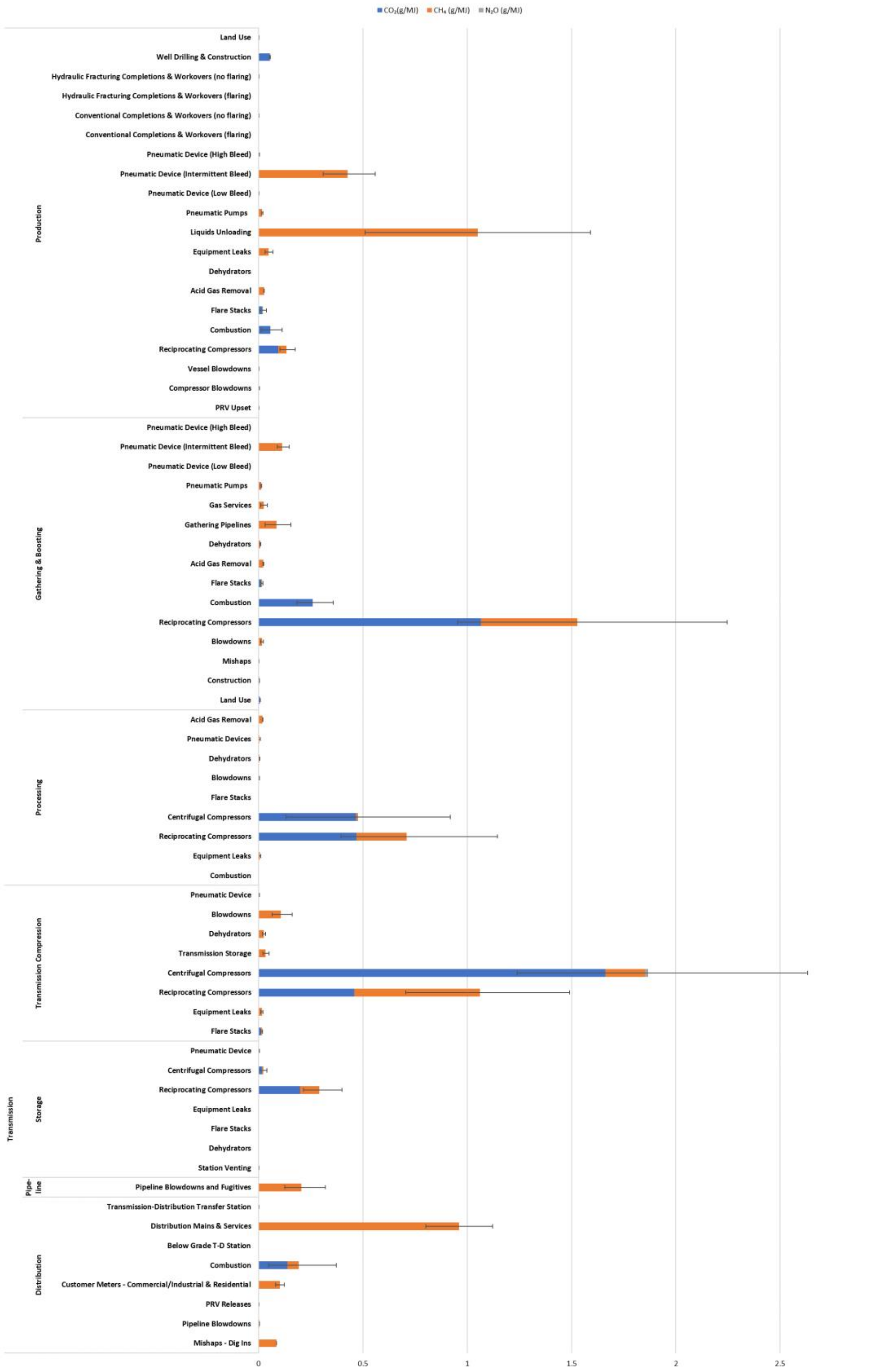


Exhibit H-8. ONE Future 100-yr GWP Results for Ohio Scenario

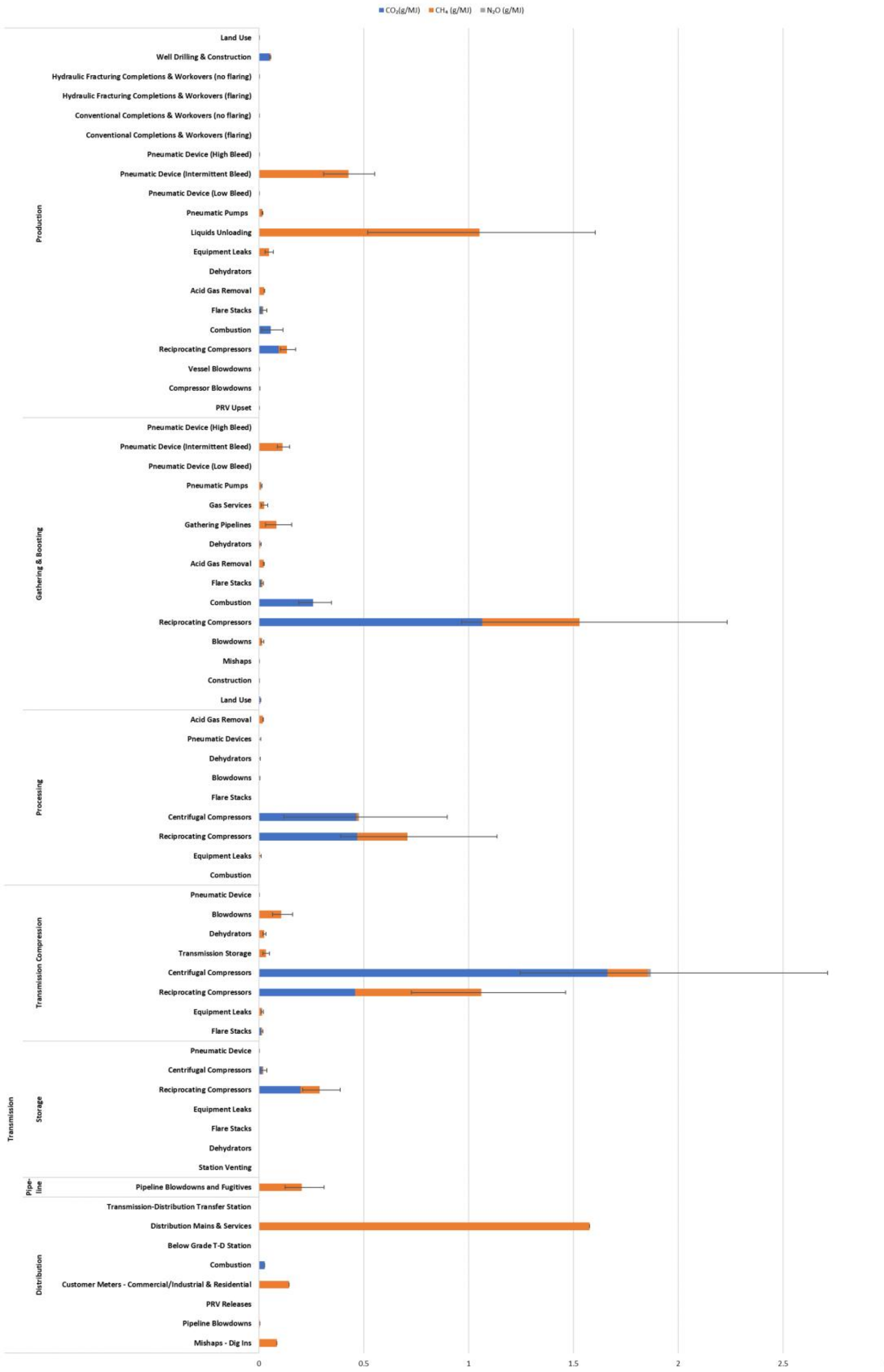


Exhibit H-9. ONE Future 100-yr GWP Results for Florida Scenario

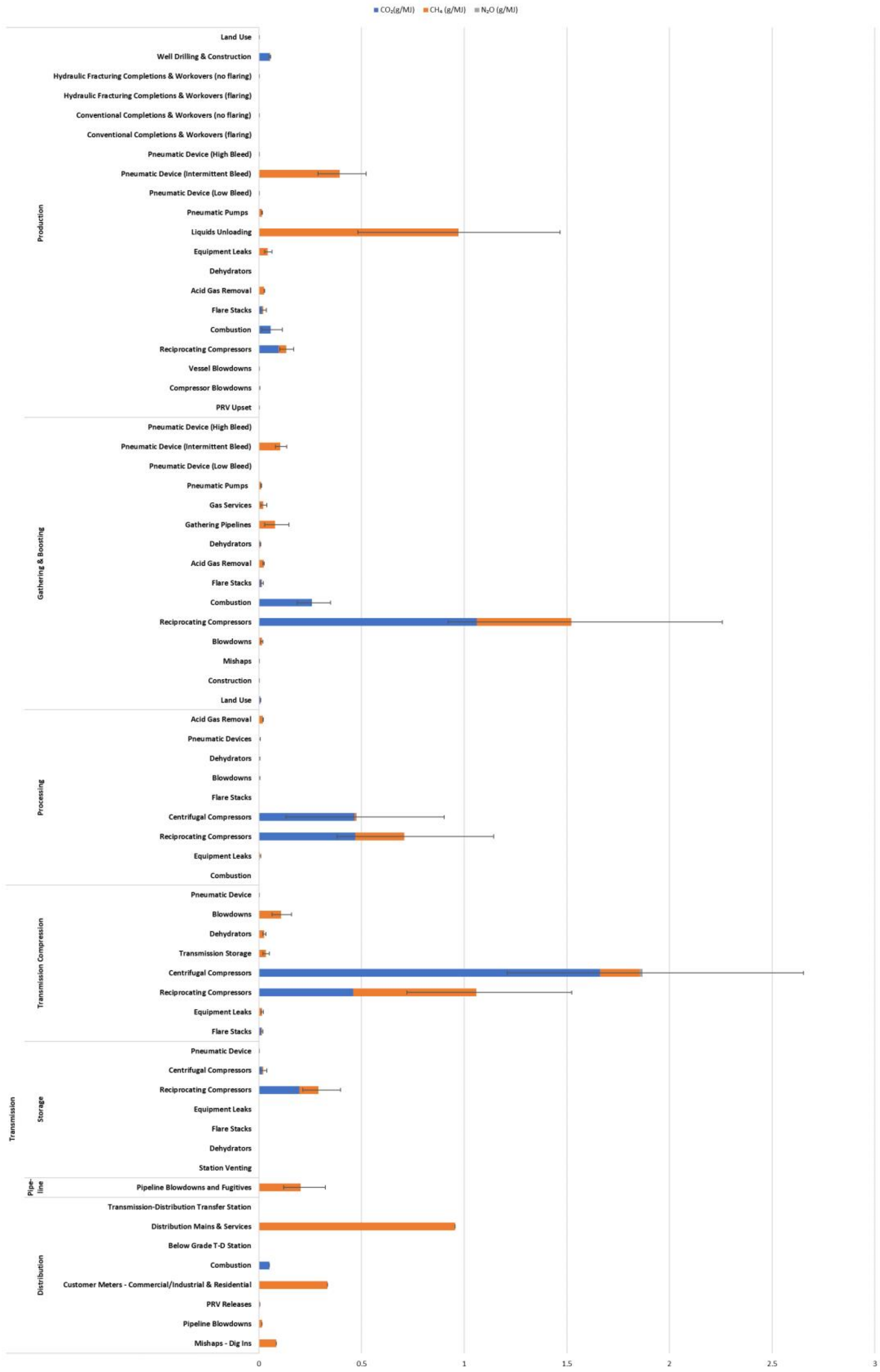


Exhibit H-10. ONE Future 100-yr GWP Results for Missouri Scenario

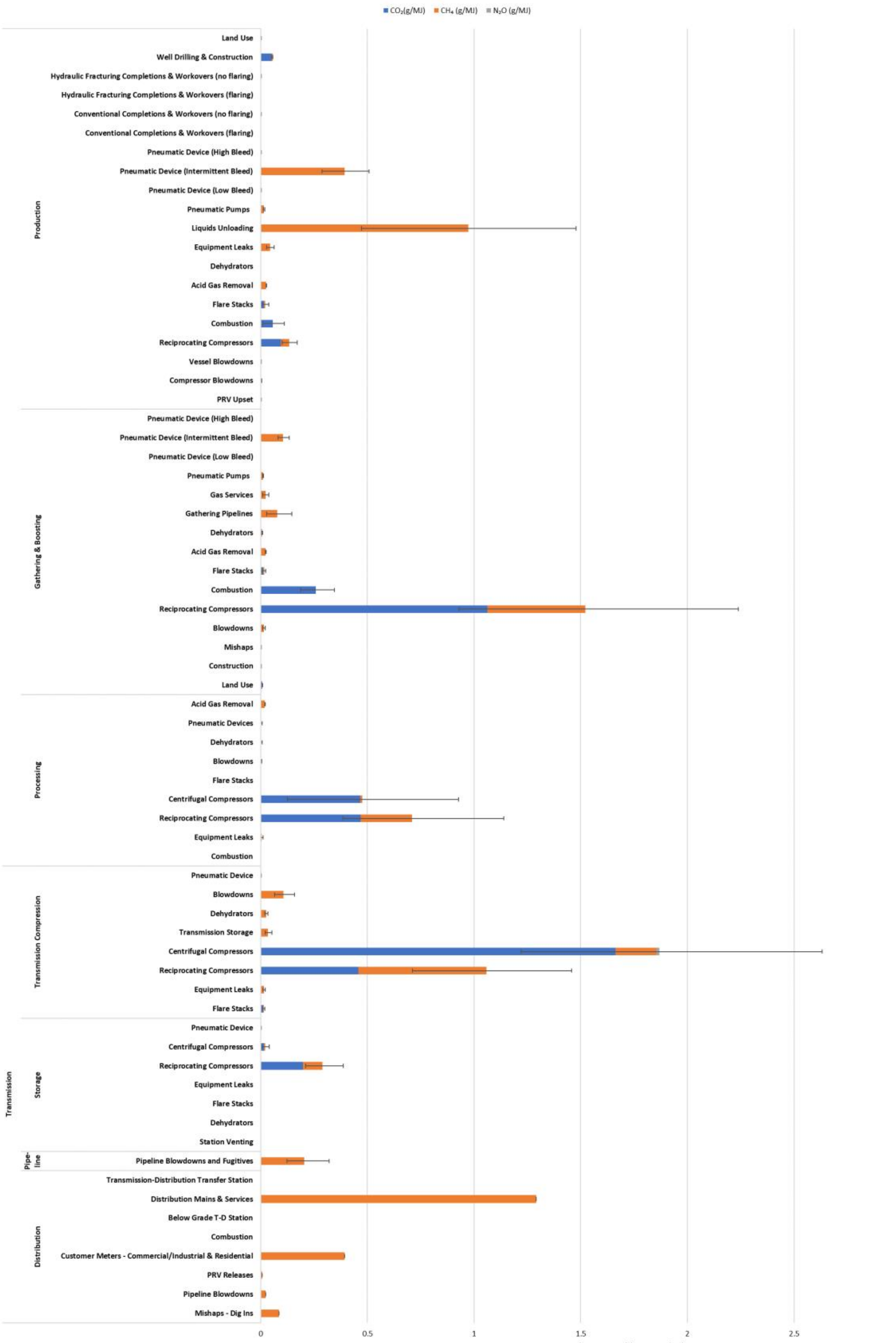


Exhibit H-11. ONE Future 100-yr GWP Results for Arkansas Scenario

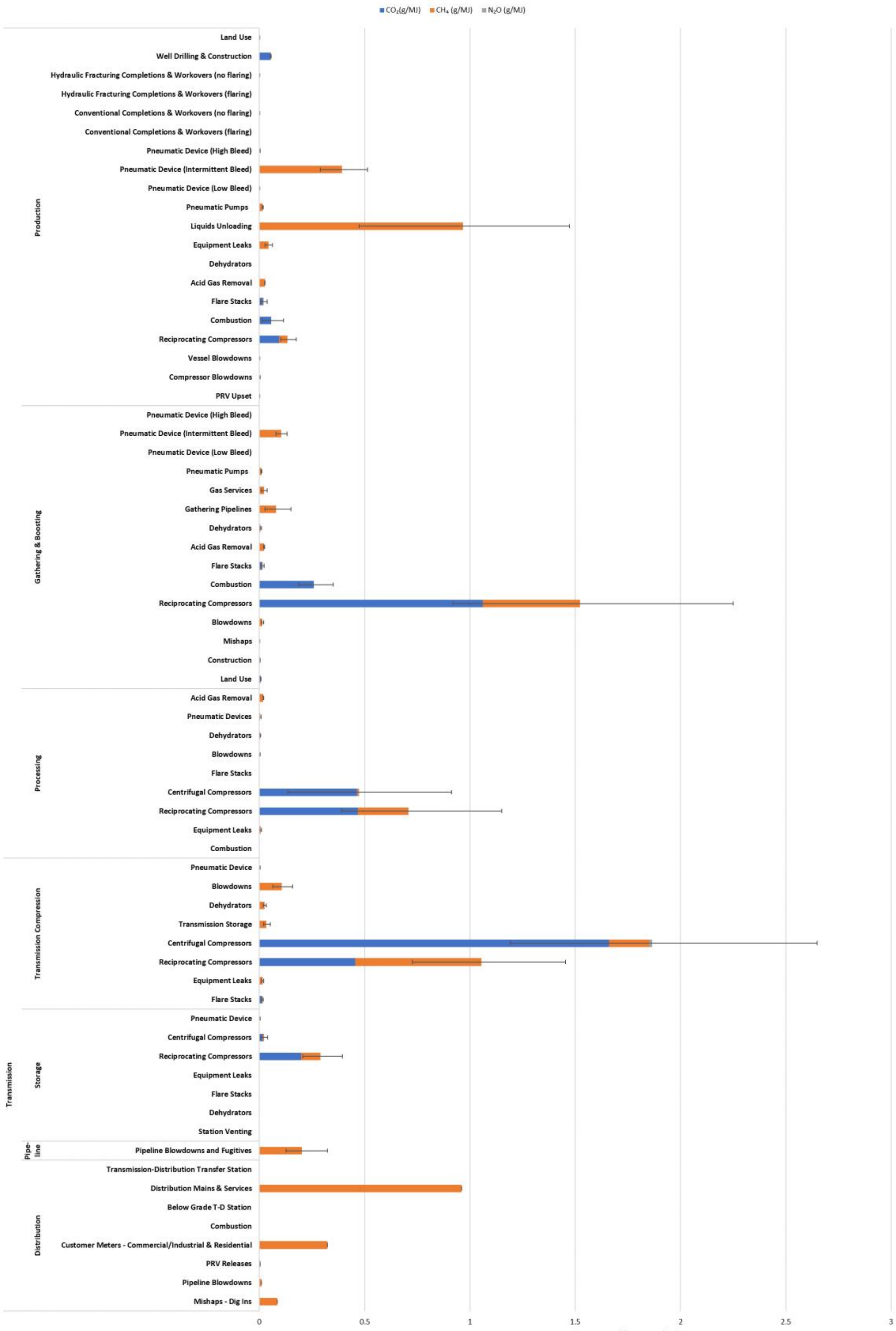


Exhibit H-12. ONE Future 100-yr GWP Results for Maryland Scenario

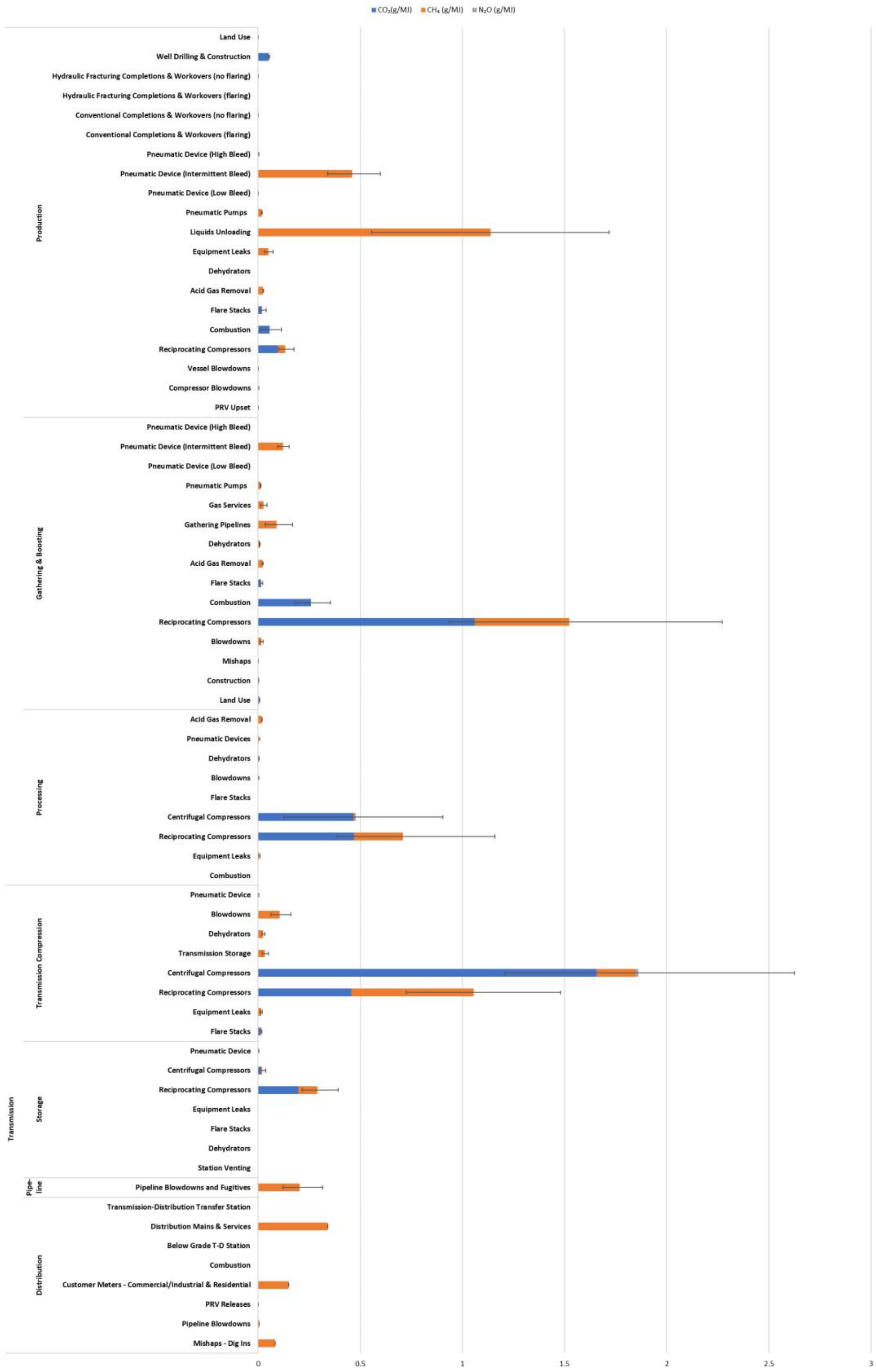


Exhibit H-13. ONE Future 100-yr GWP Results for Tennessee Scenario

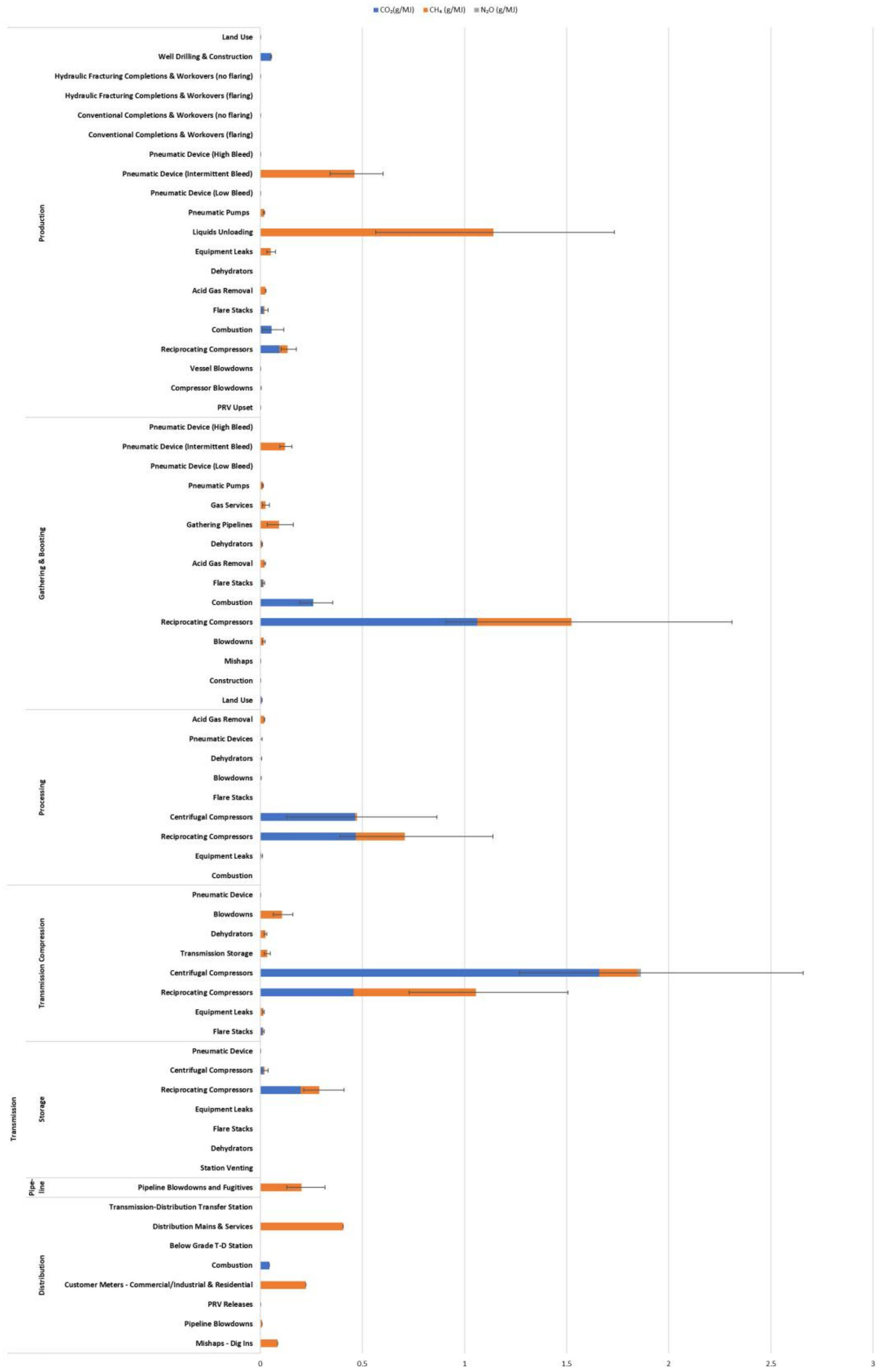


Exhibit H-14. ONE Future 100-yr GWP Results for Utah Scenario

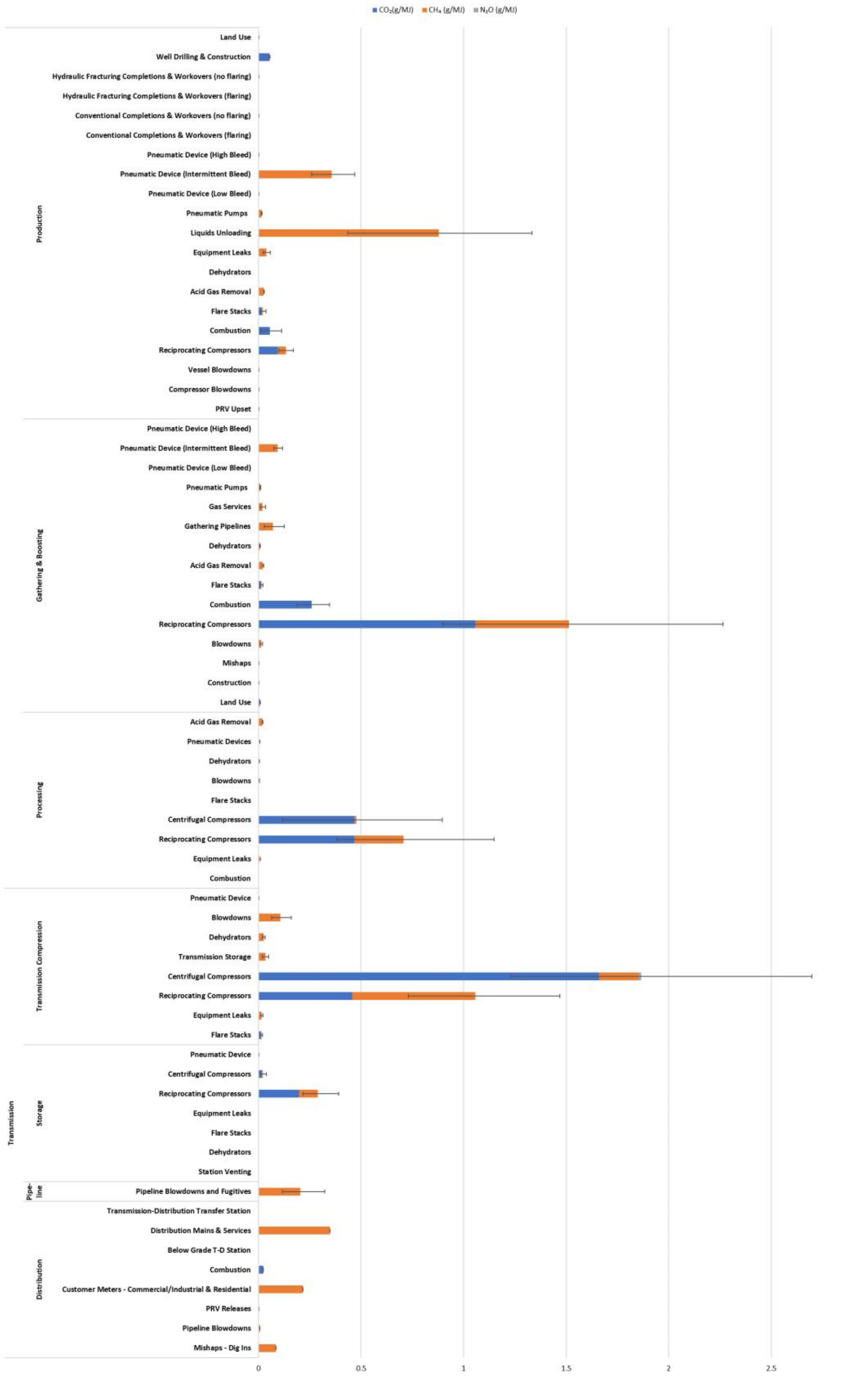


Exhibit H-15. ONE Future 100-yr GWP Results for Colorado Scenario

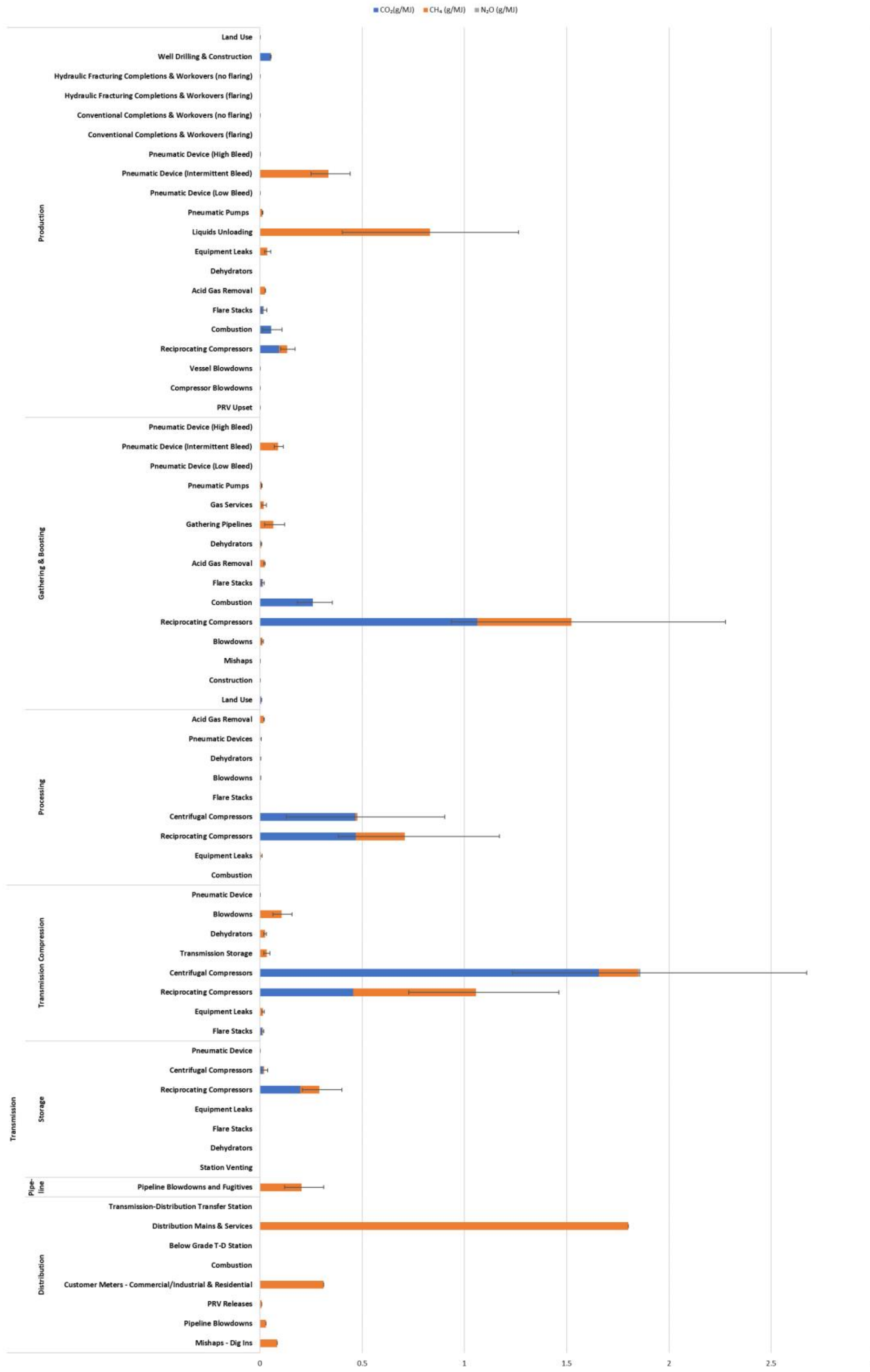


Exhibit H-16. ONE Future 100-yr GWP Results for Illinois Scenario

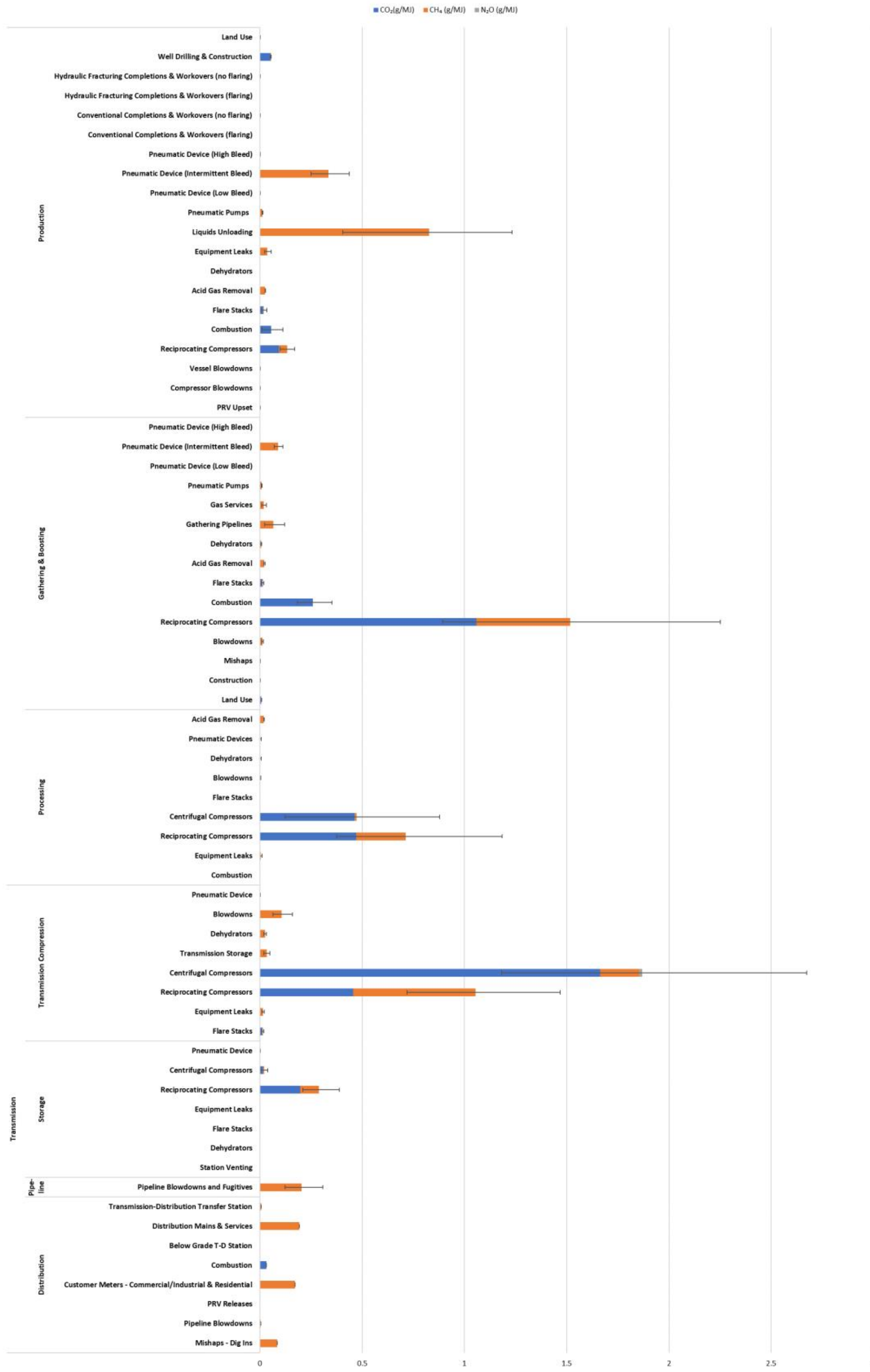


Exhibit H-17. ONE Future 100-yr GWP Results for New Jersey Scenario

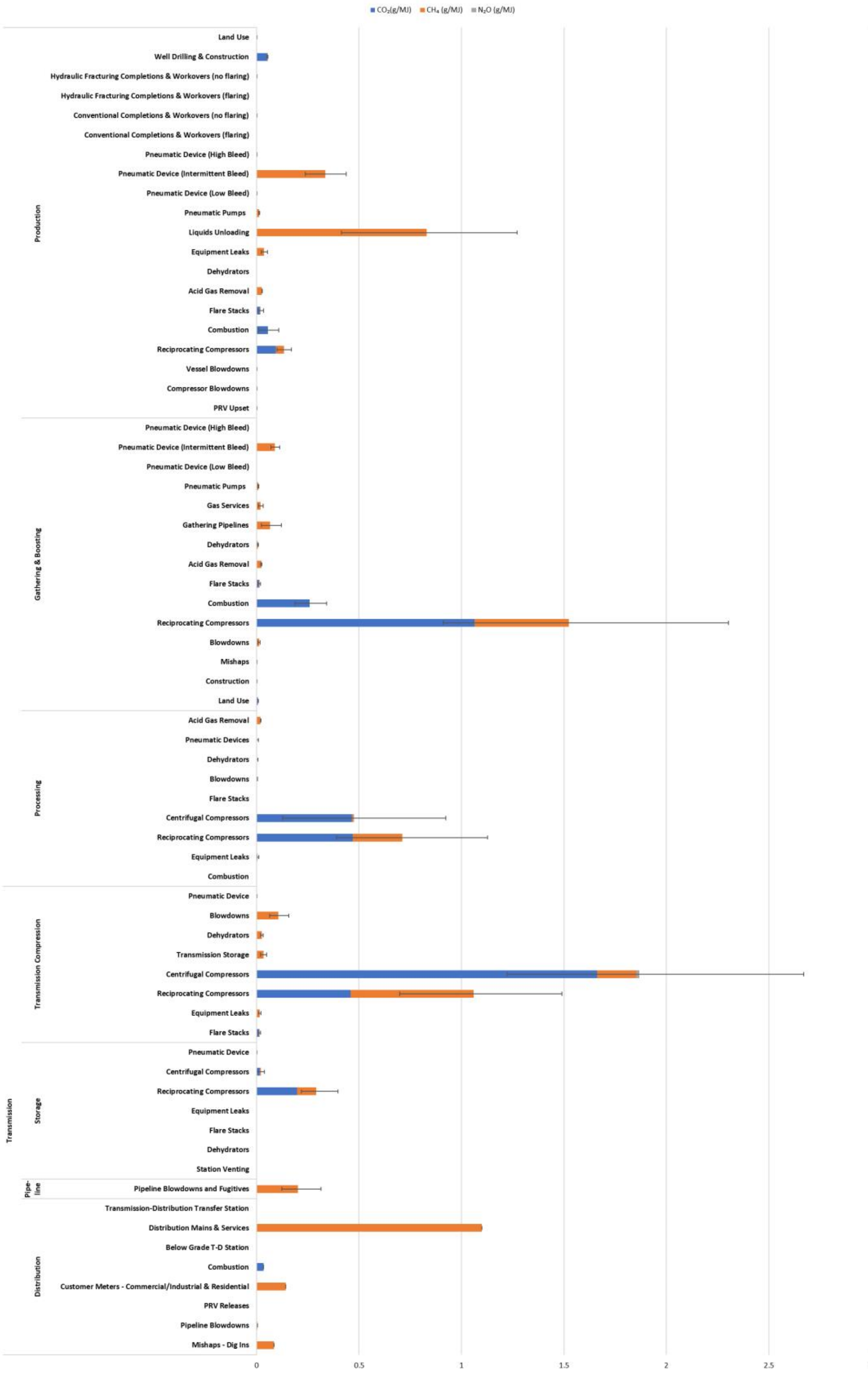


Exhibit H-18. ONE Future 100-yr GWP Results for Oklahoma Scenario

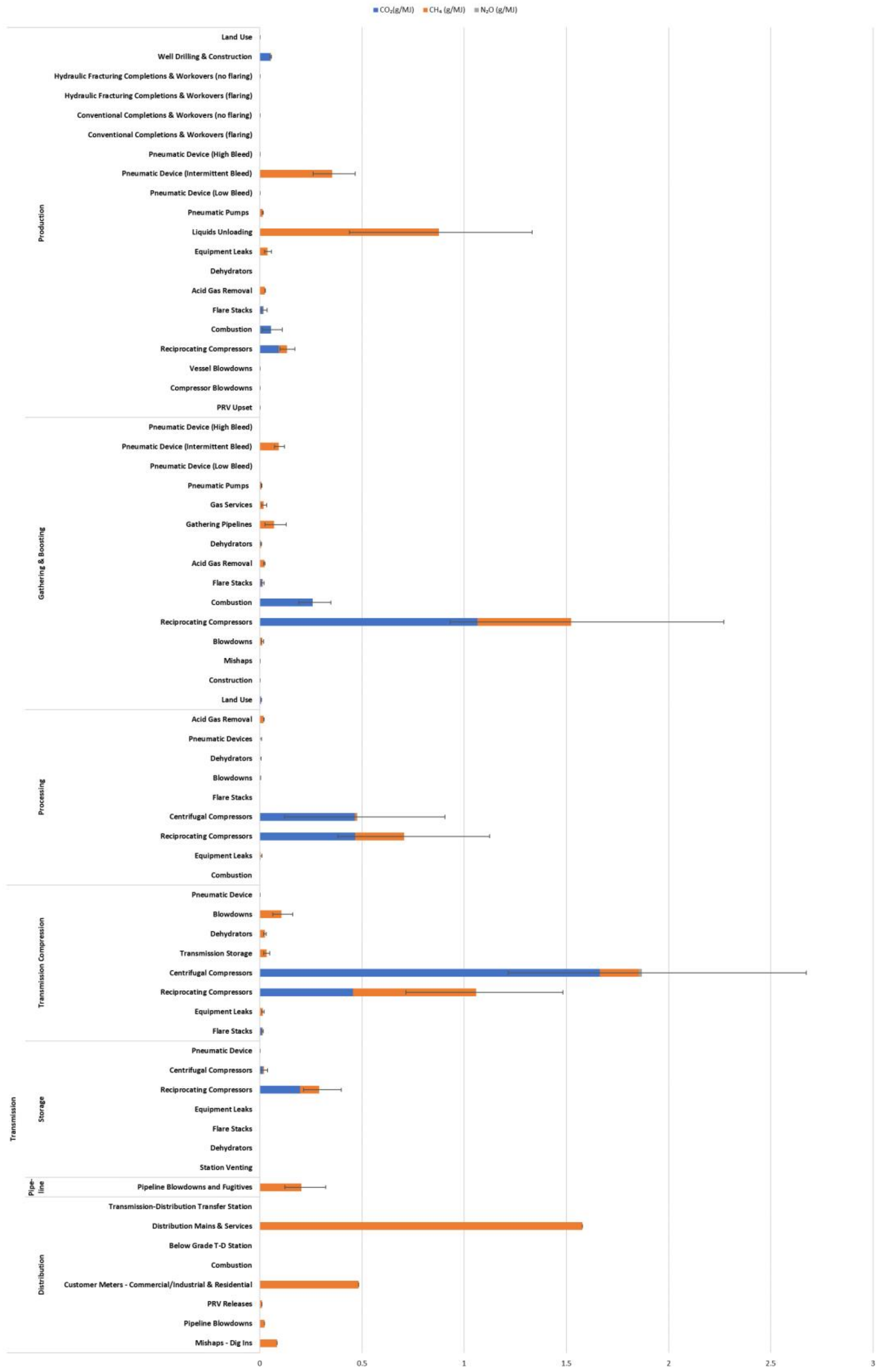


Exhibit H-19. ONE Future 100-yr GWP Results for Maine Scenario

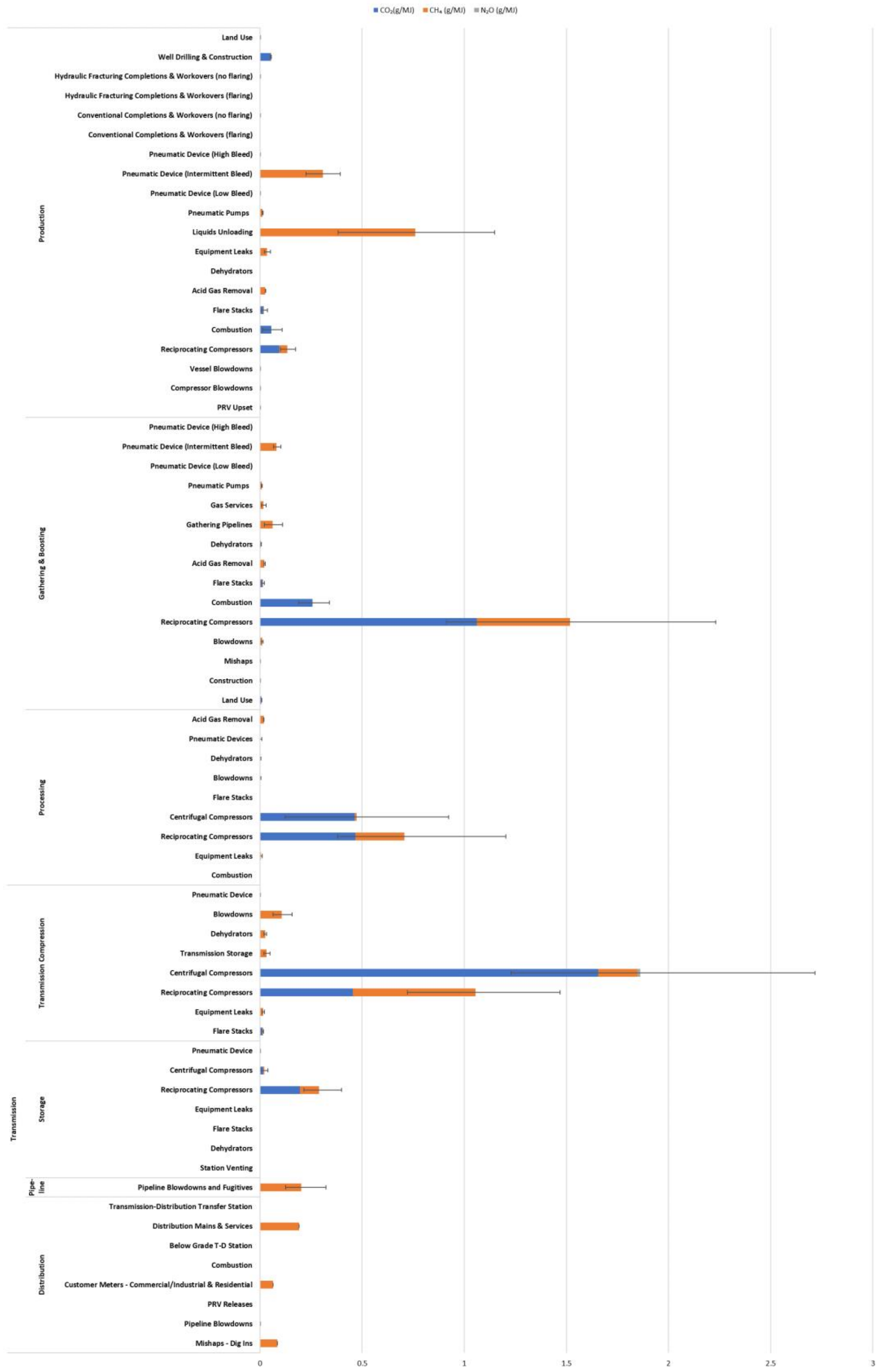


Exhibit H-20. ONE Future 100-yr GWP Results for Rhode Island Scenario

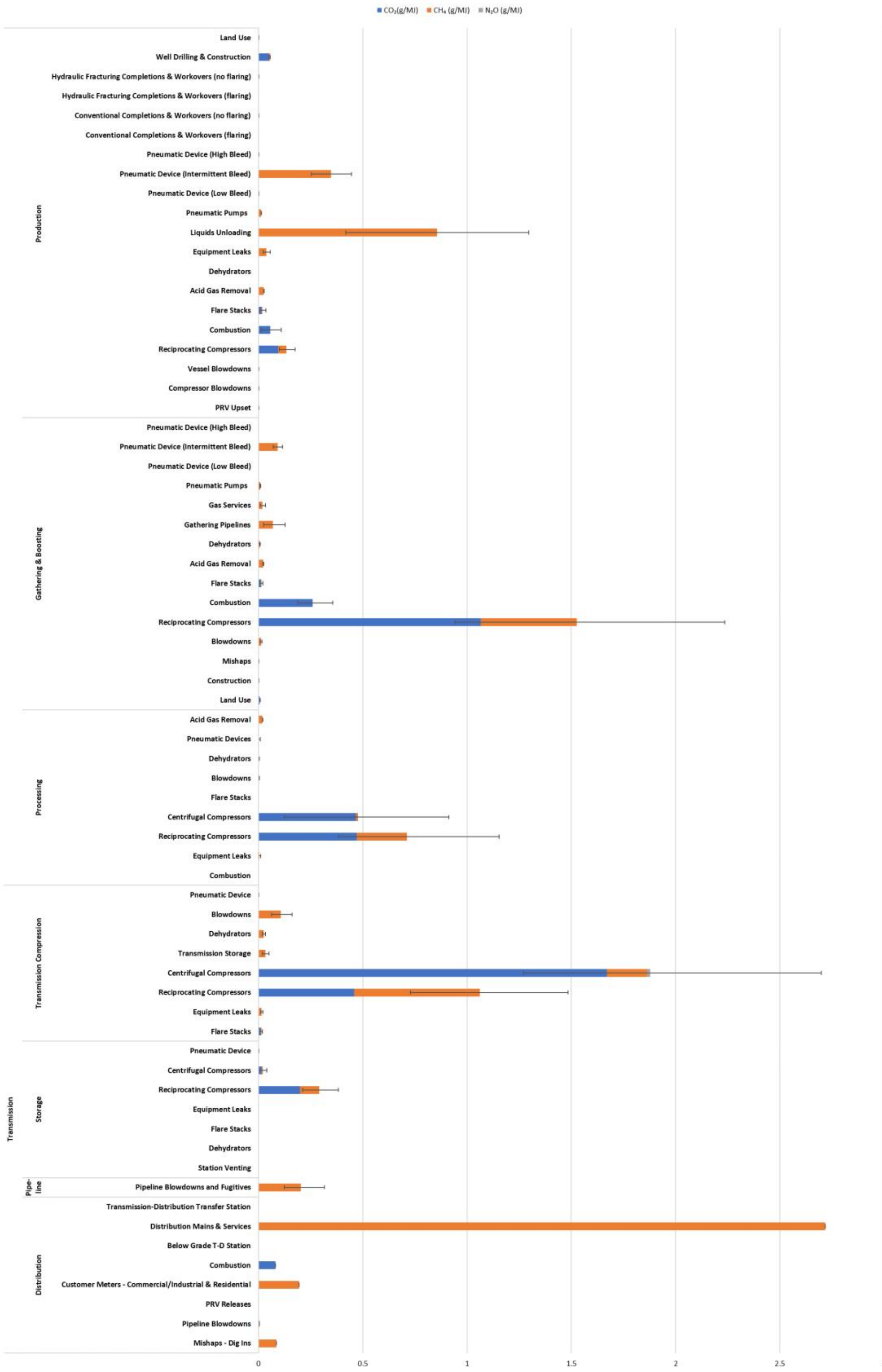


Exhibit H-21. ONE Future 100-yr GWP Results for Virginia Scenario

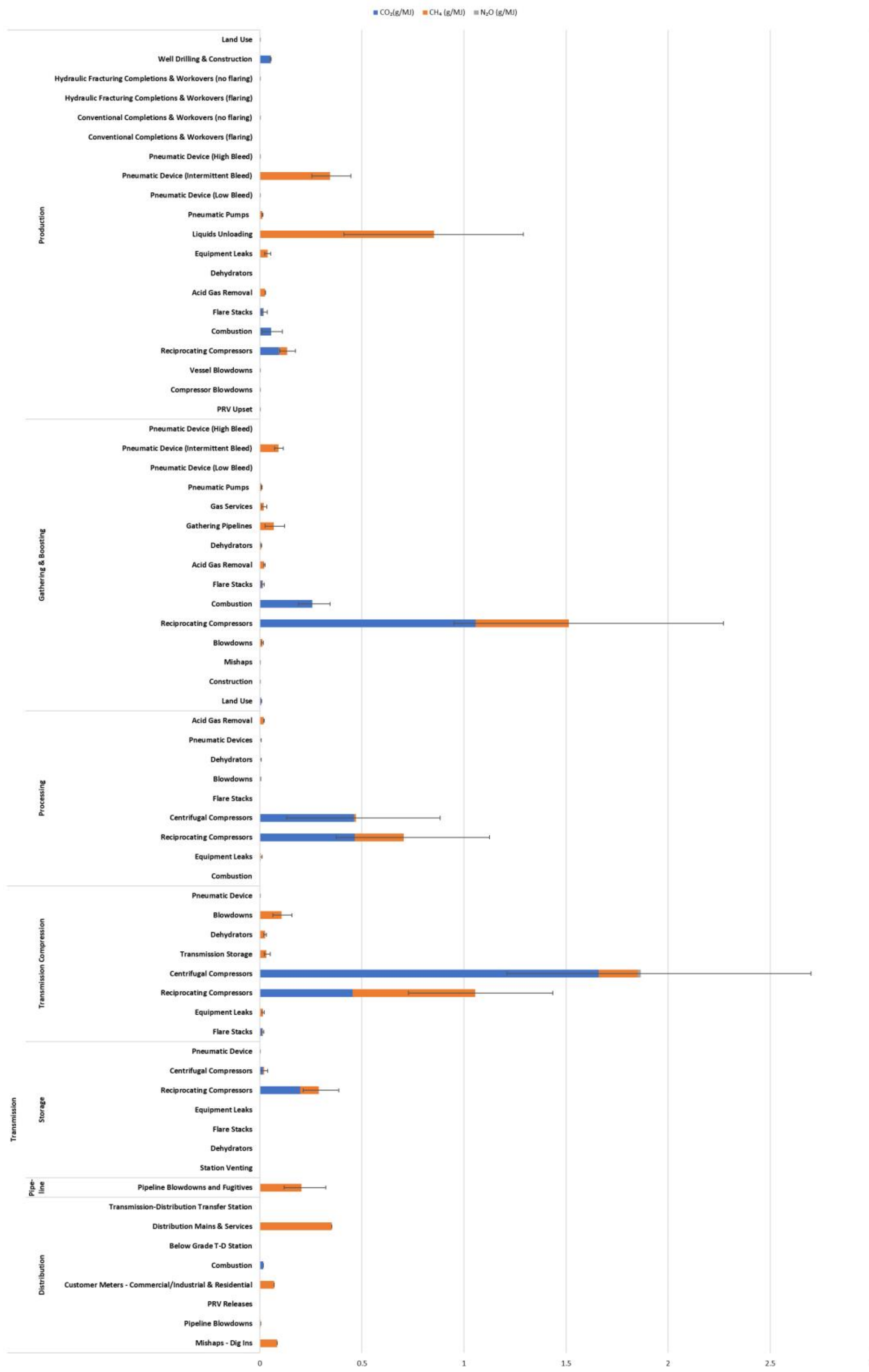


Exhibit H-22. ONE Future 100-yr GWP Results for Georgia Scenario

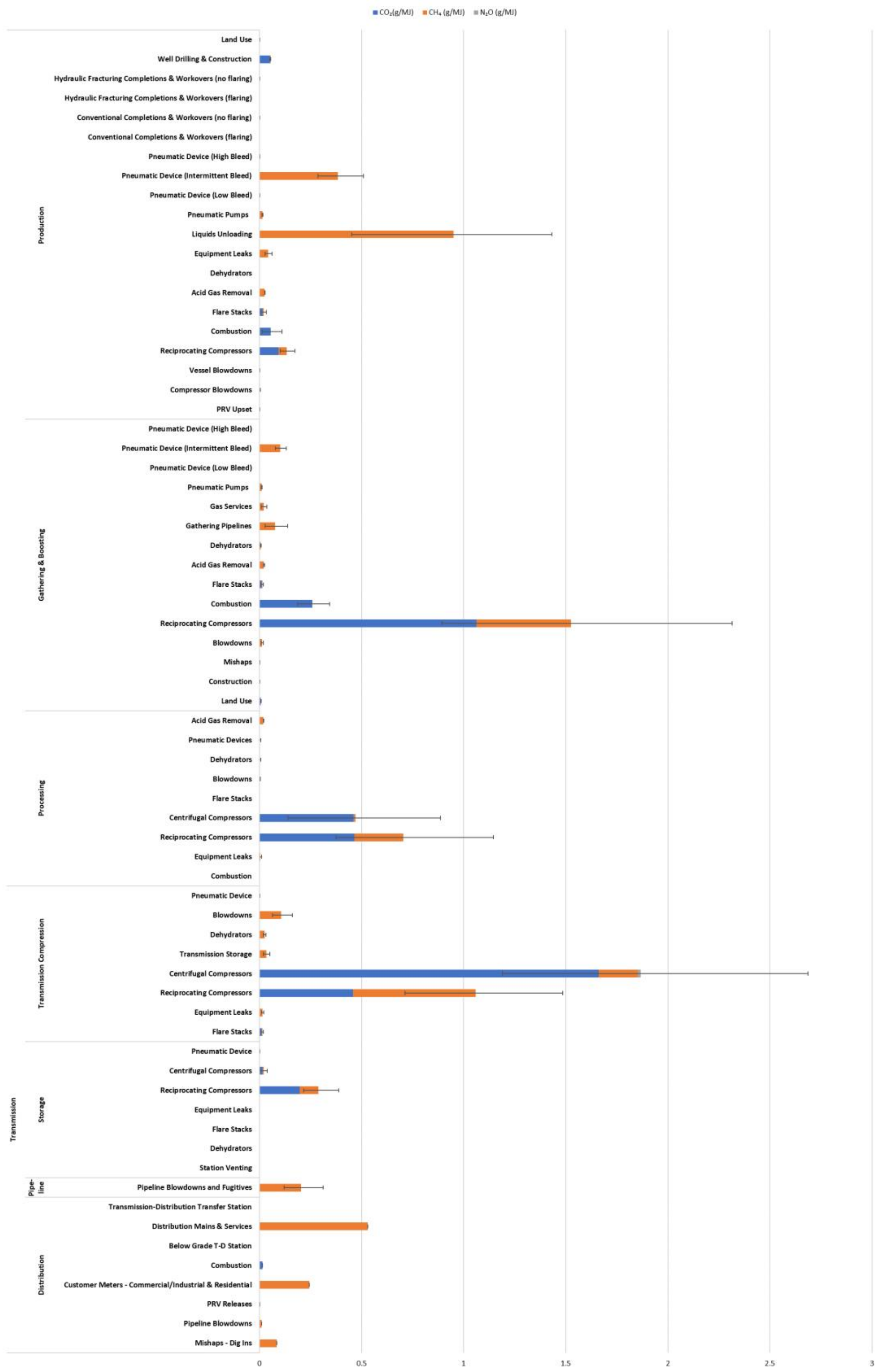


Exhibit H-23. ONE Future 100-yr GWP Results for West Virginia Scenario

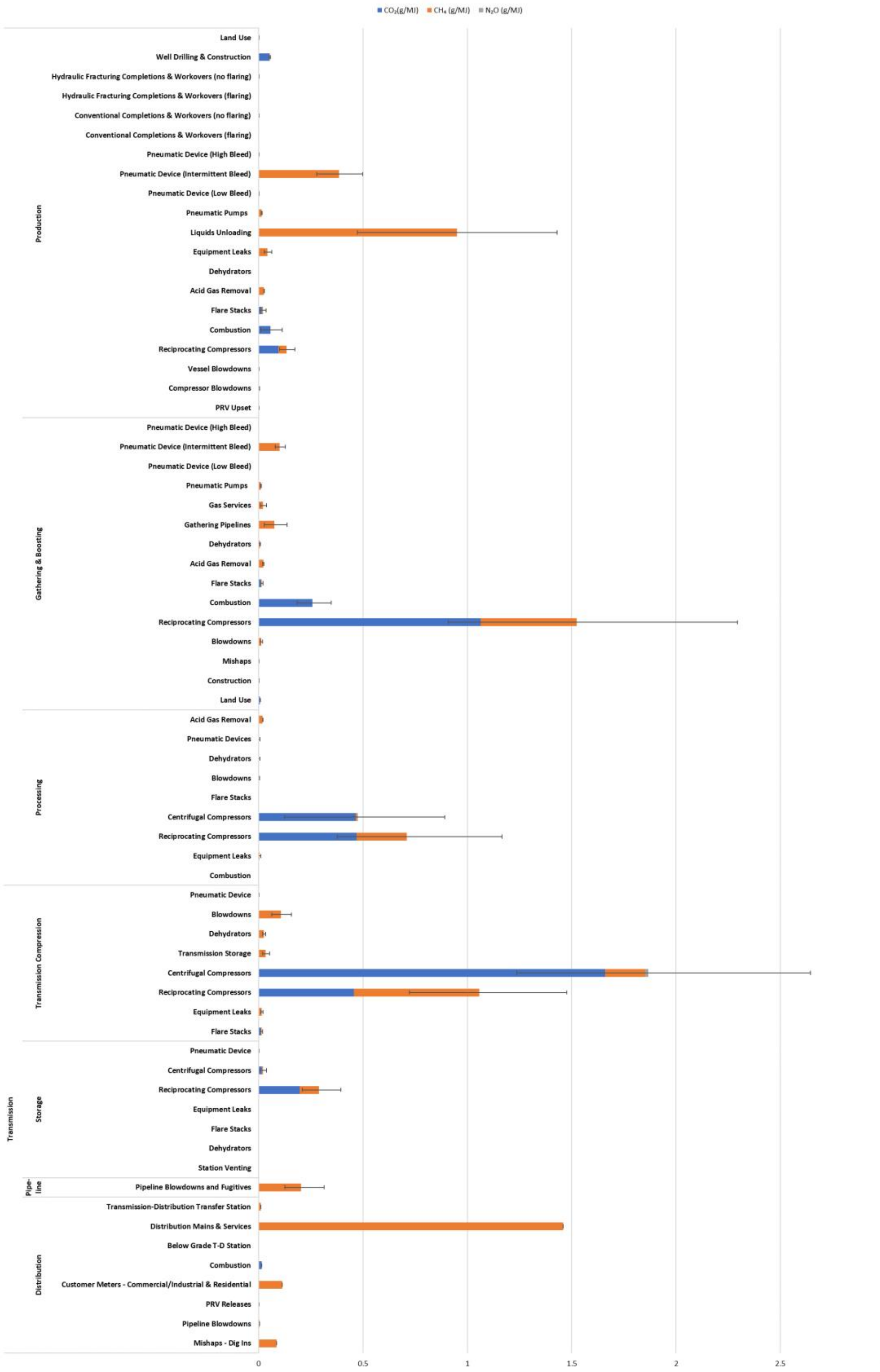


Exhibit H-24. Life Cycle GHG Emissions for all ONE Future Scenarios (100-year CO_2-eq)

Scenario	Mean CO_2-eq for Specific GHGs			Total CO_2-eq (IPCC AR5, 100-yr GWP)		
	CO_2	CH_4	N_2O	P2.5	Expected	P97.5
Gulf Coast Basin (LA TX)	11.39	7.10	0.02	7.04	18.50	43.45
Appalachian Basin (Eastern Overthrust Area)	5.59	3.53	0.03	4.15	9.16	18.64
Permian Basin	14.16	10.47	0.02	8.14	24.65	60.43
Williston Basin	24.23	7.36	0.02	11.47	31.60	64.82
Arkoma Basin	8.90	12.76	0.01	10.48	21.68	39.94
Massachusetts	4.97	6.57	0.02	6.36	11.56	18.72
New York	4.98	5.13	0.02	6.39	10.13	14.71
Ohio	4.87	5.74	0.02	7.25	10.63	14.84
Florida	4.89	5.18	0.02	6.68	10.09	14.29
Missouri	4.84	5.58	0.02	7.04	10.44	14.54
Arkansas	4.83	5.16	0.02	6.62	10.00	14.17
Maryland	4.83	4.65	0.02	6.00	9.50	13.79
Tennessee	4.87	4.80	0.02	6.27	9.69	14.05
Utah	4.85	4.28	0.02	5.82	9.15	13.27
Colorado	4.83	5.78	0.02	7.38	10.63	14.73
Illinois	4.86	3.99	0.02	5.52	8.88	12.91
New Jersey	4.87	4.87	0.02	6.46	9.76	13.87
Oklahoma	4.84	5.80	0.02	7.34	10.66	14.77
Maine	4.82	3.76	0.02	5.39	8.60	12.69
Rhode Island	4.94	6.59	0.02	8.30	11.55	15.62
Virginia	4.84	4.08	0.02	5.67	8.94	12.97
Georgia	4.84	4.62	0.02	6.05	9.48	13.68
West Virginia	4.85	5.42	0.02	6.91	10.29	14.44
Average	**4.88**	**4.80**	**0.02**	**6.03**	**9.70**	**14.29**

Exhibit H-25. Life Cycle GHG Emissions for all ONE Future Scenarios (20-year CO_2-eq)

Scenario	Mean CO_2-eq for Specific GHGs			Total CO_2-eq (IPCC AR5, 20-yr GWP)		
	CO_2	CH_4	N_2O	P2.5	Expected	P97.5
Gulf Coast Basin (LA TX)	11.39	17.15	0.01	11.50	28.56	66.19
Appalachian Basin (Eastern Overthrust Area)	5.59	8.54	0.03	6.89	14.16	28.30
Permian Basin	14.16	25.30	0.01	13.25	39.48	95.81
Williston Basin	24.23	17.78	0.02	16.17	42.02	85.16
Arkoma Basin	8.90	30.85	0.01	18.56	39.76	72.91
Massachusetts	4.97	15.88	0.02	11.15	20.87	34.40
New York	4.98	12.40	0.02	11.17	17.40	24.84
Ohio	4.87	13.87	0.02	13.25	18.76	25.47
Florida	4.89	12.52	0.02	11.95	17.42	24.11
Missouri	4.84	13.49	0.02	12.85	18.35	24.85
Arkansas	4.83	12.46	0.02	11.86	17.31	23.91
Maryland	4.83	11.24	0.02	10.35	16.08	22.98
Tennessee	4.87	11.60	0.02	10.84	16.49	23.49
Utah	4.85	10.33	0.02	9.90	15.20	21.66
Colorado	4.83	13.96	0.02	13.64	18.81	25.20
Illinois	4.86	9.65	0.02	9.24	14.53	20.80
New Jersey	4.87	11.77	0.02	11.42	16.66	23.05
Oklahoma	4.84	14.02	0.02	13.59	18.87	25.33
Maine	4.82	9.07	0.02	8.87	13.91	20.19
Rhode Island	4.94	15.93	0.02	15.69	20.89	27.24
Virginia	4.84	9.86	0.02	9.51	14.72	21.01
Georgia	4.84	11.16	0.02	10.50	16.02	22.65
West Virginia	4.85	13.10	0.02	12.53	17.96	24.51
Average	**4.88**	**11.61**	**0.02**	**10.40**	**16.50**	**23.96**

APPENDIX I: U.S. GWP RESULTS FOR 2017

TABLE OF CONTENTS

LIST OF EXHIBITS

ACRONYMS AND ABBREVIATIONS

GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
LA	Louisiana
TX	Texas
yr	Year

I-1. U.S. SCENARIO RESULTS: GWP (100-YR)

Exhibit I-1. U.S. 100-yr GWP Results for Appalachian (Eastern Overthrust Area) Shale Scenario

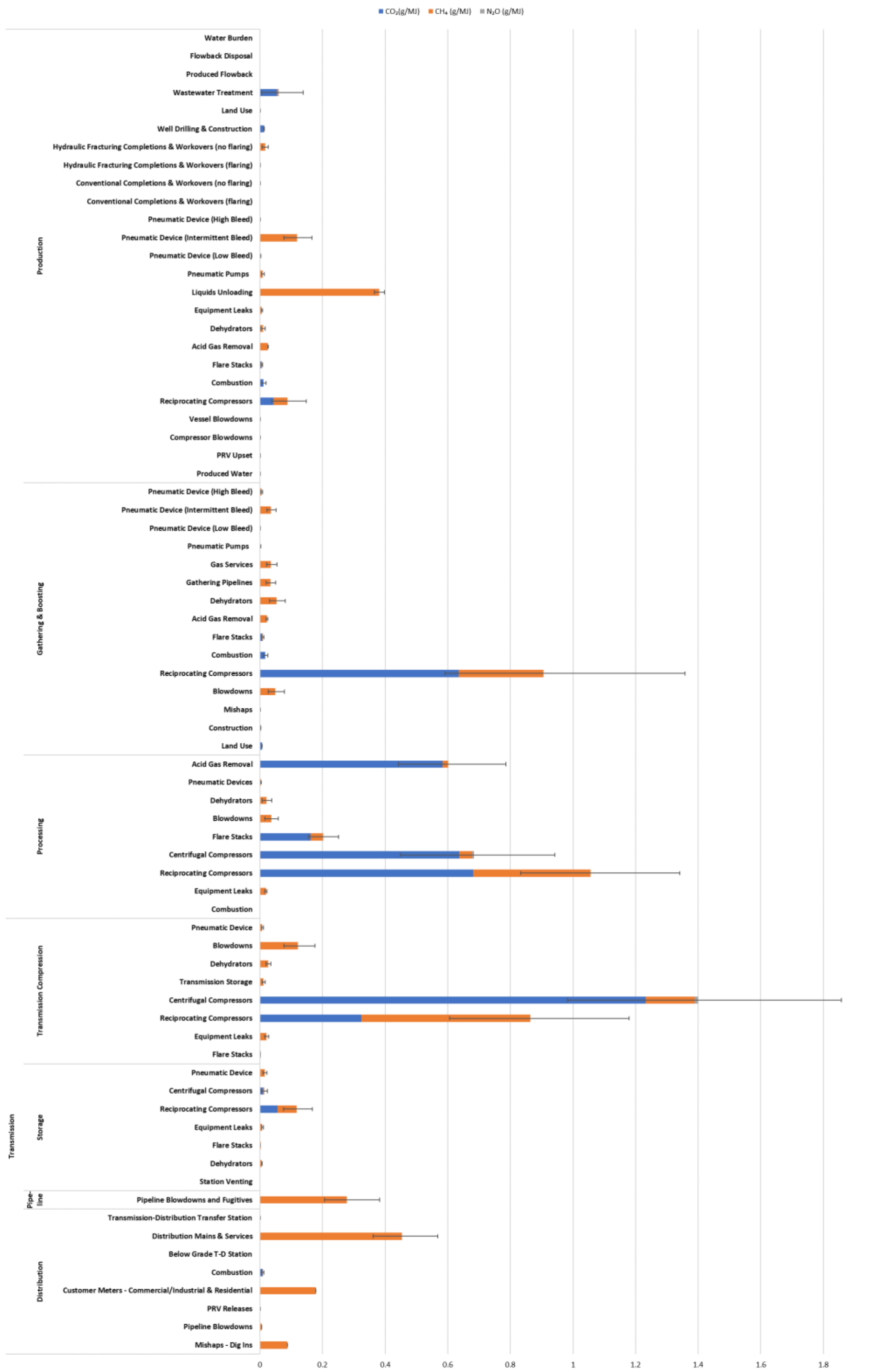


Exhibit I-2. U.S. 100-yr GWP Results for Gulf Coast (LA TX) Conventional Scenario

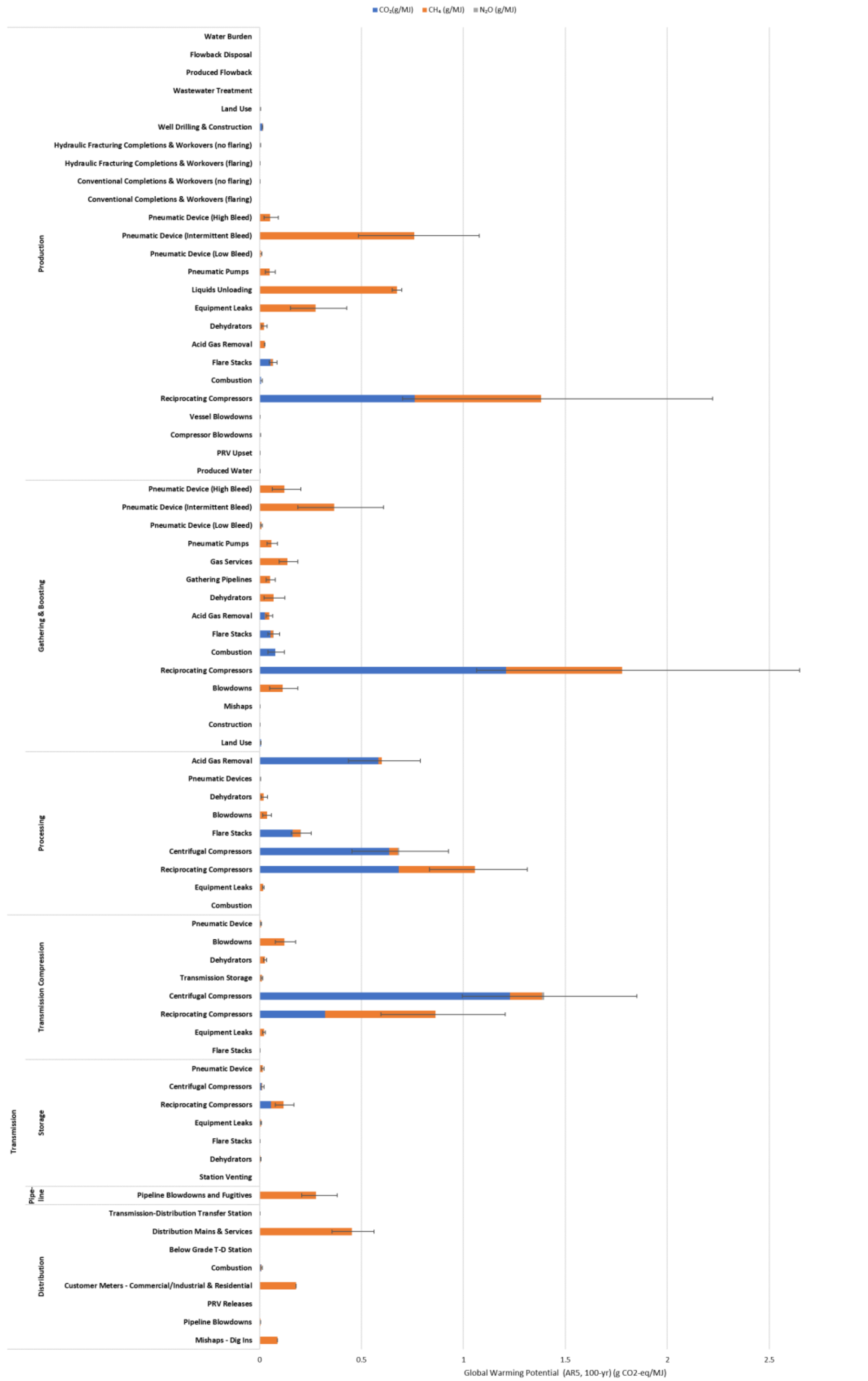


Exhibit I-3. U.S. 100-yr GWP Results for Gulf Coast (LA TX) Shale Scenario

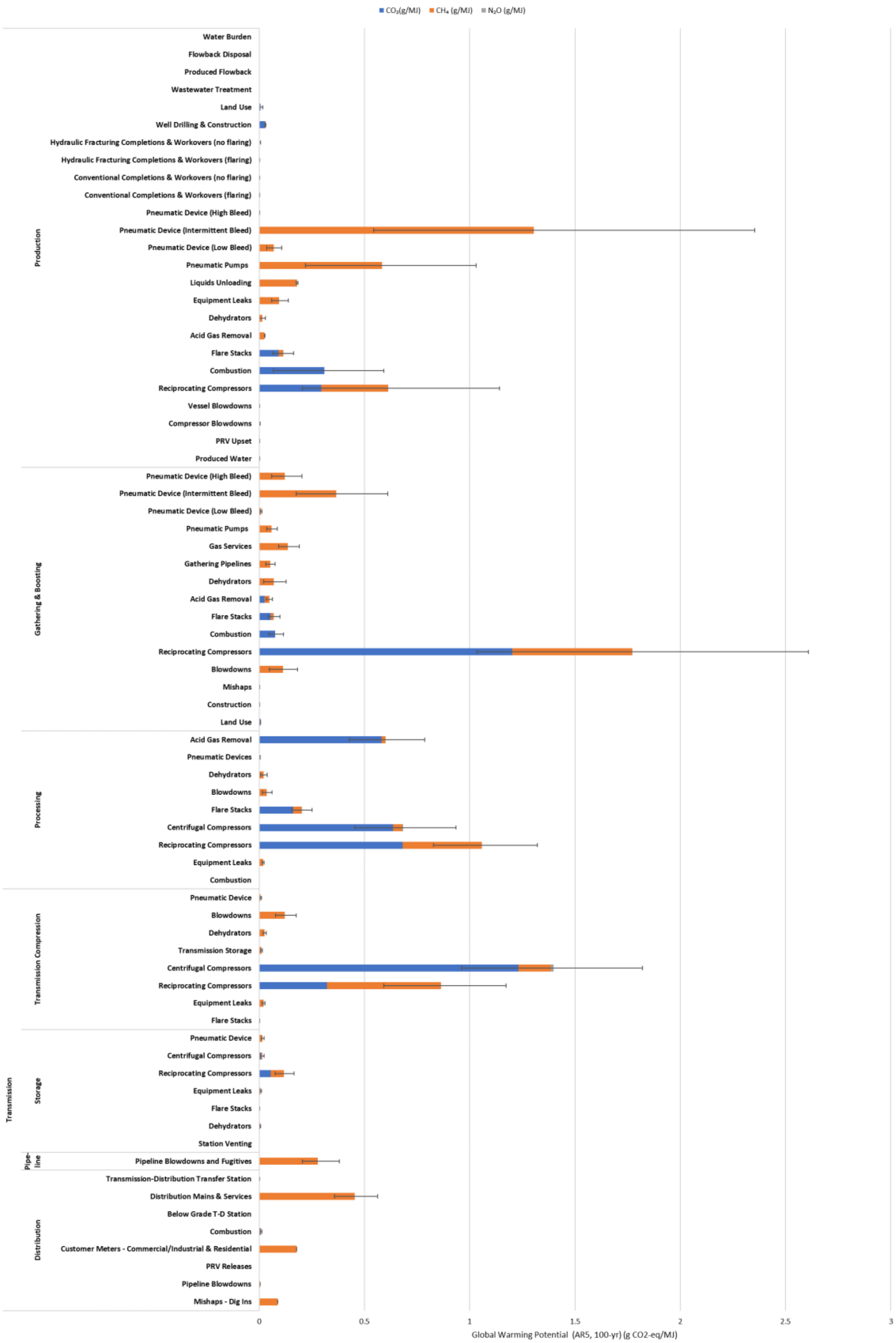


Exhibit I-4. U.S. 100-yr GWP Results for Gulf Coast (LA TX) Tight Scenario

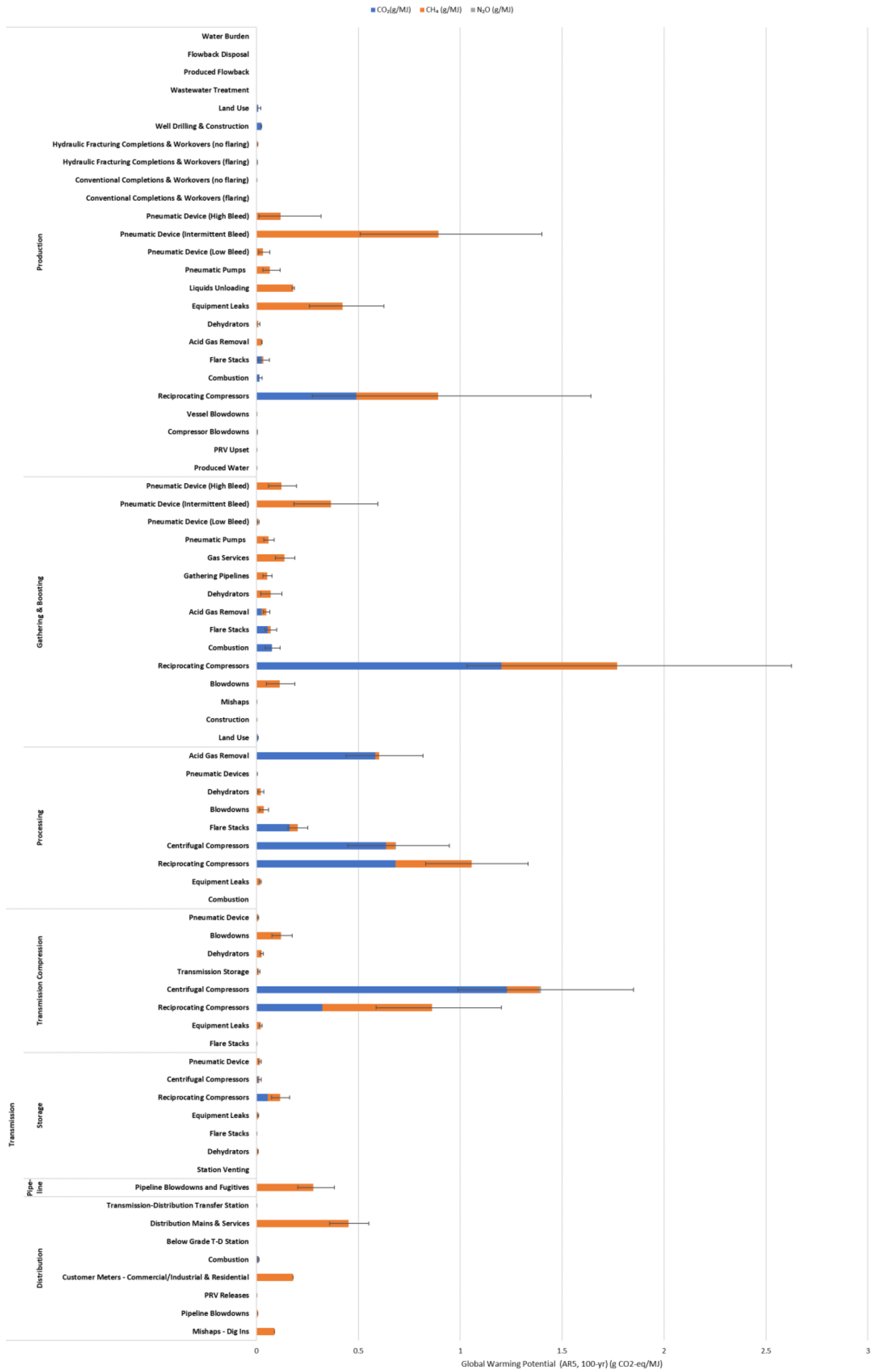


Exhibit I-5. U.S. 100-yr GWP Results for Arkla Conventional Scenario

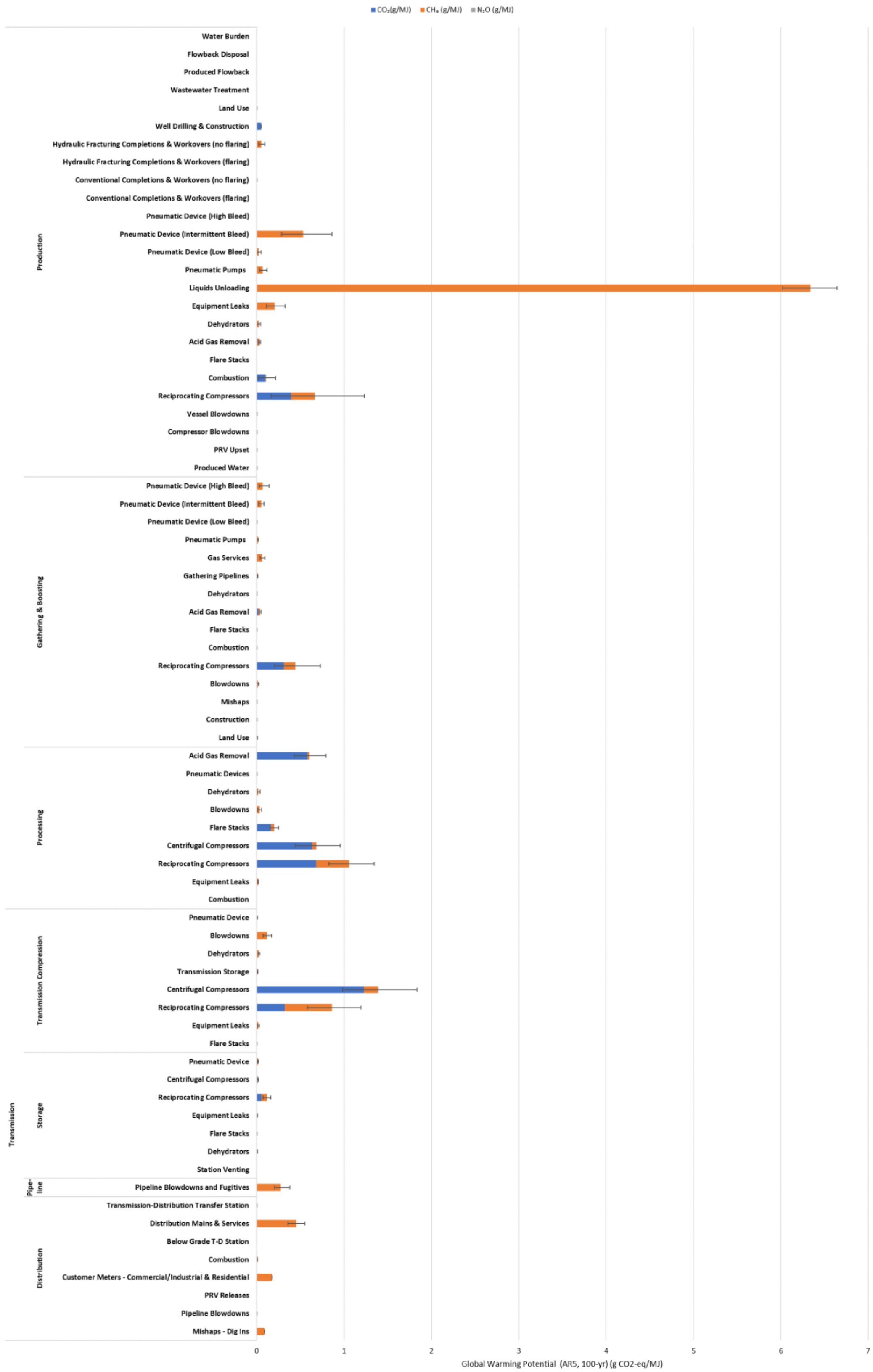


Exhibit I-6. U.S. 100-yr GWP Results for Arkla Shale Scenario

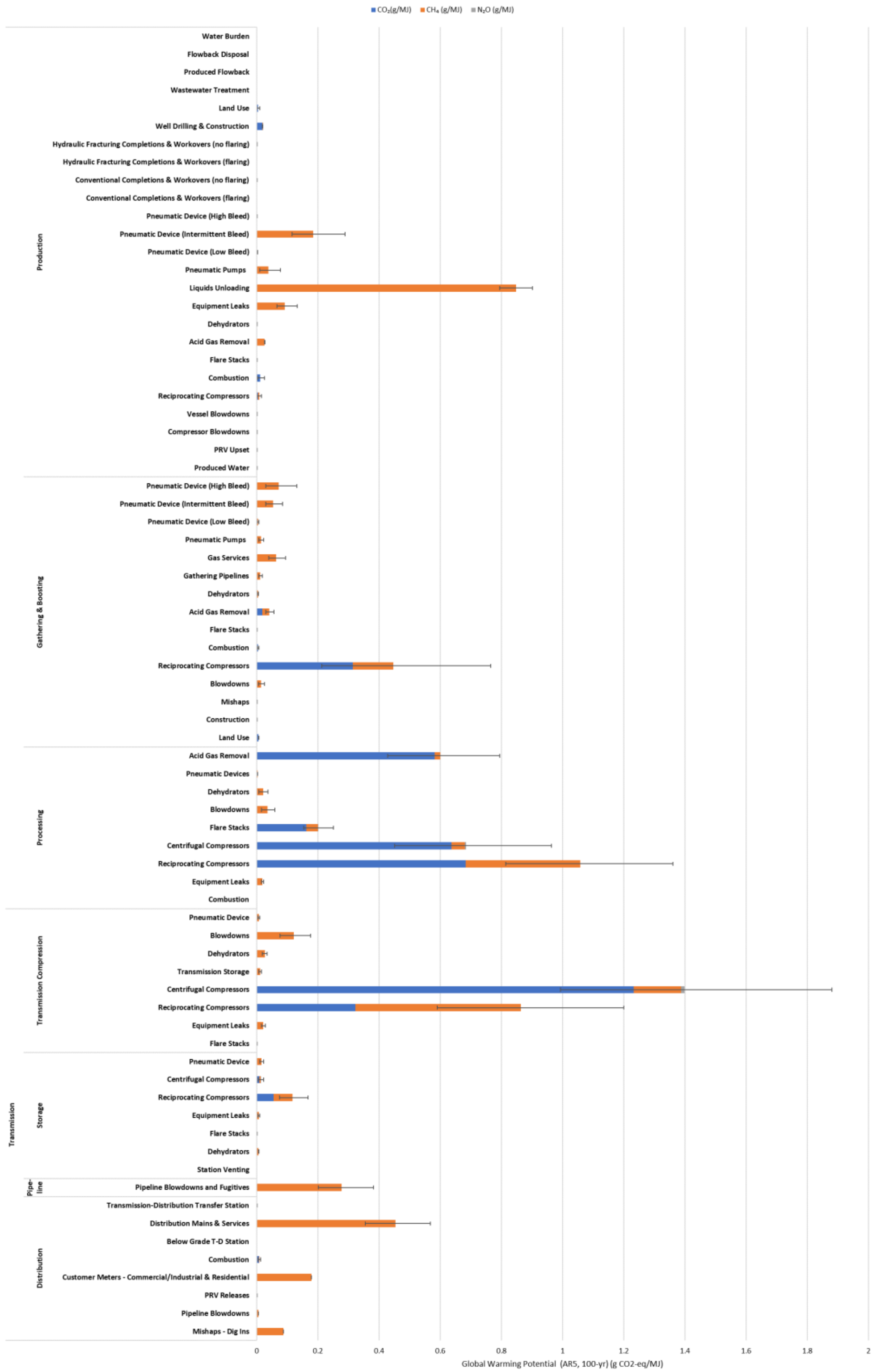


Exhibit I-7. U.S. 100-yr GWP Results for Arkla Tight Scenario

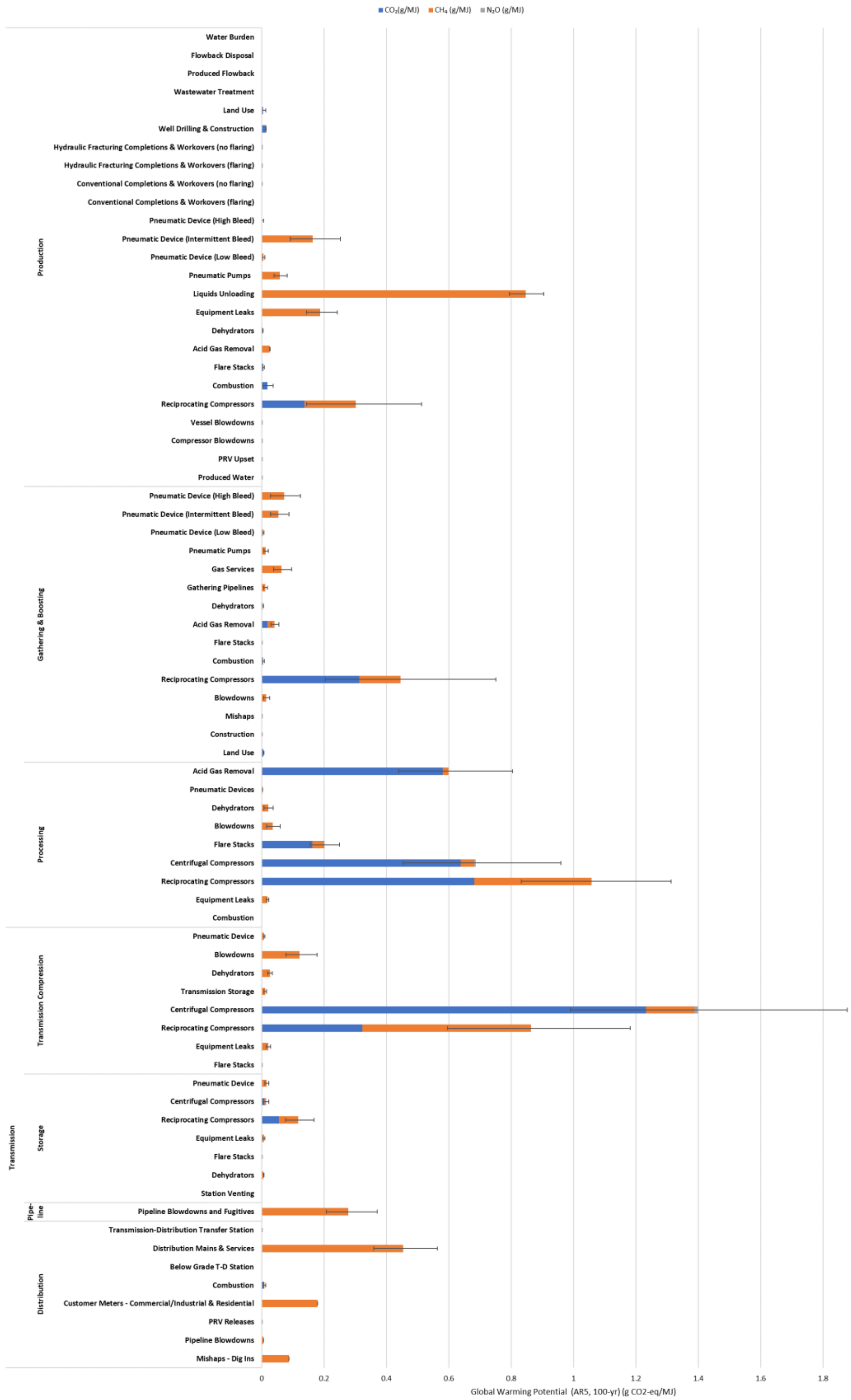


Exhibit I-8. U.S. 100-yr GWP Results for East Texas Conventional Scenario

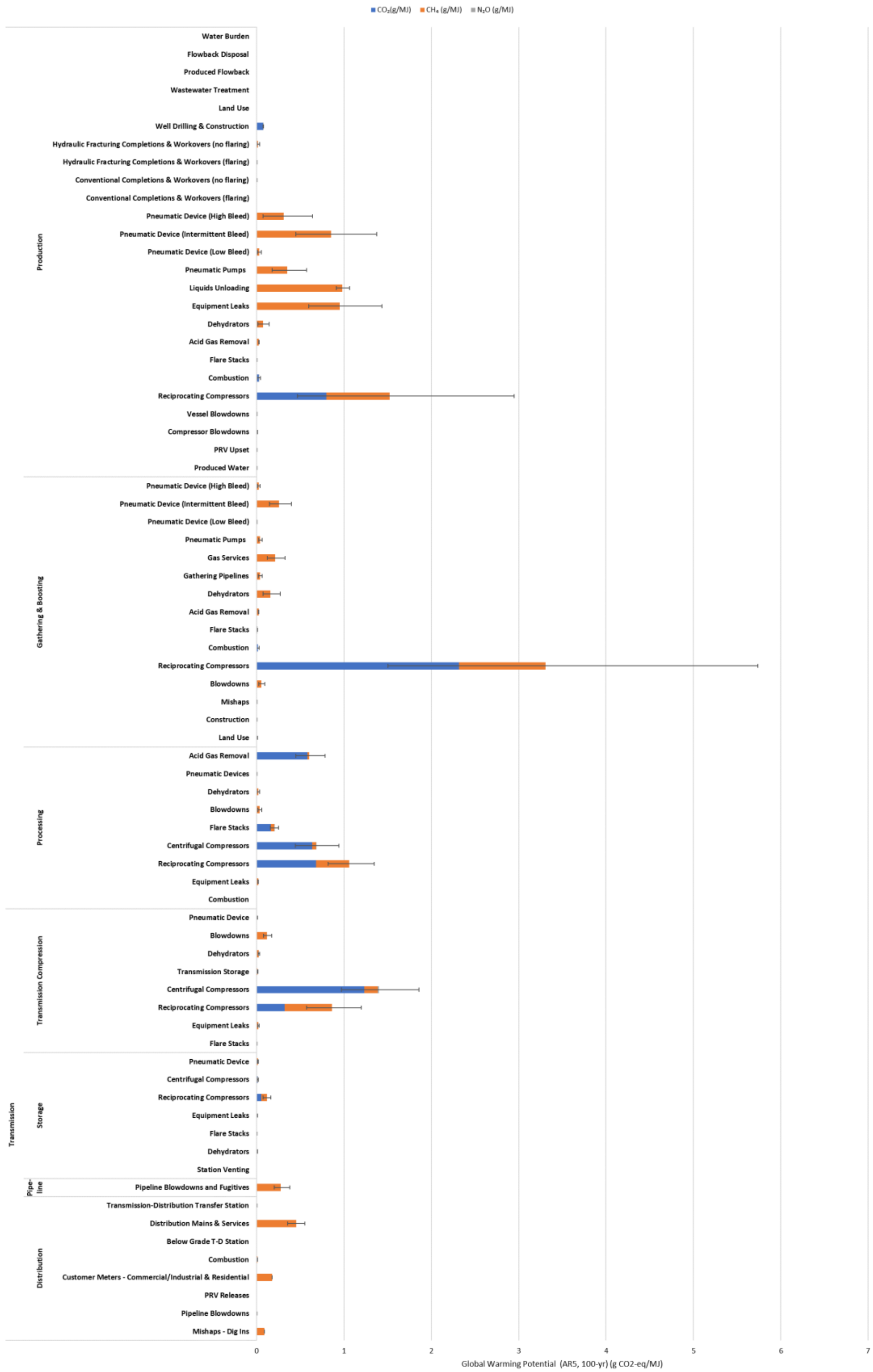


Exhibit I-9. U.S. 100-yr GWP Results for East Texas Shale Scenario

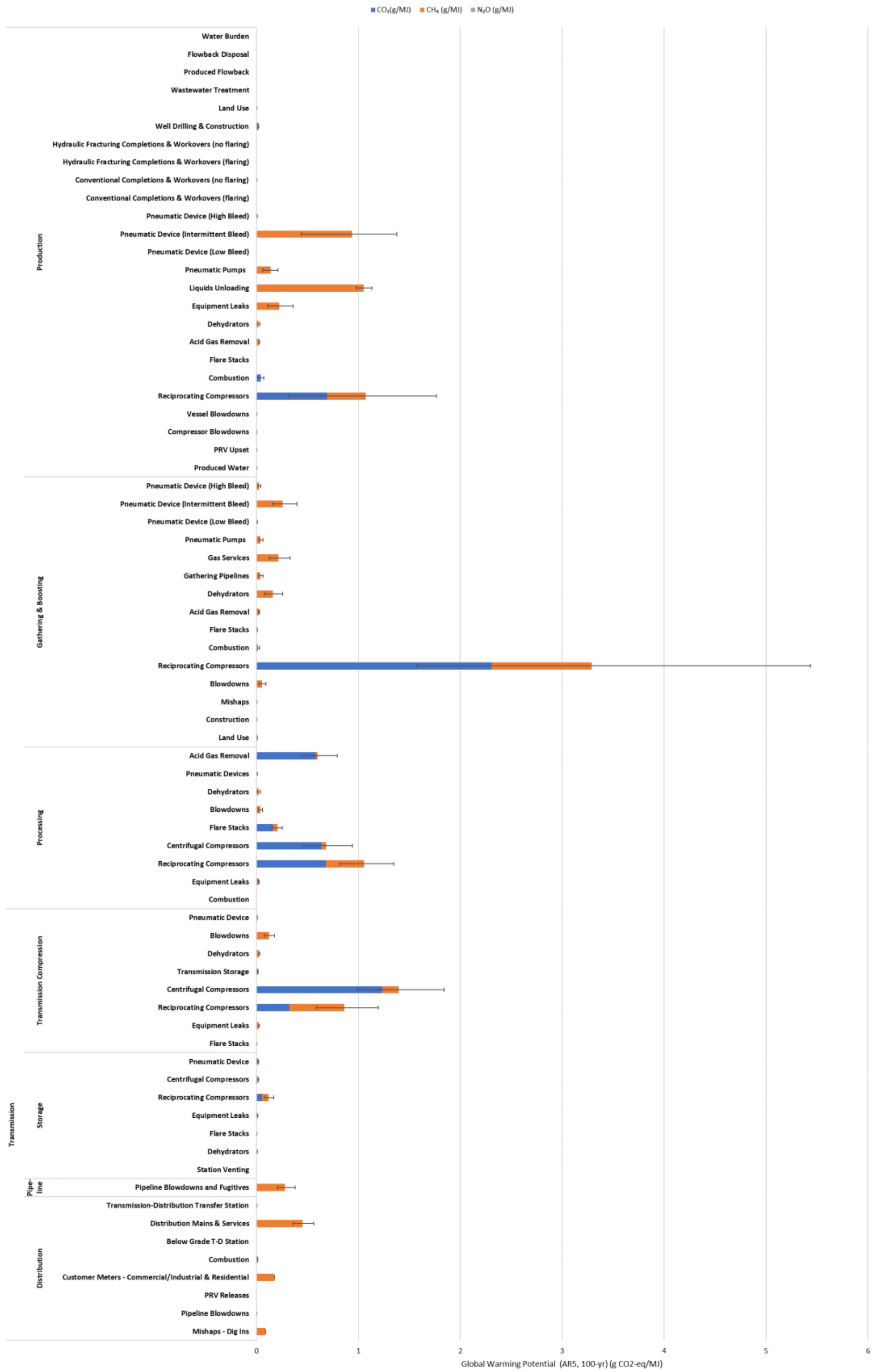


Exhibit I-10. U.S. 100-yr GWP Results for East Texas Tight Scenario

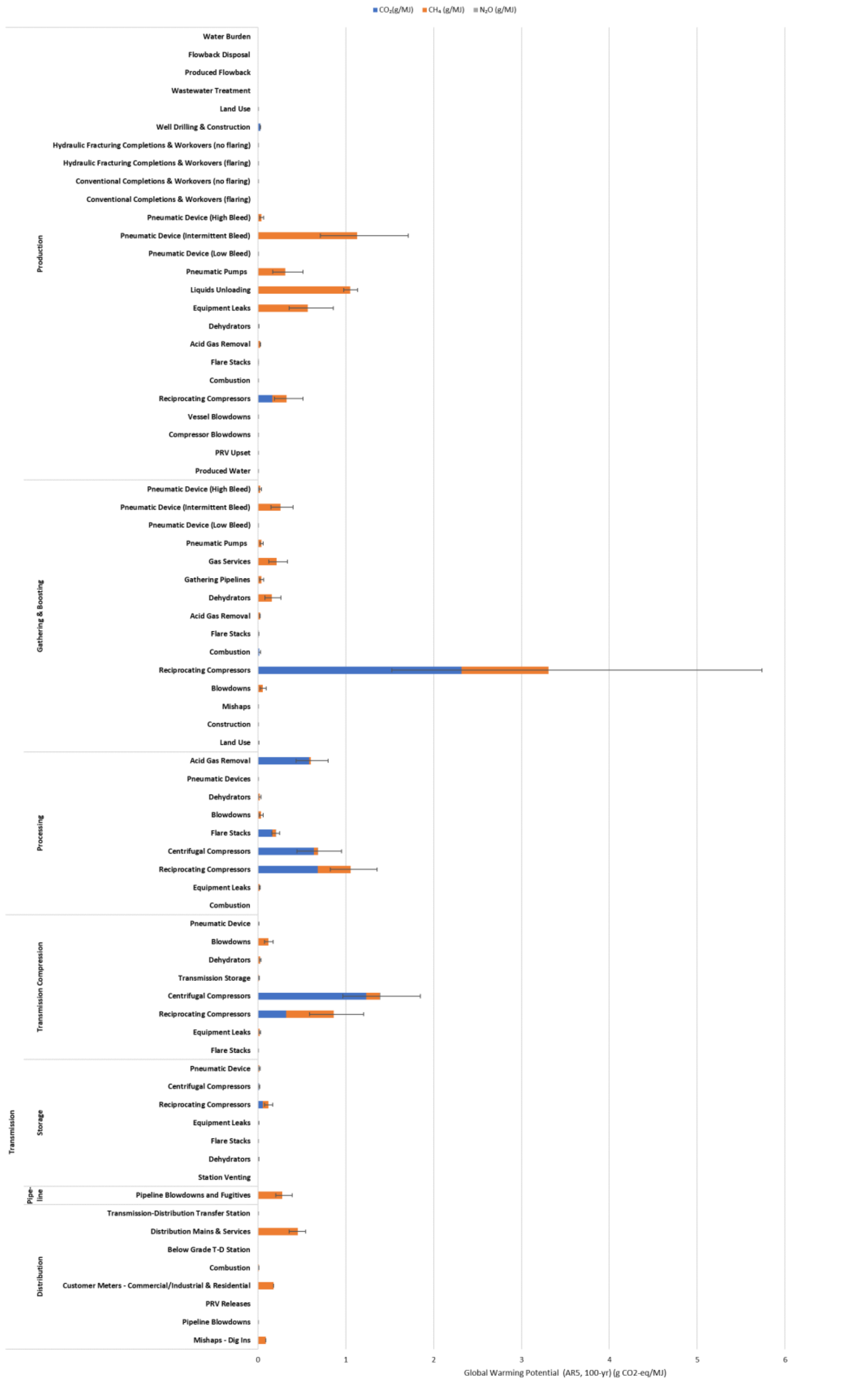


Exhibit I-11. U.S. 100-yr GWP Results for Arkoma Conventional Scenario

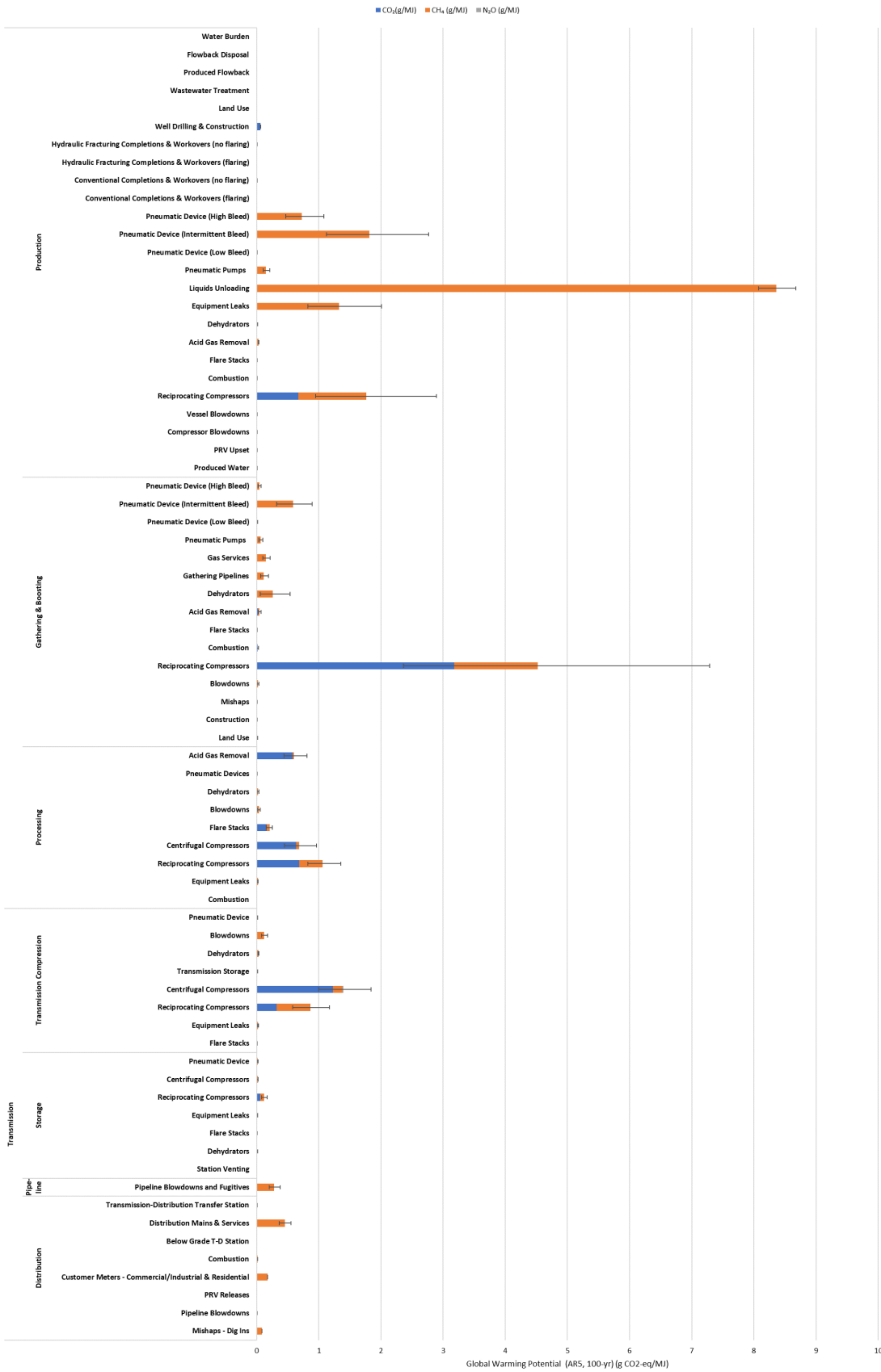


Exhibit I-12. U.S. 100-yr GWP Results for Arkoma Shale Scenario

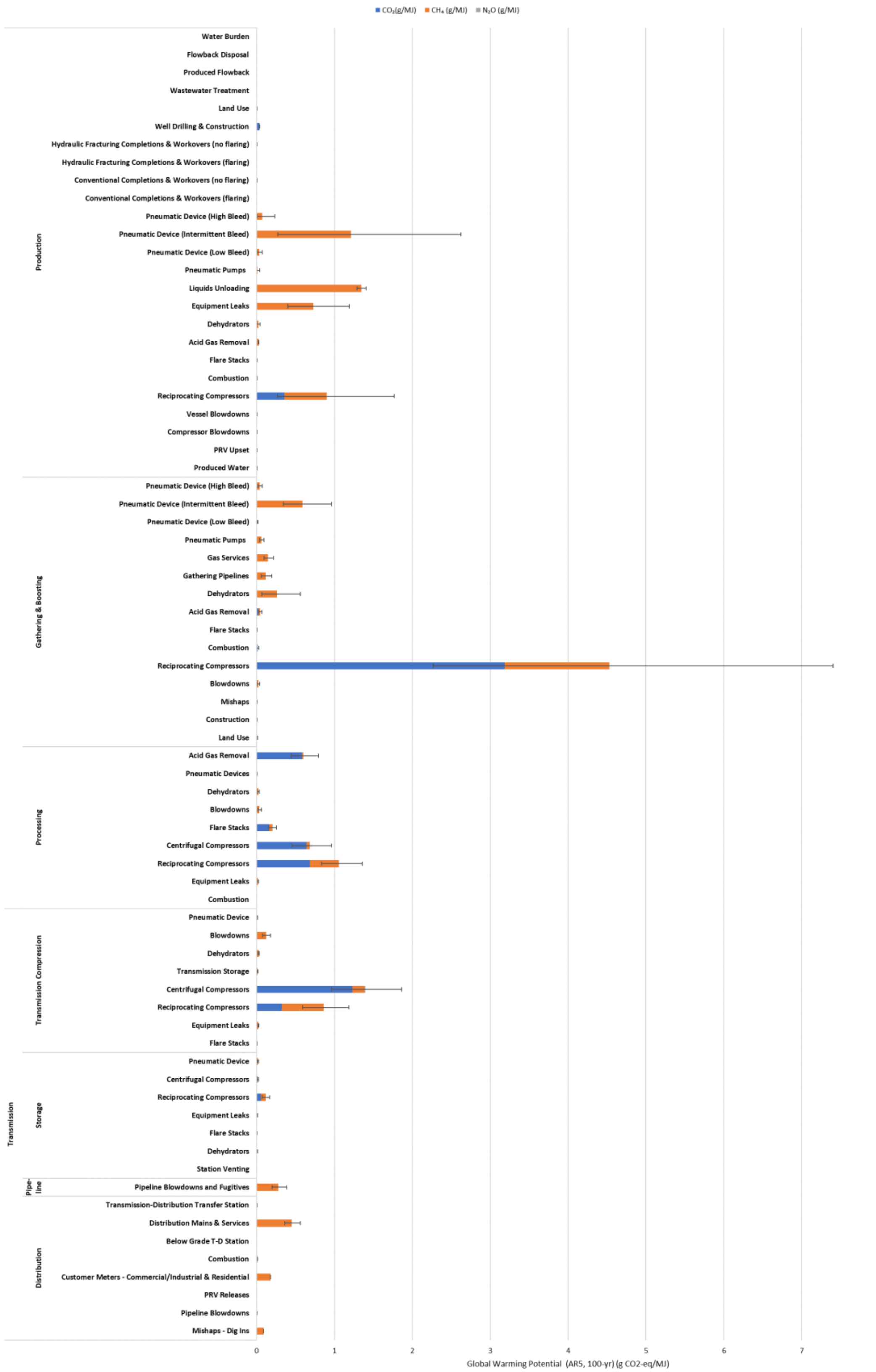


Exhibit I-13. U.S. 100-yr GWP Results for South Oklahoma Shale Scenario

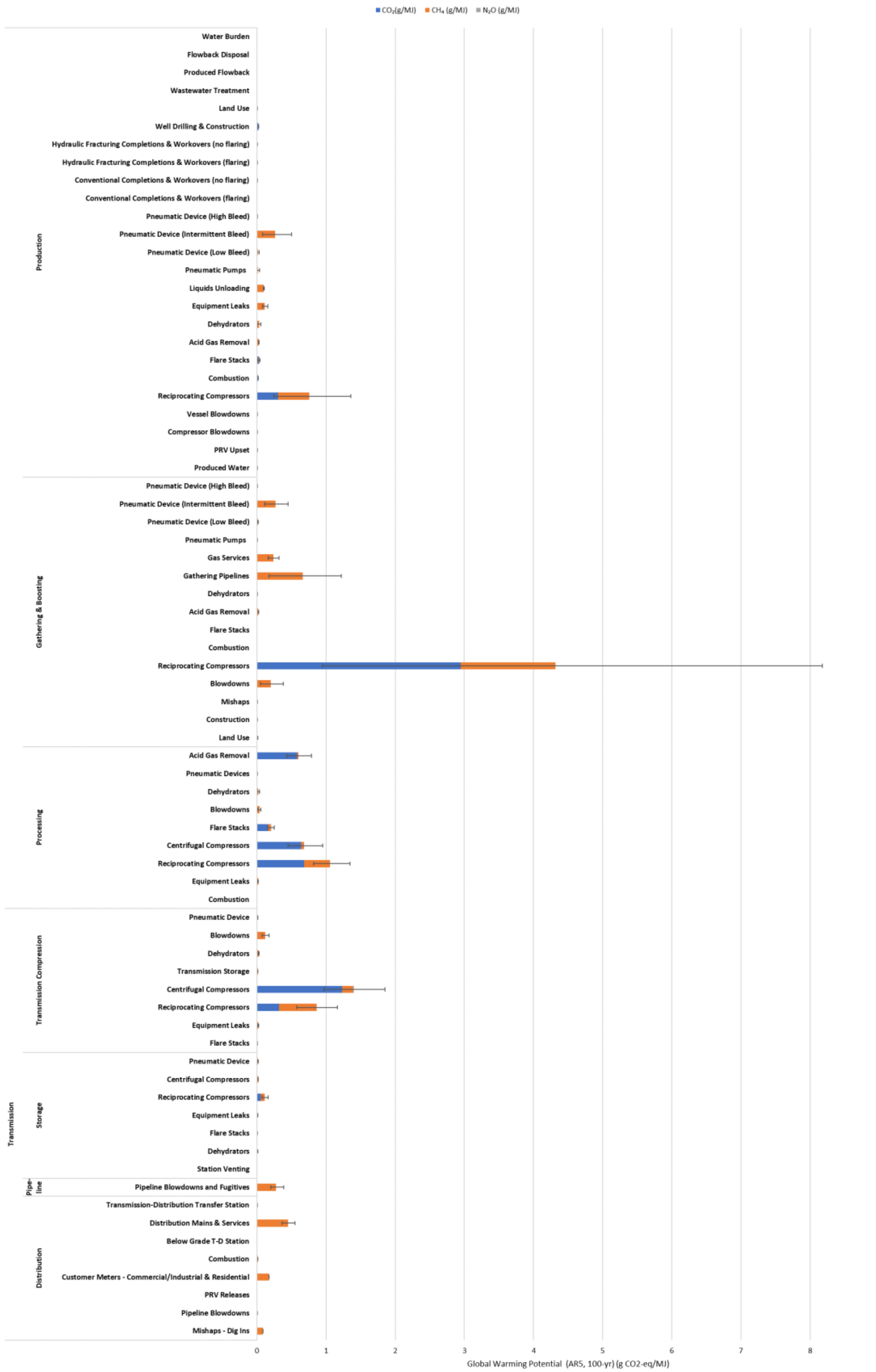


Exhibit I-14. U.S. 100-yr GWP Results for Anadarko Conventional Scenario

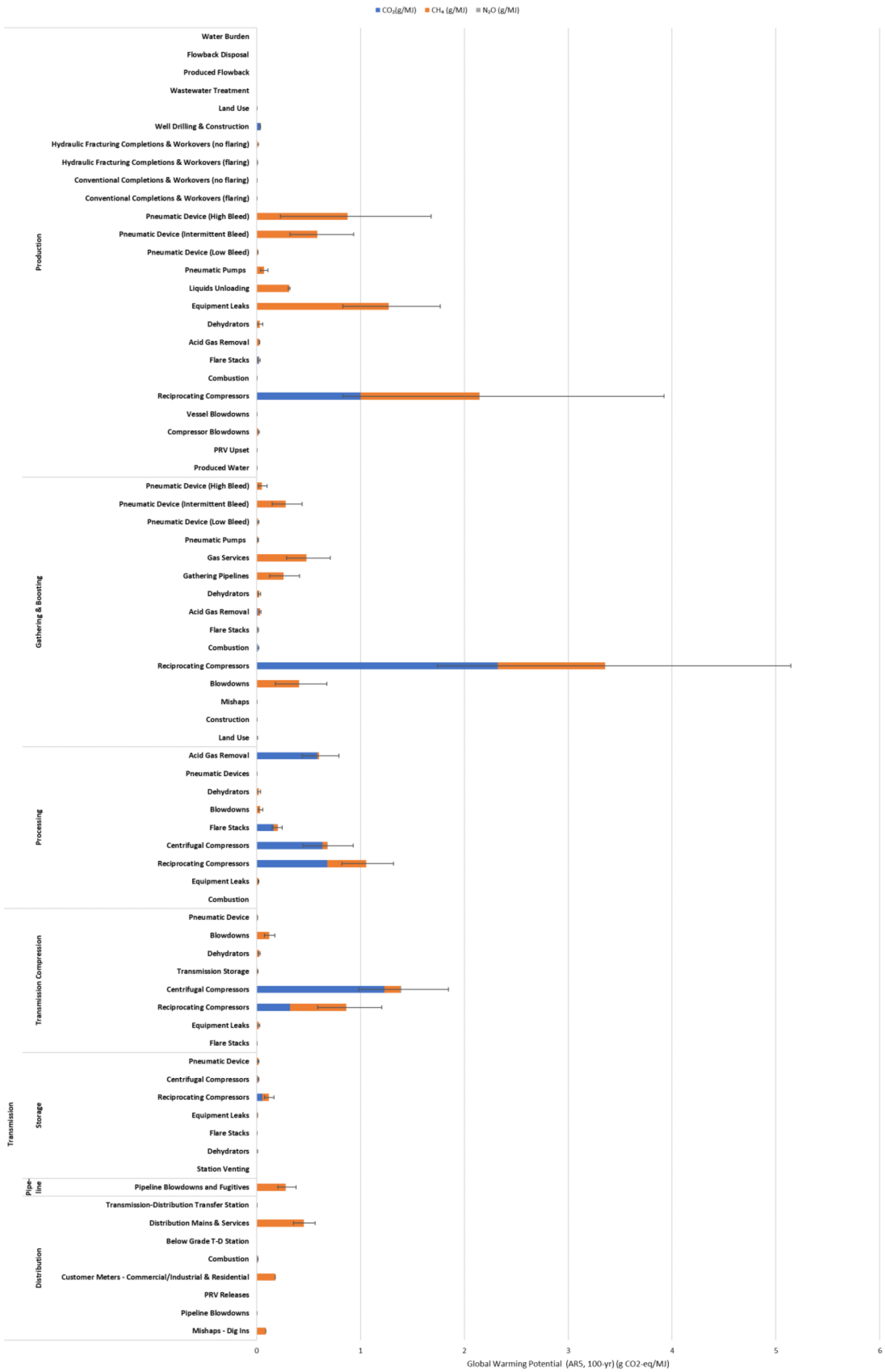


Exhibit I-15. U.S. 100-yr GWP Results for Anadarko Shale Scenario

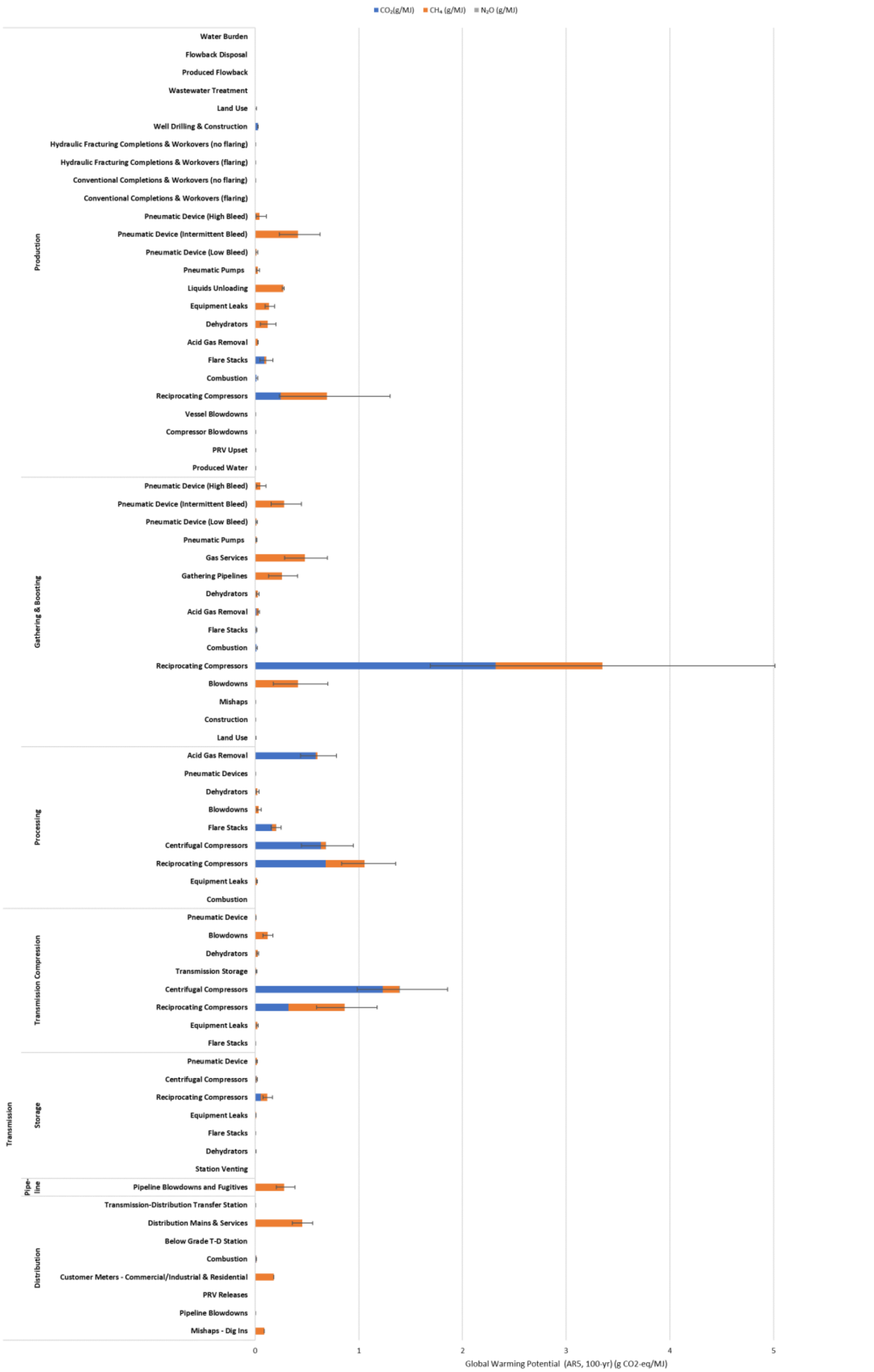


Exhibit I-16. U.S. 100-yr GWP Results for Anadarko Tight Scenario

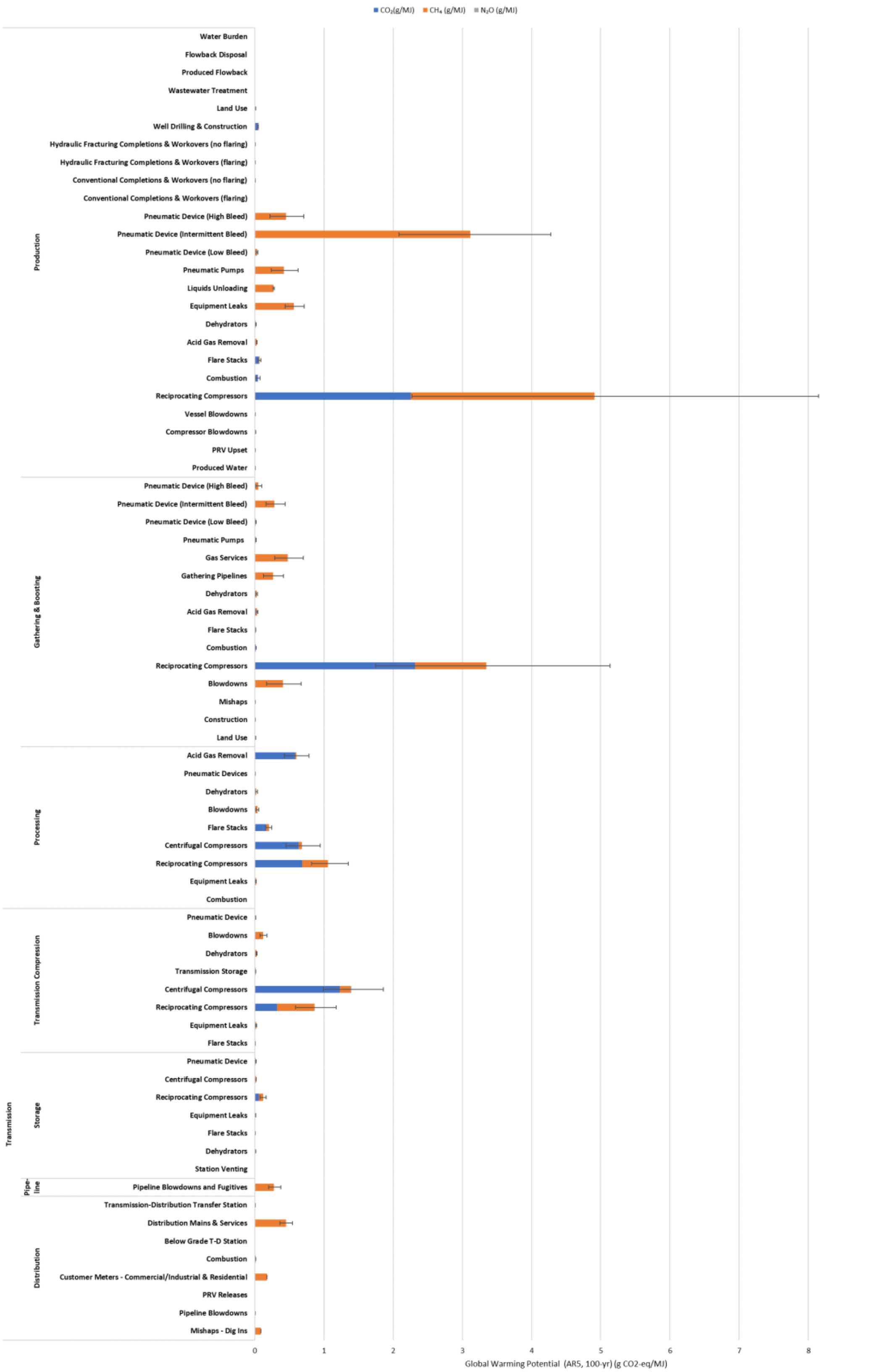


Exhibit I-17. U.S. 100-yr GWP Results for Strawn Shale Scenario

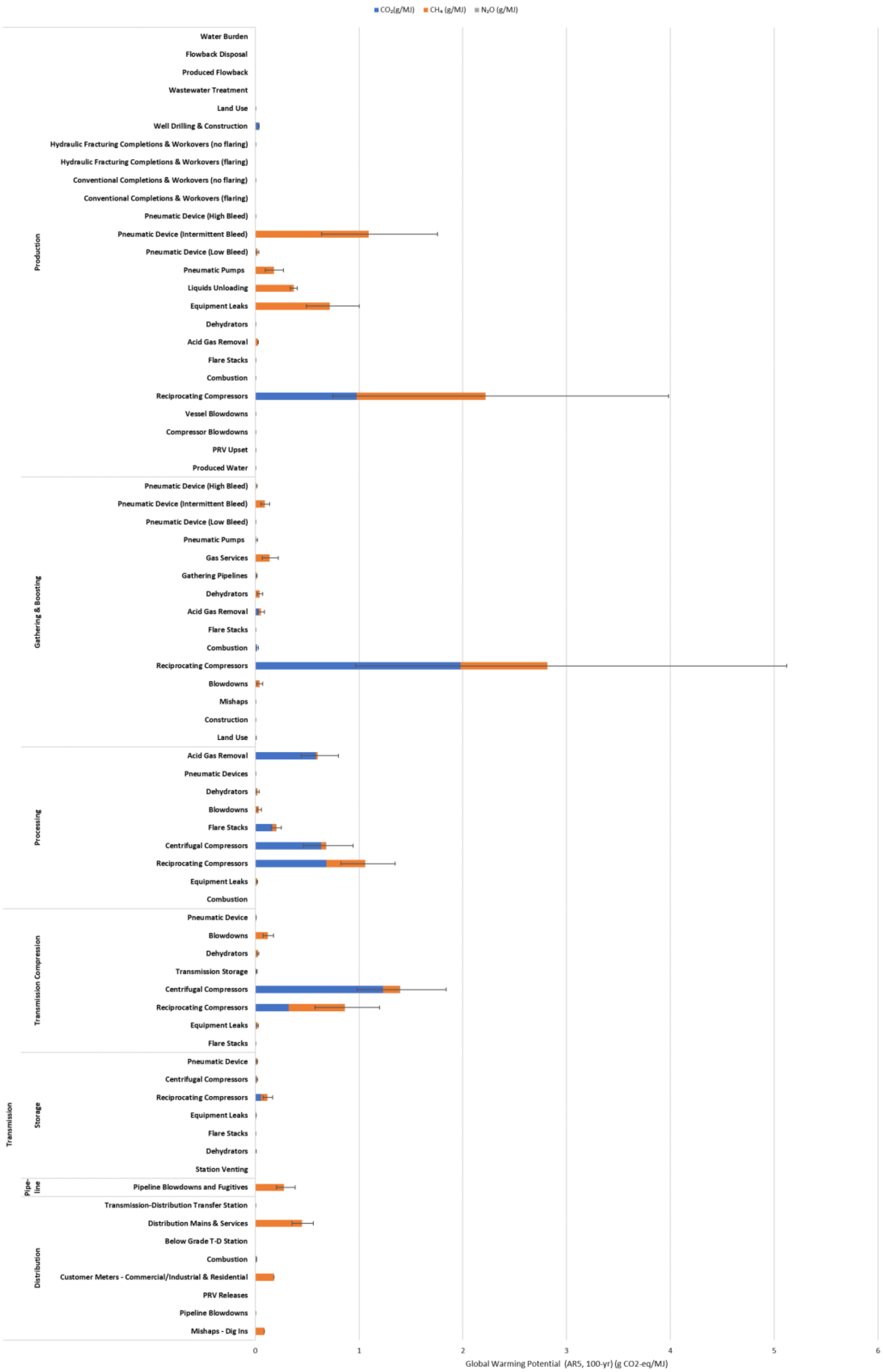


Exhibit I-18. U.S. 100-yr GWP Results for Fort Worth Shale Scenario

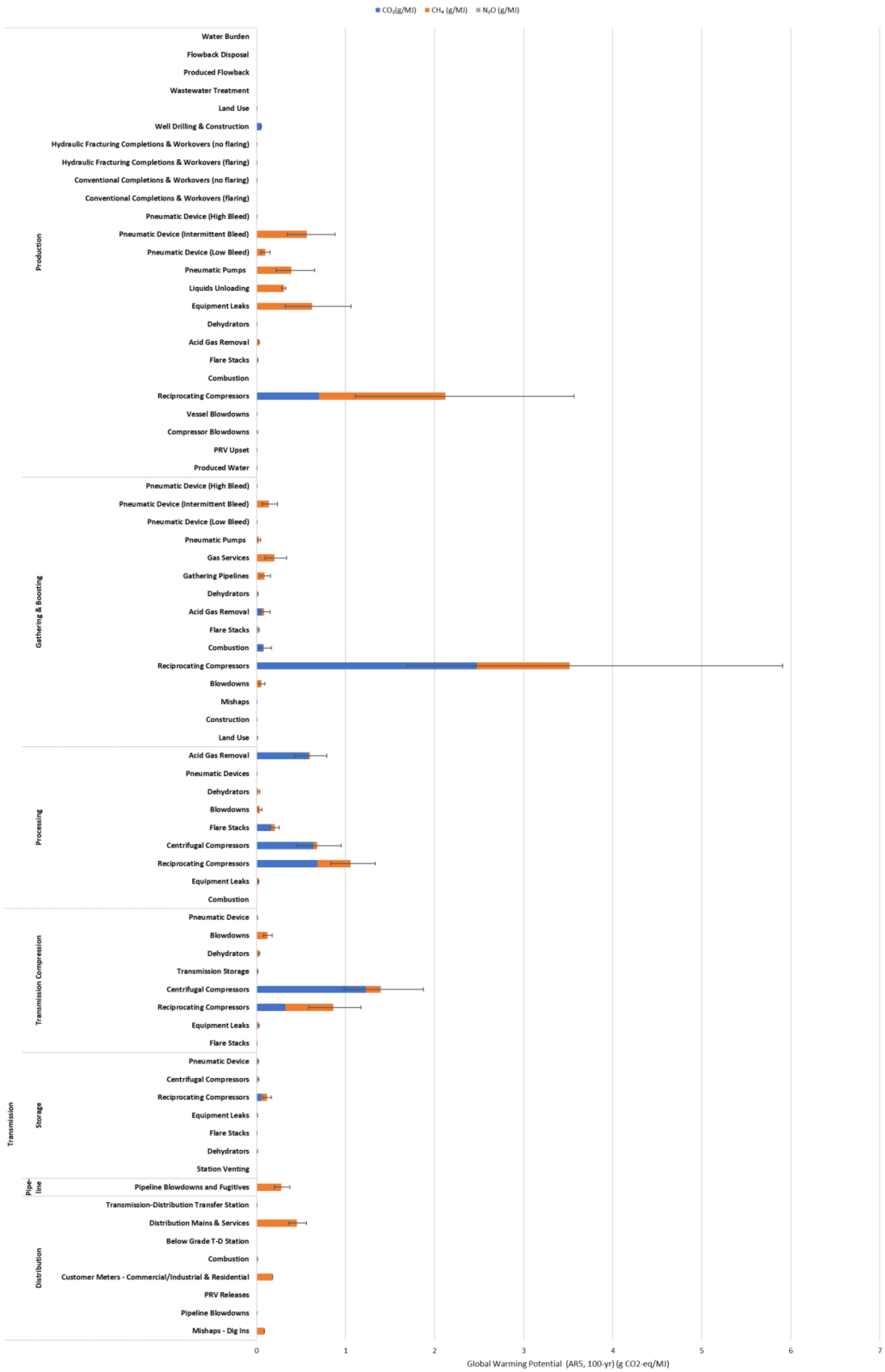


Exhibit I-19. U.S. 100-yr GWP Results for Permian Conventional Scenario

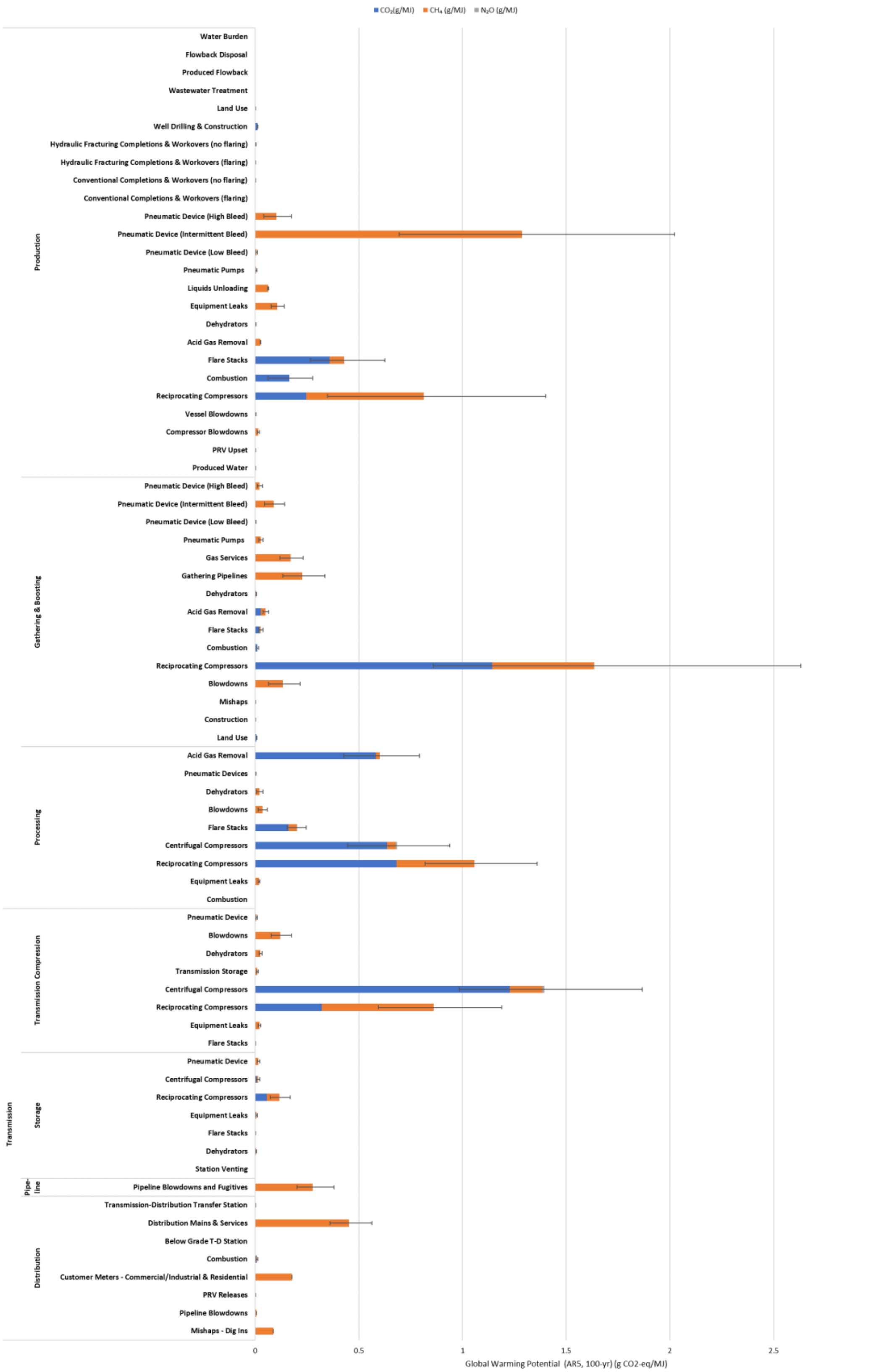


Exhibit I-20. U.S. 100-yr GWP Results for Permian Shale Scenario

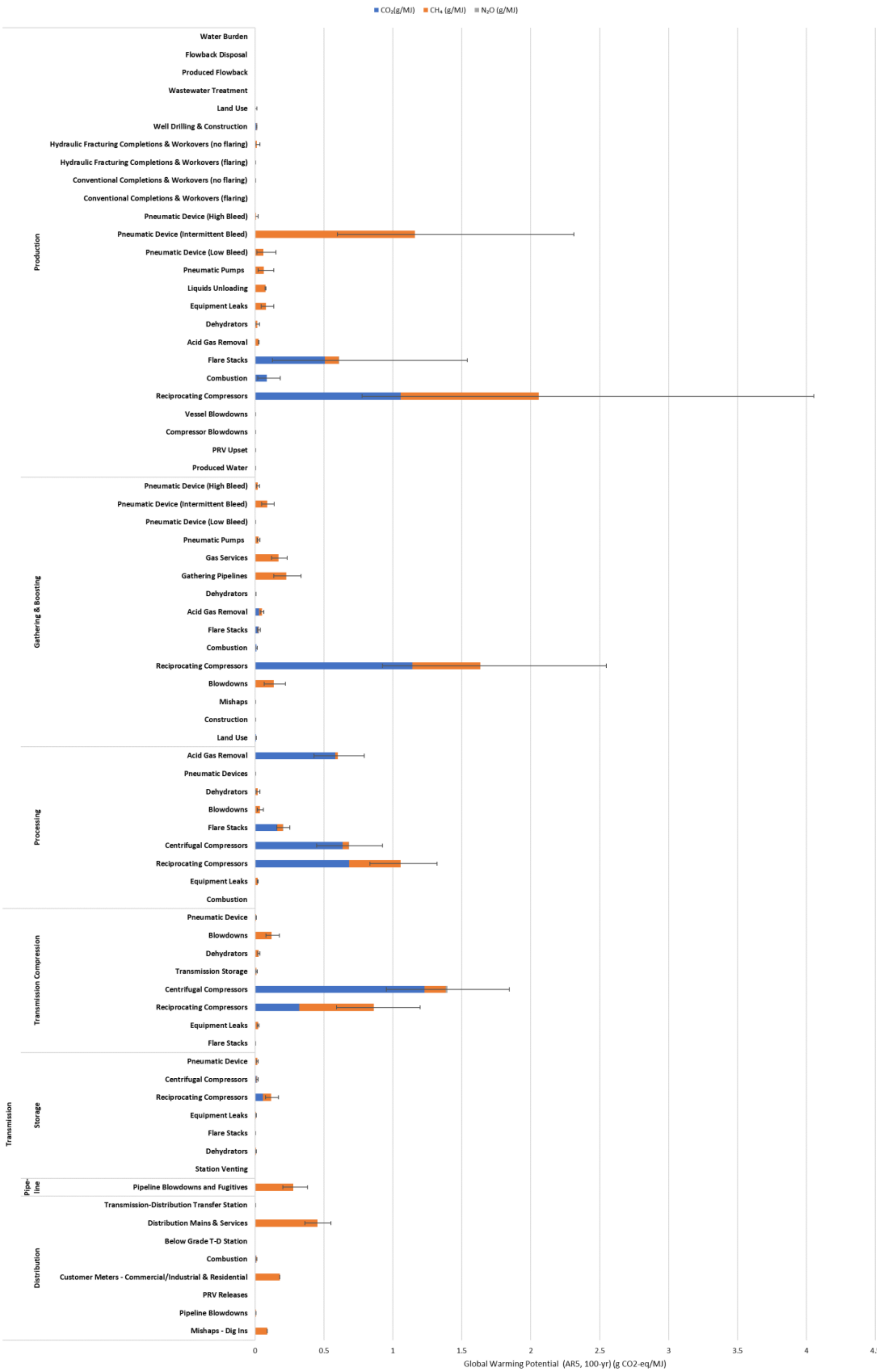


Exhibit I-21. U.S. 100-yr GWP Results for Green River Conventional Scenario

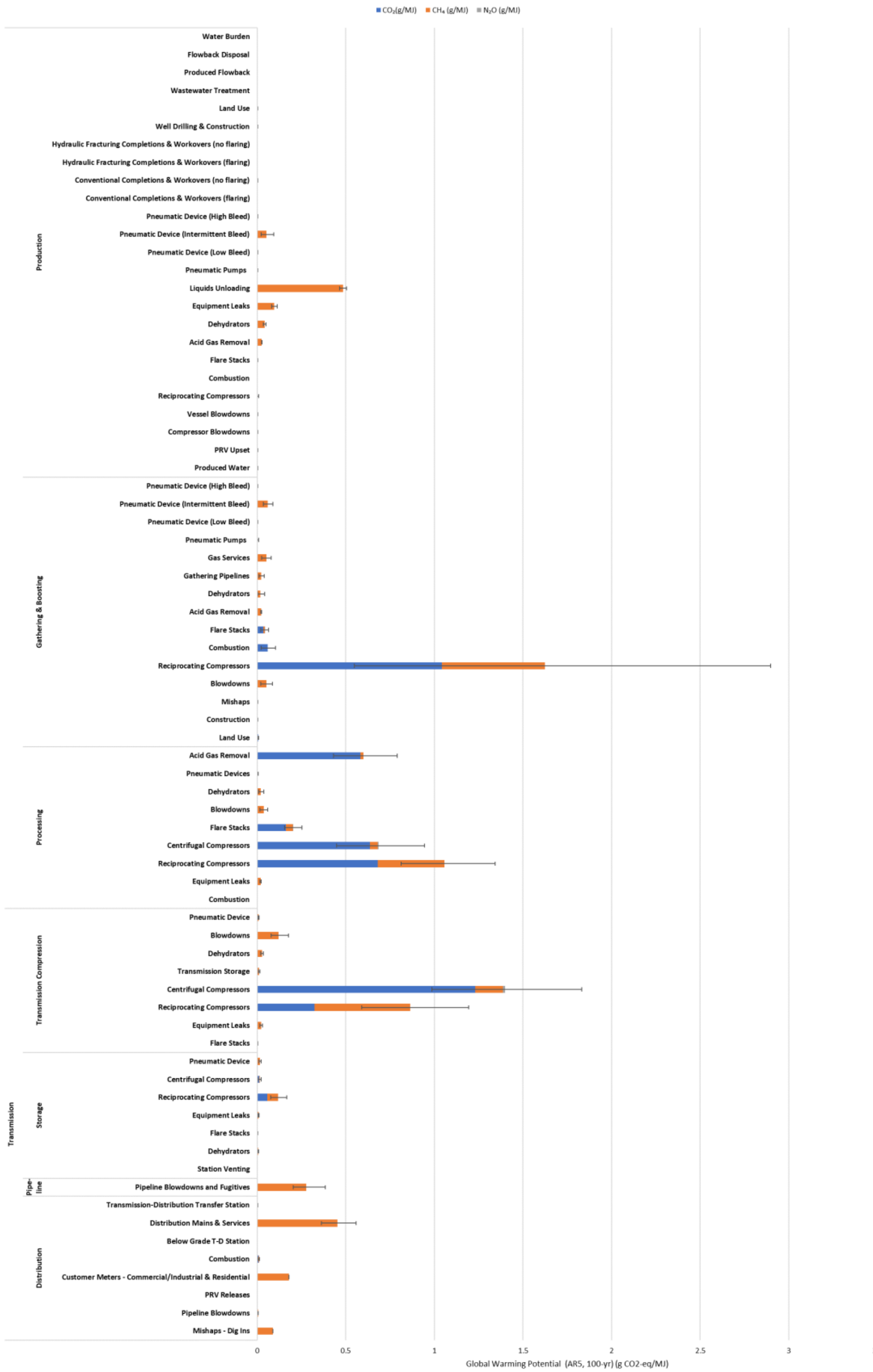


Exhibit I-22. U.S. 100-yr GWP Results for Green River Tight Scenario

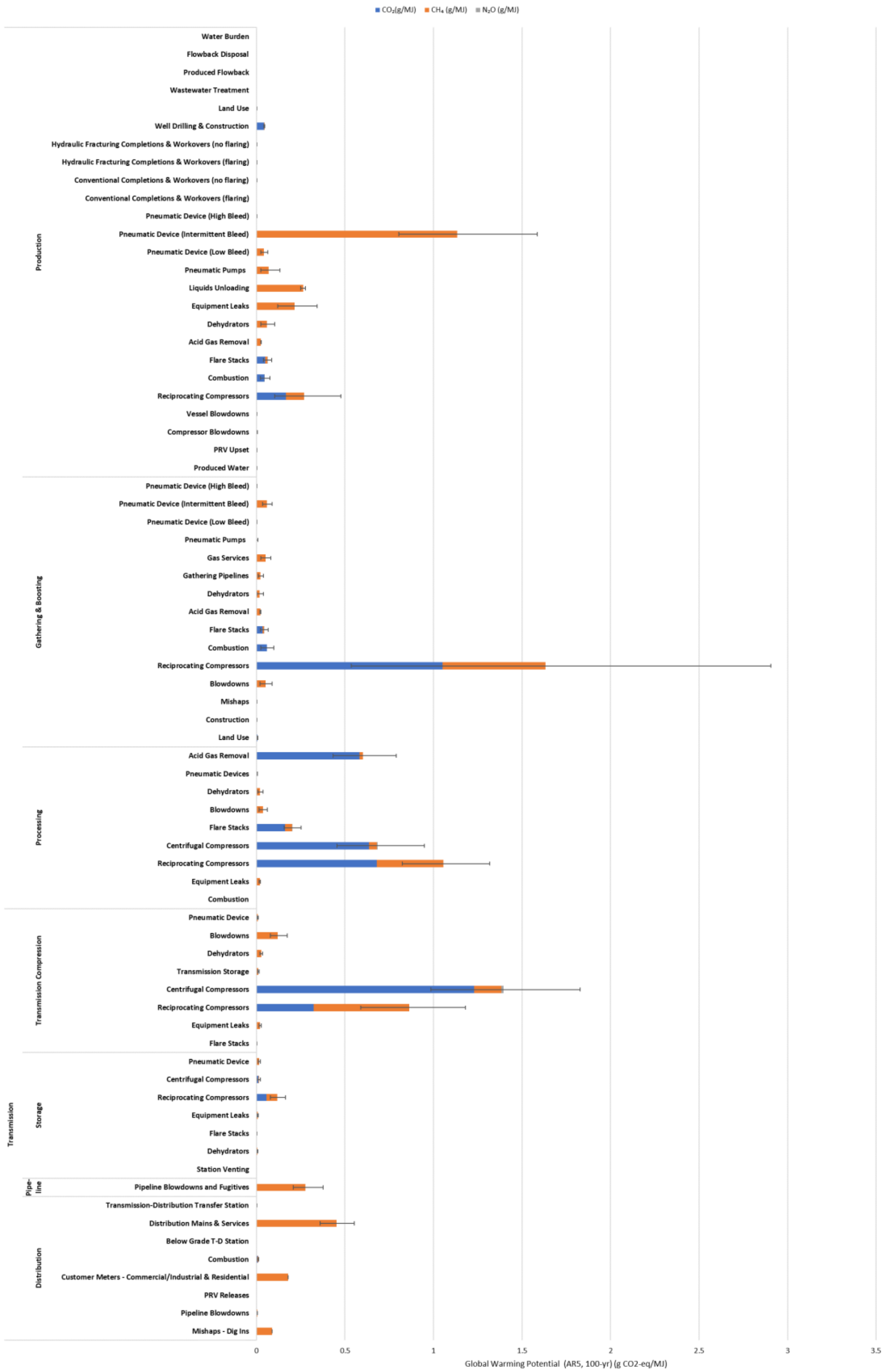


Exhibit I-23. U.S. 100-yr GWP Results for Uinta Conventional Scenario

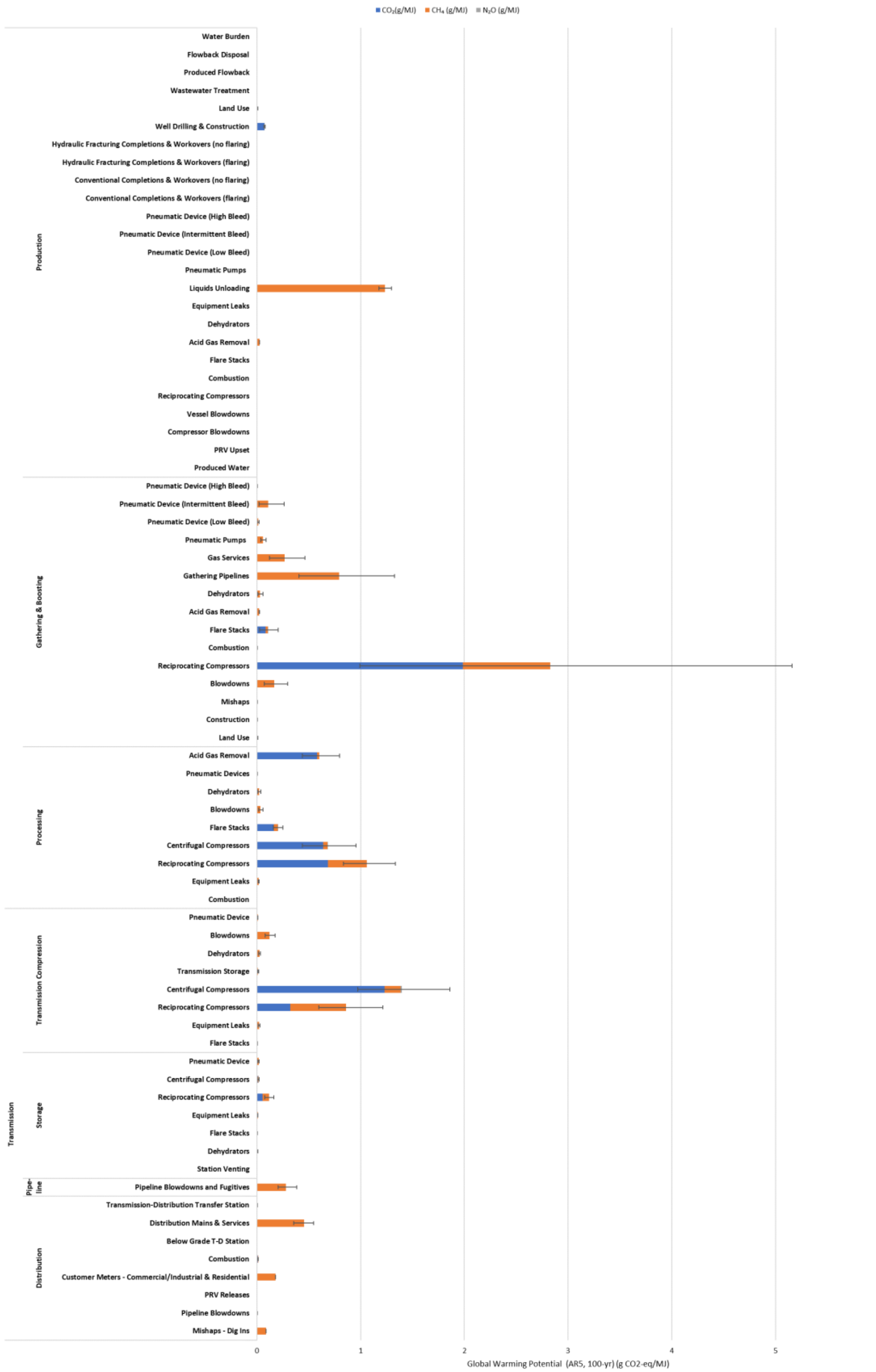


Exhibit I-24. U.S. 100-yr GWP Results for Uinta Tight Scenario

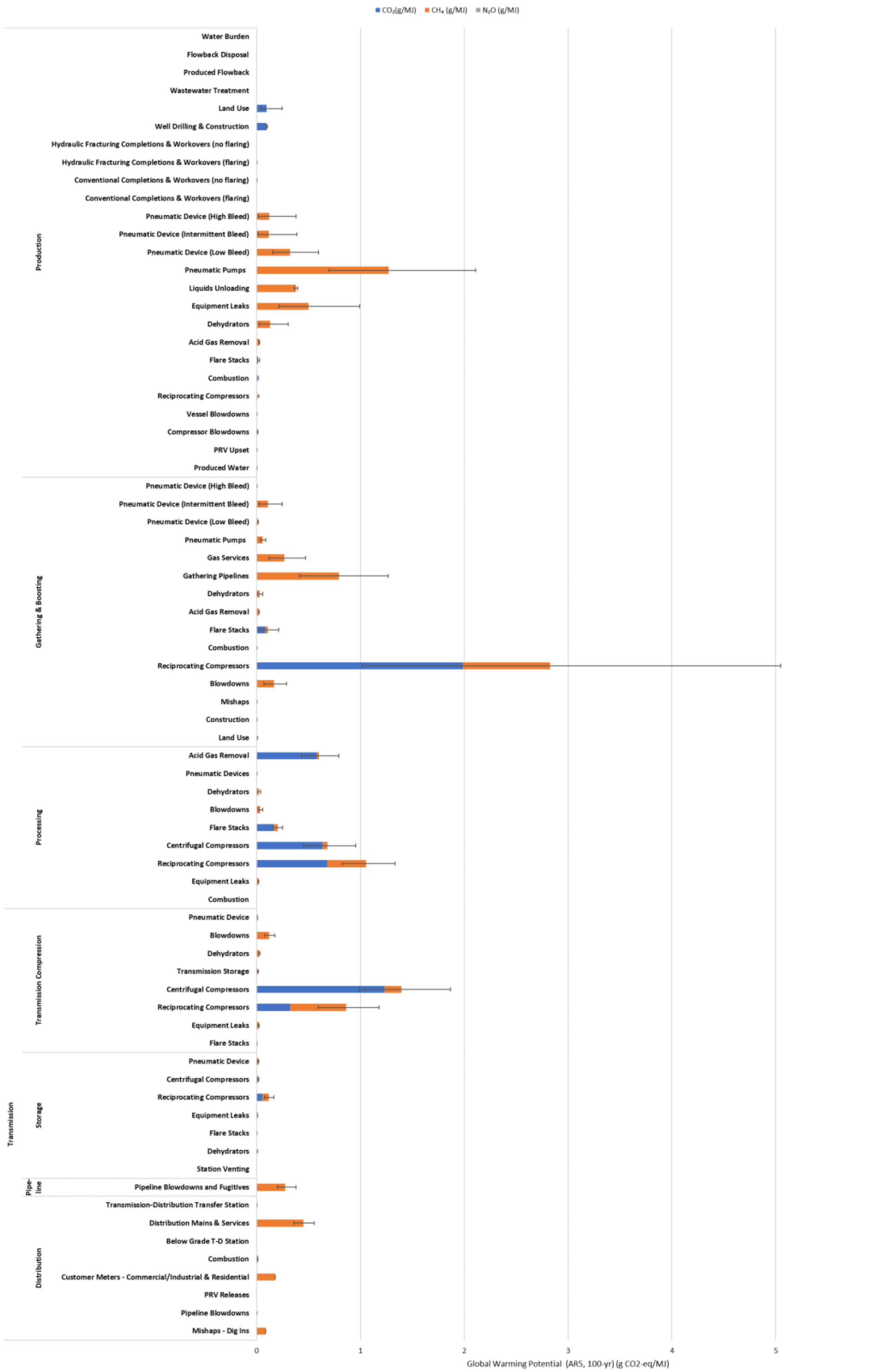


Exhibit I-25. U.S. 100-yr GWP Results for San Juan CBM Scenario

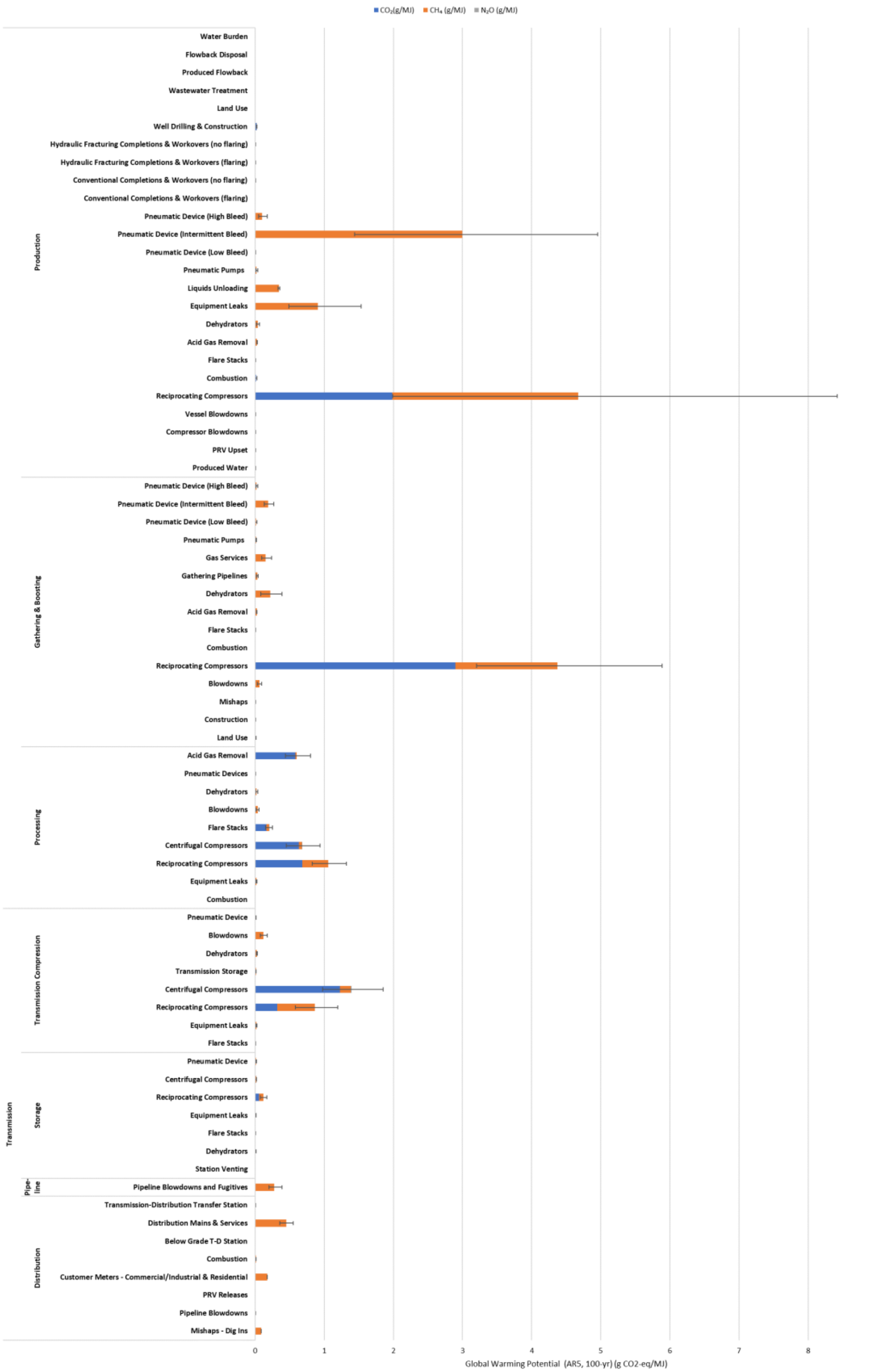


Exhibit I-26. U.S. 100-yr GWP Results for San Juan Conventional Scenario

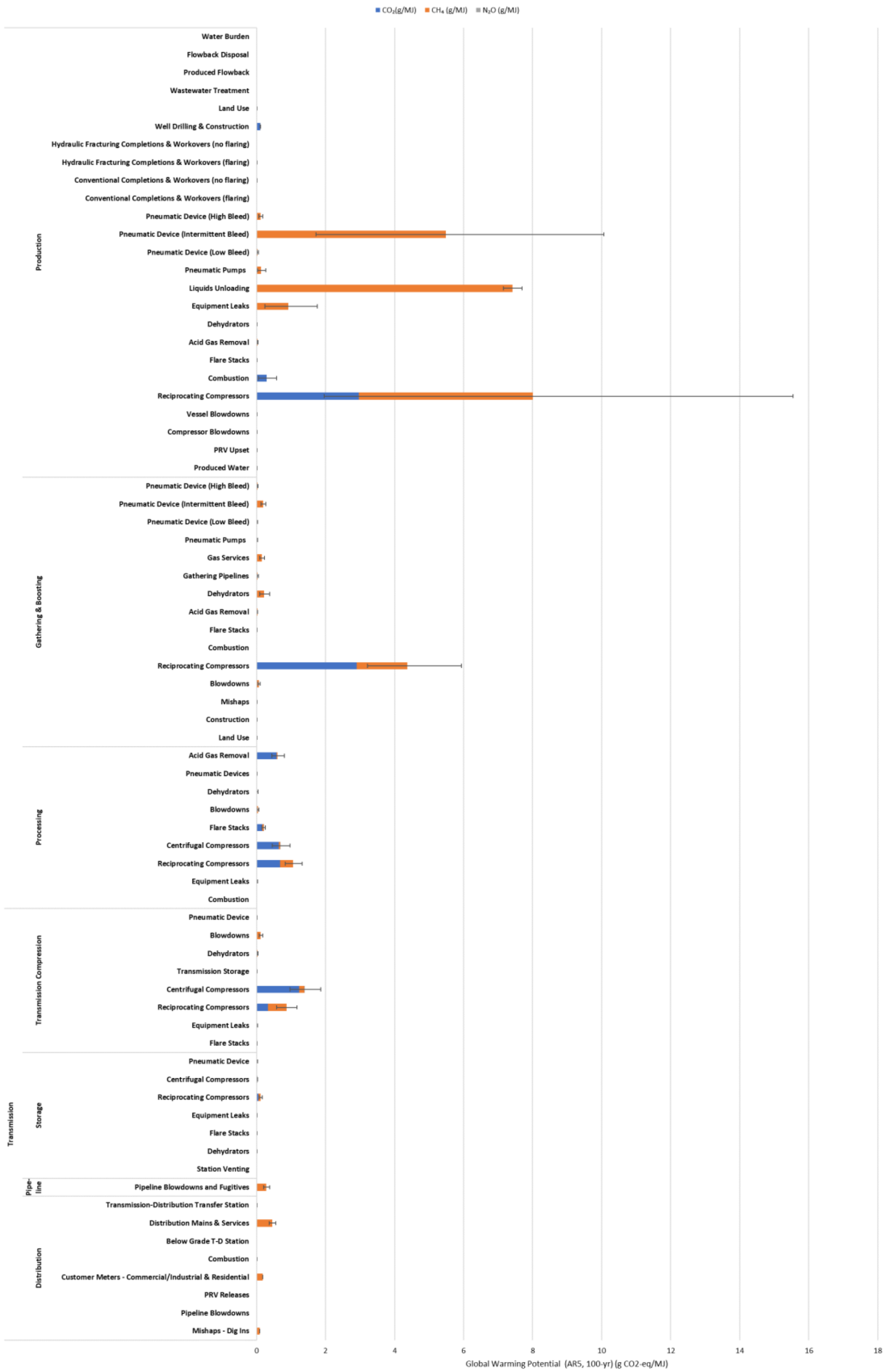


Exhibit I-27. U.S. 100-yr GWP Results for Piceance Tight Scenario

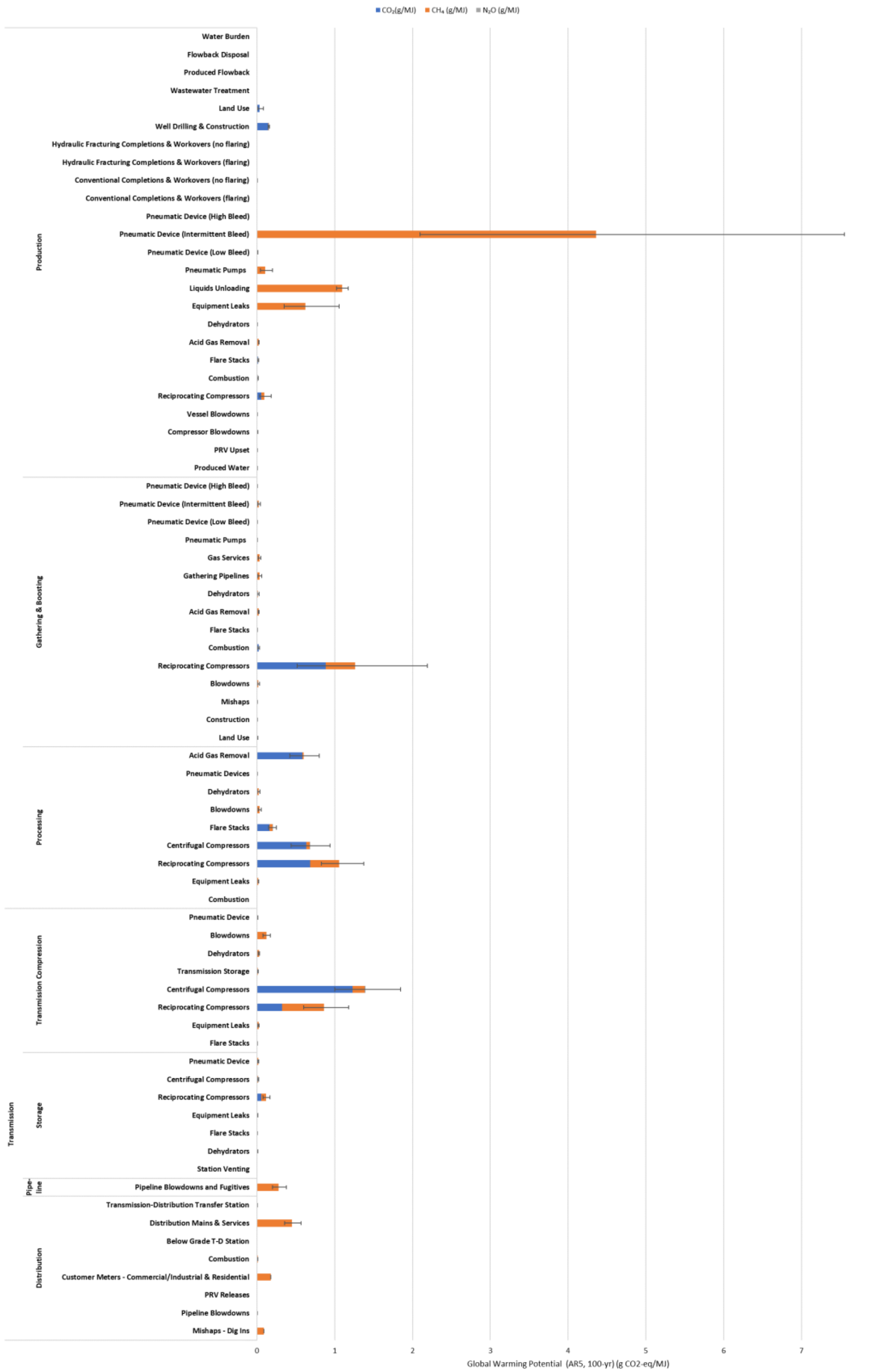


Exhibit I-28. U.S. 100-yr GWP Results for Offshore Alaska Scenario

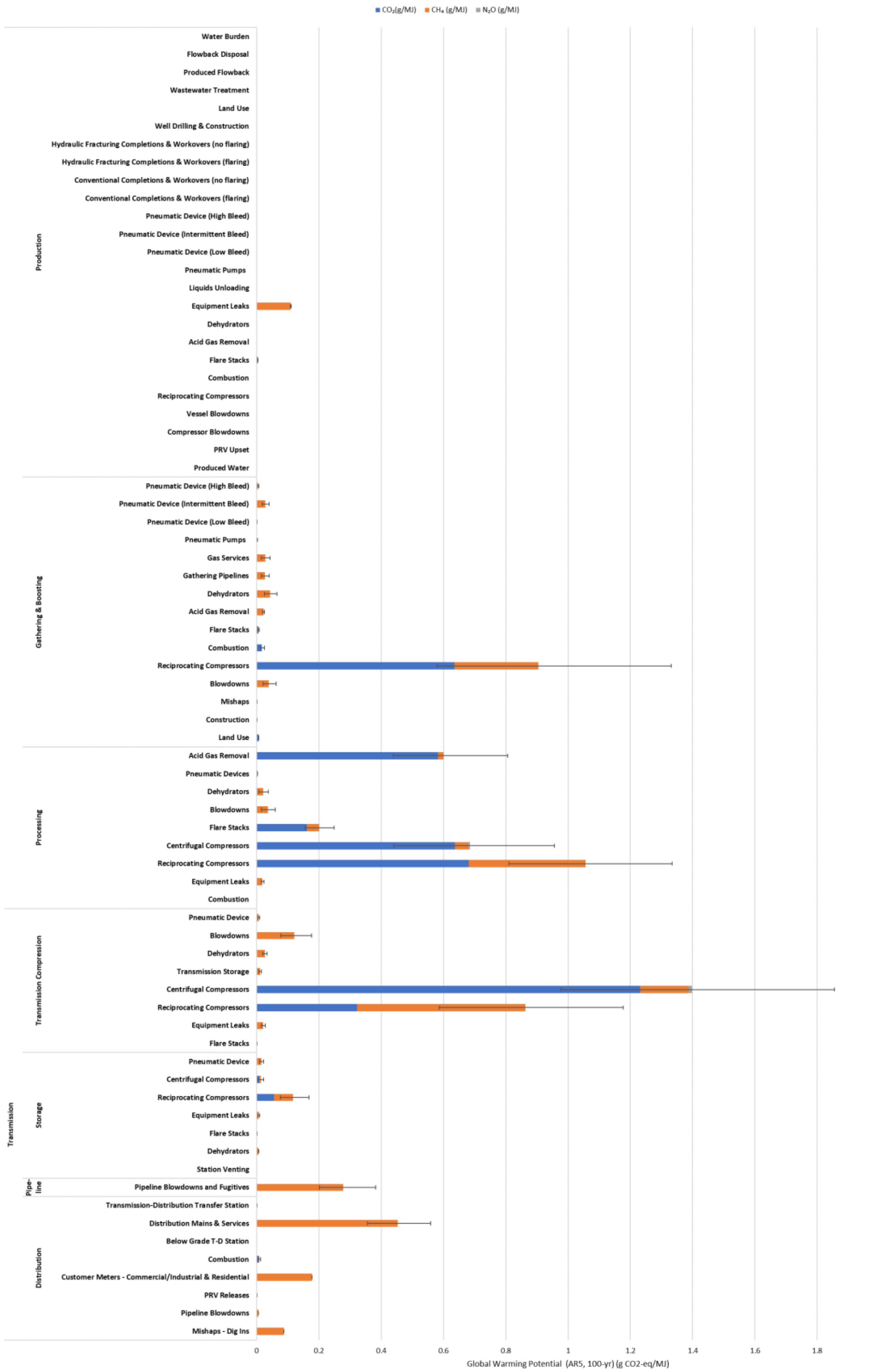


Exhibit I-29. U.S. 100-yr GWP Results for Offshore Gulf of Mexico Scenario

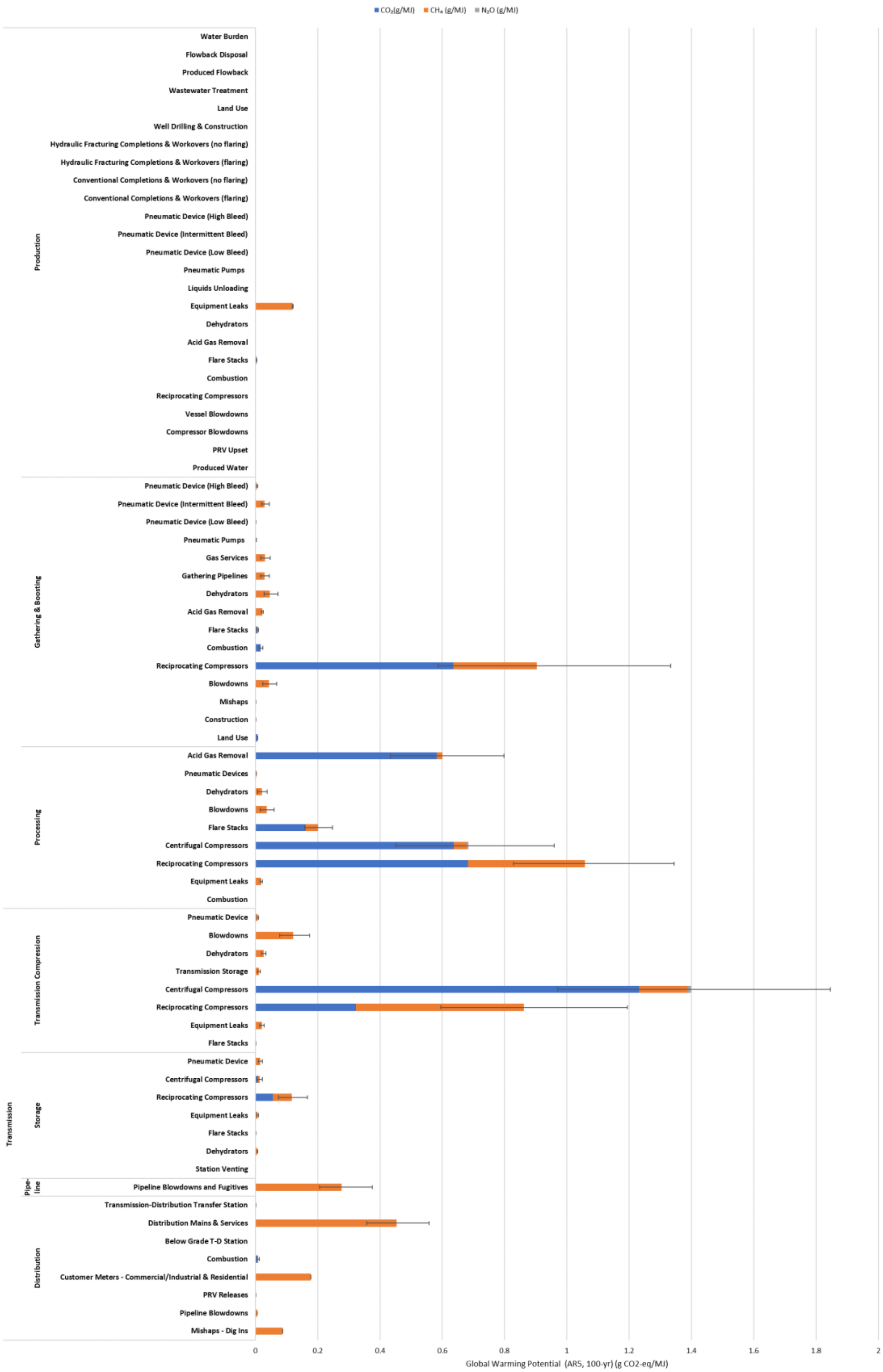
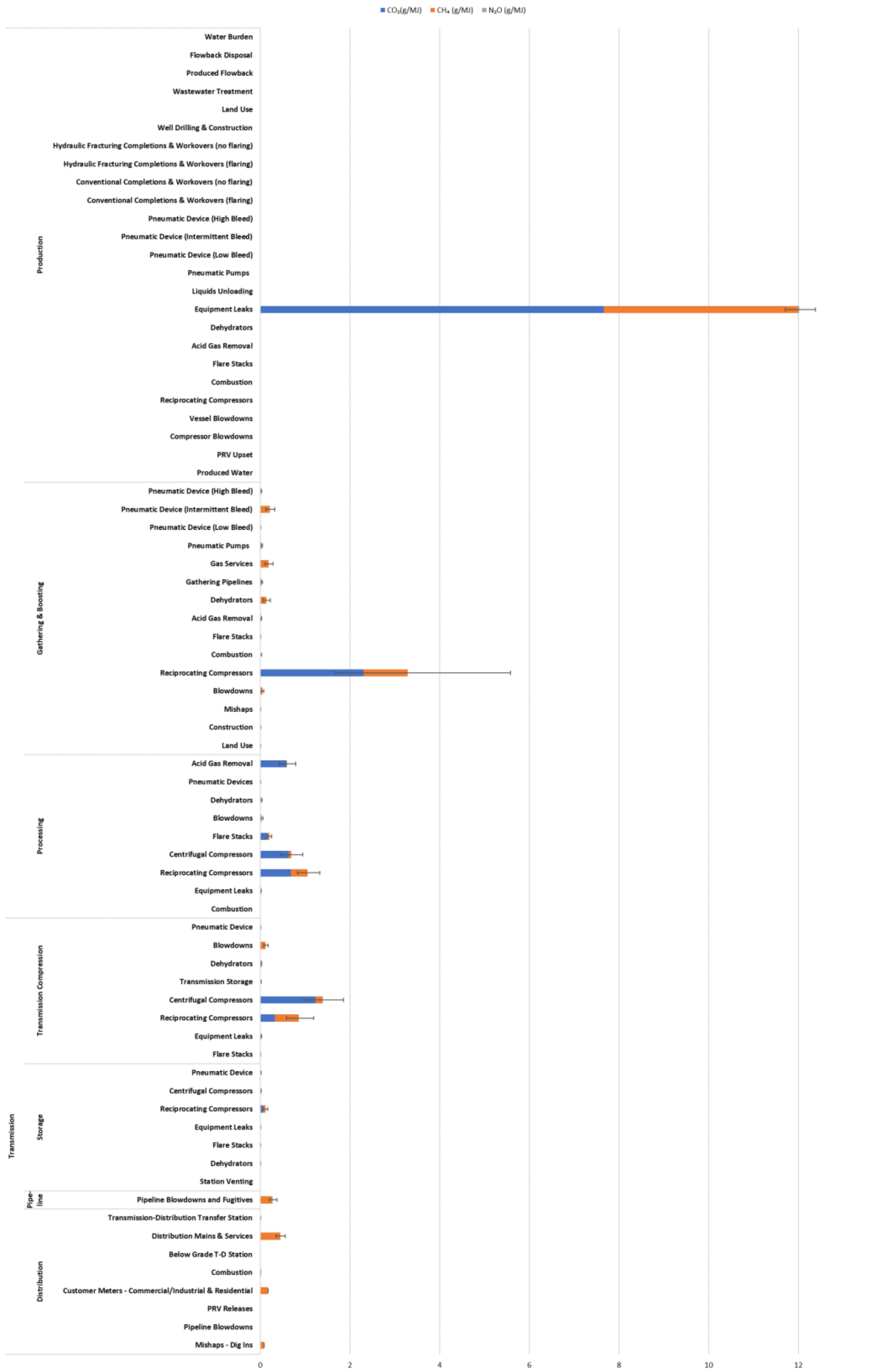


Exhibit I-30. U.S. 100-yr GWP Results for Associated Natural Gas Scenario*



* For the associated natural gas scenario only, production equipment leaks are used as proxy to account all production emissions from associated gas.

Exhibit I-31. Life Cycle GHG Emissions for all U.S. Scenarios (100-year CO_2-eq)

Scenario	Mean CO_2-eq for Specific GHGs			Total CO_2-eq (IPCC AR5, 100-yr GWP)		
	CO_2	CH_4	N_2O	P2.5	Expected	P97.5
Appalachian - Shale	4.49	3.66	0.02	5.91	8.17	10.98
Gulf - Conventional	5.90	6.58	0.02	8.42	12.49	17.43
Gulf - Shale	5.79	6.69	0.02	7.62	12.50	18.38
Gulf - Tight	5.62	6.23	0.02	7.55	11.87	17.18
Arkla - Conventional	4.60	10.50	0.02	11.70	15.11	19.15
Arkla - Shale	4.08	4.13	0.02	5.96	8.22	11.06
Arkla - Tight	4.21	4.39	0.02	6.22	8.62	11.57
East Texas - Conventional	6.94	8.68	0.02	9.32	15.63	23.76
East Texas - Shale	6.77	7.13	0.02	8.58	13.92	20.01
East Texas - Tight	6.23	7.65	0.02	9.02	13.89	20.24
Arkoma - Conventional	7.64	18.67	0.02	19.22	26.33	35.48
Arkoma - Shale	7.31	9.17	0.02	9.83	16.50	25.44
South Oklahoma - Shale	7.02	6.36	0.02	6.60	13.39	21.24
Anadarko - Conventional	7.11	9.49	0.02	9.79	16.62	24.83
Anadarko - Shale	6.43	6.65	0.02	8.10	13.09	18.82
Anadarko - Tight	8.45	12.69	0.02	12.81	21.16	30.93
Strawn - Shale	6.75	7.40	0.02	8.13	14.17	21.60
Fort Worth - Shale	7.08	7.56	0.02	8.96	14.65	22.13
Permian - Conventional	5.68	5.99	0.02	7.49	11.69	16.83
Permian - Shale	6.56	6.34	0.02	7.64	12.92	20.61
Green River - Conventional	4.84	4.06	0.02	5.89	8.91	12.46
Green River - Tight	5.14	5.29	0.02	6.76	10.45	14.85
Uinta - Conventional	5.85	6.13	0.02	7.56	11.99	17.59
Uinta - Tight	5.98	7.76	0.02	7.99	13.76	21.61
San Juan - CBM	8.62	11.87	0.02	12.55	20.50	30.91
San Juan - Conventional	9.96	23.93	0.02	19.56	33.91	51.64
Piceance - Tight	4.87	9.33	0.02	8.94	14.22	21.27
Alaska Offshore	4.36	3.11	0.02	5.36	7.49	10.02
GoM Offshore	4.36	3.14	0.02	5.42	7.51	10.06
Associated Gas	13.69	8.56	0.04	18.36	22.29	27.34

Exhibit I- 32. Life Cycle GHG Emissions for all U.S. Scenarios (20-year CO_2-eq)

Scenario	Mean CO_2-eq for Specific GHGs			Total CO_2-eq (IPCC AR5, 20-yr GWP)		
	CO_2	CH_4	N_2O	P2.5	Expected	P97.5
Appalachian - Shale	4.49	8.85	0.02	9.80	13.35	17.80
Gulf - Conventional	5.90	15.89	0.01	14.72	21.81	30.46
Gulf - Shale	5.79	16.18	0.01	13.17	21.98	32.83
Gulf - Tight	5.62	15.07	0.01	13.09	20.70	30.19
Arkla - Conventional	4.60	25.37	0.01	24.02	29.98	37.07
Arkla - Shale	4.08	9.98	0.01	10.37	14.07	18.72
Arkla - Tight	4.21	10.62	0.01	10.88	14.84	19.72
East Texas - Conventional	6.94	20.97	0.01	16.83	27.93	42.28
East Texas - Shale	6.77	17.22	0.01	15.06	24.01	34.18
East Texas - Tight	6.23	18.48	0.01	16.34	24.72	35.73
Arkoma - Conventional	7.64	45.12	0.01	39.61	52.78	69.81
Arkoma - Shale	7.31	22.16	0.01	17.52	29.48	45.91
South Oklahoma - Shale	7.02	15.37	0.01	11.14	22.40	35.50
Anadarko - Conventional	7.11	22.94	0.01	17.52	30.06	45.37
Anadarko - Shale	6.43	16.07	0.01	13.93	22.51	32.47
Anadarko - Tight	8.45	30.68	0.01	23.84	39.14	57.16
Strawn - Shale	6.75	17.89	0.01	14.41	24.66	37.40
Fort Worth - Shale	7.08	18.26	0.01	15.43	25.36	38.54
Permian - Conventional	5.68	14.47	0.01	12.86	20.17	29.21
Permian - Shale	6.56	15.32	0.01	13.01	21.90	35.15
Green River - Conventional	4.84	9.80	0.01	9.93	14.65	20.26
Green River - Tight	5.14	12.78	0.01	11.78	17.93	25.38
Uinta - Conventional	5.85	14.81	0.01	13.37	20.67	30.00
Uinta - Tight	5.98	18.76	0.01	14.28	24.76	39.37
San Juan - CBM	8.62	28.69	0.01	22.14	37.32	57.46
San Juan - Conventional	9.96	57.84	0.01	39.33	67.81	103.58
Piceance - Tight	4.87	22.55	0.01	17.02	27.44	41.59
Alaska Offshore	4.36	7.52	0.01	8.61	11.89	15.82
GoM Offshore	4.36	7.58	0.01	8.72	11.95	15.92
Associated Gas	13.69	20.68	0.04	28.30	34.41	42.25

This page intentionally left blank.

ADDENDUM – SUMMARY OF REPORT REVISION CHANGES

DATE – February 12, 2021

This addendum modifies the device count in the mitigation strategy “pipeline pump-down before maintenance” in the Marginal Abatement Cost (MAC) Analysis section of the report (**Section 7**). “Pipeline pump-down before maintenance” is one of the mitigation strategies evaluated in the MAC analysis in the transmission pipeline stage. In this method, an inline or portable compressor is installed on the smallest section of the pipeline as a strategy by relieving system pressure. The device count for this strategy was updated to represent the number of compressors instead of the miles of pipeline. This work assumes that one compressor will be needed every 20 miles of the pipeline. In 2017, the total miles of transmission pipeline reported by the ONE Future group was 32,352 miles, this suggests the need of 1,618 compressors for the mitigation strategy of “pipeline pump-down before maintenance”. This modification of the device count from 32,352 to 1,618 reduces the amount of CH_4 reduced that was estimated earlier due to this strategy. As a result, the following changes were made to the report:

1. **Exhibit 7-2 –** The value in the row “Pipeline pump-down before maintenance” and the column “Methane Reduced, Mcf/year” was changed from 1.71E+06 to *8.53E+04*.
2. **Exhibit 7-3 –** The width of the bar representing “pipeline pump-down before maintenance” reduced, thus reducing the final total on the scale.
3. **Conclusions and recommendations – Conclusion #3 for average natural gas –** Instead of 6.5 Bcf CH_4/yr, there are *4.8 Bcf CH_4/yr* of mitigation opportunities that can be achieved using mature technologies, but at high costs.
4. **Conclusions and recommendations – Recommendation #3 –** The high cost emission mitigation opportunities reduced changed from 6.5 Bcf CH_4/yr. The statement now read: “There are significant (1.4 Bcf CH_4/yr) low cost emission mitigation opportunities within ONE Future’s assets, but there are even more (*4.8 Bcf CH_4/yr*) high cost emission mitigation opportunities.”
5. **Appendix D – Exhibit D-2 –** The value in the row “Pipeline pump-down before maintenance” and the column "Device count or Pipeline Length, number of miles” was changed from 32,352 to *1,618*.
6. **Appendix D – Exhibit D-5 –** The values in the row “Pipeline pump-down before maintenance” and the columns “Bcf CH_4 reduced – Transmission” and “Bcf CH_4 reduced – Total” were changed from 1.71 to *0.09* for both. And the value in the row “Total” and the column “Bcf CH_4 reduced – Total” was changed from 6.47 to *4.84*.

Timothy J. Skone
Timothy.Skone@netl.doe.gov

James Littlefield
James.Littlefield@netl.doe.gov

Srijana Rai
Srijana.Rai@netl.doe.gov

www.netl.doe.gov
Albany, OR • Anchorage, AK • Morgantown, WV • Pittsburgh, PA • Sugar Land, TX
(800) 553-7681

NATIONAL ENERGY TECHNOLOGY LABORATORY