U.S. DEPARTMENT OF ENERGY | National Energy Technology Laboratory

OFFICE OF FOSSIL ENERGY

# Life Cycle Analysis of Natural Gas Extraction and Power Generation

August 30, 2016

**DOE/NETL-2015/1714**

# Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference therein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed therein do not necessarily state or reflect those of the United States Government or any agency thereof.

**Author List:**

**National Energy Technology Laboratory (NETL)**

**Timothy J. Skone, P.E.**

**Senior Environmental Engineer**

**Strategic Energy Analysis and Planning Division**

**Energy Sector Planning and Analysis (ESPA)**

**James Littlefield, Joe Marriott, Greg Cooney, Laura Demetrion, Matt Jamieson, Chris Jones, Michele Mutchek, Chung Yan Shih, Greg Schivley, and Michelle Krynock**
**Booz Allen Hamilton, Inc.**

This report was prepared by Energy Sector Planning and Analysis (ESPA) for the United States Department of Energy (DOE), National Energy Technology Laboratory (NETL). This work was completed under DOE NETL Contract Number DE-FE0004001. This work was performed under ESPA Task 150.08.

The authors wish to acknowledge the excellent guidance, contributions, and cooperation of the NETL staff, particularly:

**Erik Shuster**, NETL Technical Monitor

**Evelyn Dale**, NETL Technical Monitor

**DOE Contract Number DE-FE0004001**

This page intentionally left blank.

# Table of Contents

Executive Summary ..... 1
1 Introduction ..... 3
2 Method and Assumptions ..... 3
2.1 Basis of Comparison (Functional Unit) ..... 4
2.2 Boundaries ..... 4
2.3 Representativeness ..... 4
2.3.1 Temporal ..... 4
2.3.2 Technological ..... 5
2.3.3 Geographic ..... 5
2.4 Impact Assessment ..... 6
2.5 Monte Carlo Analysis ..... 7
2.6 Summary of Key Model Parameters ..... 7
2.7 Model Structure ..... 7
3 Data ..... 10
3.1 Sources of Natural Gas ..... 10
3.2 Composition of Production Natural Gas ..... 12
3.3 Production Rate ..... 14
3.4 Venting and Flaring ..... 16
3.5 Extraction of Natural Gas ..... 18
3.5.1 Extraction Land Use ..... 18
3.5.2 Well Construction and Installation ..... 22
3.5.3 Well Completions and Workovers ..... 23
3.5.4 Liquids Unloading ..... 25
3.5.5 Pneumatic Devices (Extraction) ..... 31
3.5.6 Fugitive Emissions (Extraction) ..... 36
3.5.7 Produced Water Tanks ..... 41
3.5.8 Point Source and Fugitive Emissions from Offshore Extraction ..... 41
3.6 Processing of Natural Gas ..... 42
3.6.1 Acid Gas Removal ..... 42
3.6.2 Dehydration ..... 43
3.6.3 Liquids Separation ..... 43
3.6.4 Pneumatic Devices (Processing) ..... 44
3.6.5 Other Point Source Emissions (Processing) ..... 44
3.6.6 Fugitive Emissions (Processing) ..... 45
3.6.7 Natural Gas Compression ..... 45
3.7 Transmission of Natural Gas ..... 46
3.7.1 Natural Gas Transport Construction ..... 47
3.7.2 Natural Gas Transport Operations ..... 47
3.8 Distribution of Natural Gas ..... 47
3.9 Electricity Generation from Natural Gas ..... 48
3.9.1 Advanced Natural Gas Power ..... 48
3.9.2 Fleet Natural Gas Power ..... 49
3.9.3 Power Plant and $CO_2$ Sequestration Land Use ..... 53
3.10 Electricity Transmission and Distribution ..... 54
4 Results ..... 55
4.1 Delivered Natural Gas ..... 55

4.1.1 Sensitivity Analysis ..... 62
4.2 $CH_4$ Emission Rate ..... 64
4.3 Delivered Natural gas-fired Electricity ..... 68
5 References ..... 70
Appendix A: Unit Process Maps for Upstream Natural Gas ..... A-1
Appendix B: Upstream Parameters by NETL Region and Extraction Technology ..... B-1
Appendix C: GHG and Non-GHG Emissions Data for Natural Gas Systems ..... C-1
Appendix D: Parameter Inputs for Unit Processes Used in Natural Gas Model ..... D-1

# Figures

Figure ES-1: $CH_4$ Emission Rates and GHG Emissions for the Delivery of NG to Consumers ..... 1
Figure 2-1: NETL Natural Gas Production Regions (Alaska and Alaska Offshore not pictured) ..... 6
Figure 2-2: Natural Gas Modeling Structure ..... 9
Figure 3-1: Emissions Pathways for Offshore Extraction ..... 42
Figure 3-2: Multi-box Scatterplot for Fleet Natural Gas Power Plants ..... 50
Figure 3-3: Capacity Factor vs. Cumulative Net Annual Generation, Natural Gas ..... 51
Figure 3-4: Capacity Factor vs. Percent Net Annual Generation, Natural Gas ..... 51
Figure 4-1: Upstream Cradle-to-gate Natural Gas GHG Emissions by Source ..... 56
Figure 4-2: Expanded Greenhouse Gas Results for Appalachian Shale Gas ..... 59
Figure 4-3: Expanded Greenhouse Gas Results for the Next Appalachian Shale Well ..... 61
Figure 4-4: Sensitivity of Appalachian Shale Natural Gas GHG Emissions to Changes in Parameters ..... 63
Figure 4-5: $CH_4$ Emission Rates and GHG Emissions for the Delivery of NG to Consumers ..... 65
Figure 4-6: Uncertainty Contributions to Marcellus Shale GHGs ..... 67
Figure 4-7: Life Cycle GHG Emissions for Electricity Production from Natural Gas ..... 68

# Tables

Table ES-1: $CH_4$ Emission Rates and GHG Emissions for Three Upstream Boundaries ..... 1
Table 2-1: IPCC Global Warming Potentials (IPCC, 2013) ..... 7
Table 3-1: Mix of U.S. Natural Gas Sources in 2012 (EIA, 2014) ..... 11
Table 3-2: Natural Gas Composition on a Mass Basis (EPA, 2011d, 2013b) ..... 13
Table 3-3: EUR Values by Technology and Production Region ..... 15
Table 3-4: Flaring Activity for Well Completions and Workovers ..... 17
Table 3-5: Flaring Activity Factors for Other Processes ..... 18
Table 3-6: Land Use Area by Technology and Production Region ..... 19
Table 3-7: $CO_2$ Emission Factors by Production Region and Technology ..... 20
Table 3-8: Land Use Fractions by Production Region and Technology ..... 21
Table 3-9: Drill Depth (m) by Production Region and Technology ..... 22
Table 3-10: Initial Production (scf/day) of Tight Gas and Shale Wells ..... 24
Table 3-11: Conventional (onshore & offshore) and CBM Completion Emission Factors (EPA, 2010a) ..... 25
Table 3-12: Workover Episodes by Technology and Workover Emission Factors for Conventional (onshore and offshore) and CBM Wells (EPA, 2010a) ..... 25
Table 3-13: Parameters for Calculation of Potential Emissions from Liquids Unloading ..... 26
Table 3-14: Liquid Unloading Data by Production Region and Technology ..... 27

Table 3-15: Liquid Unloading Data by Production Region and Technology ..... 28
Table 3-16: Liquid Unloading Data by Production Region and Technology ..... 29
Table 3-17: Liquid Unloading Data by Production Region and Technology ..... 30
Table 3-18: Pneumatic Device Data by Production Region and Technology ..... 32
Table 3-19: Pneumatic Device Data by Production Region and Technology ..... 33
Table 3-20: Pneumatic Device Data by Production Region and Technology ..... 34
Table 3-21: Pneumatic Device Data by Production Region and Technology ..... 35
Table 3-22: Fugitive Emissions Data by Production Region and Technology ..... 37
Table 3-23: Fugitive Emissions Data by Production Region and Technology ..... 38
Table 3-24: Fugitive Emissions Data by Production Region and Technology ..... 39
Table 3-25: Fugitive Emissions Data by Production Region and Technology ..... 40
Table 3-26: Produced Water Tank Data for all Production Regions ..... 41
Table 3-27: Point Source and Fugitive Emissions Data for Offshore Conventional Production ..... 42
Table 3-28: Summary of NG Processing Energy and Potential Emissions ..... 45
Table 3-29: Summary of NG Processing Compression Energy and Potential Emissions ..... 46
Table 3-30: Expected Qualitative Characteristics for U.S. Natural Gas Power Plant Types ..... 49
Table 3-31: Capacity Factor Filters for Plant Categorization ..... 52
Table 3-32: Emission Profile Results for Natural Gas Fleet Type and NERC Region Averages (EPA, 2014a) ..... 53
Table 3-33: Land Use Area Assumptions for Electricity Generation ..... 54
Table 4-1: $CH_4$ Emission Rates and GHG Emissions for Three Upstream Boundaries ..... 66

# Acronyms and Abbreviations

| | |
|---|---|
| AGR | Acid gas removal |
| ANGA | America's Natural Gas Alliance |
| API | American Petroleum Institute |
| AR5 | Fifth Assessment Report, IPCC |
| ASCC | Alaska Systems Coordinating Council |
| bbl | Barrel |
| Bcf | Billion cubic feet |
| BTS | Bureau of Transportation Statistics |
| Btu | British thermal unit |
| CBM | Coal bed methane |
| CCS | Carbon capture and sequestration |
| CenSARA | Central States Air Resource Agencies |
| $CH_4$ | Methane |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| $CO_2e$ | Carbon dioxide equivalent |
| DCA | Decline curve analysis |
| DOE | Department of Energy |
| eGRID | Emissions & Generation Resource Integrated Database |
| EF | Emission factor |
| EIA | Energy Information Administration |
| EPA | Environmental Protection Agency |
| ERCOT | Electric Reliability Council of Texas |
| EUR | Estimated ultimate recovery |
| FERC | Federal Energy Regulatory Commission |
| FRCC | Florida Reliability Coordinating Council |
| g | Gram |
| GGFRP | Global Gas Flaring Reduction Partnership |
| GHG | Greenhouse gas |
| GRI | Gas Research Institute |
| GWP | Global warming potential |
| $H_2S$ | Hydrogen sulfide |
| IPCC | Intergovernmental Panel on Climate Change |
| kg | Kilogram |
| km | Kilometer |
| kWh | Kilowatt-hour |
| LC | Life cycle |
| LCA | Life cycle assessment/analysis |
| LU | Liquid unloading |
| m | Meter |
| MRO | Midwest Reliability Organization |
| Mcf | Thousand cubic feet |
| MJ | Megajoule |
| MW | Megawatt |
| MWh | Megawatt-hour |
| $N_2O$ | Nitrous oxide |
| NERC | North American Electric Reliability Corporation |
| NETL | National Energy Technology Laboratory |
| NG | Natural gas |
| NGCC | Natural gas combined cycle |
| NGL | Natural gas liquids |
| NMVOC | Non-methane volatile organic compound |
| NOAA | National Oceanic and Atmospheric |
| $NO_X$ | Nitrogen oxides |
| NPCC | Northeast Power Coordinating Council |
| O&G Tool | Oil and Gas Emission Estimation Tool |
| OEL | Open-ended line |
| Pb | Lead |
| PM | Particulate matter |
| psig | Pounds per square inch gauge |
| RFC | Reliability First Corporation |
| RFS | Renewable Fuel Standards |
| RTO | Regional transmission organization |
| scf | Standard cubic feet |
| SERC | Southeastern Electric Reliability Council |
| $SF_6$ | Sulfur hexafluoride |
| SM | Service mark |
| $SO_2$ | Sulfur dioxide |
| SPP | Southwest Power Pool |
| T&D | Transmission and distribution |
| TDS | Total dissolved solids |
| ton | Short ton (2,000 lb) |
| tonne | Metric ton (1,000 kg) |
| TRE | Texas Reliability Entity |
| U.S. | United States |
| VOC | Volatile organic compound |
| VRU | Vapor recovery unit |
| WECC | Western Electricity Coordinating Council |
| WWTP | Wastewater treatment plant |

# Executive Summary

This analysis calculates the life cycle environmental burdens for natural gas systems. Two system boundaries are used: a cradle-to-gate boundary that allows analysis of the natural gas supply chain, and a cradle-to-grave boundary that allows analysis of electricity produced from natural gas. For the cradle-to-gate boundary, the functional unit (i.e., the delivered service) is 1 MJ of natural gas delivered by local distribution companies. When the boundaries are expanded to include power generation, the functional unit is the delivery of 1 megawatt-hour (MWh) of electricity to the consumer.

Natural gas emissions are driven by both regional and technological variability. The concentration of methane ($CH_4$) in production gas, reservoir pressure, the tendency of liquids to accumulate in the wellbore, and the amount of gas available for recovery are key parameters that vary regionally. The different practices for well completions and the types and ages of equipment used throughout upstream infrastructure are key technological differentiators. The virtually infinite combinations of these variables explain why there is a three-fold difference between the high and low values for the expected upstream GHG results.

While the variability in results is explained by the many combinations of regional and technological variables, the use of Monte Carlo simulation allows for the production of uncertainty ranges that represent a likely distribution of results. Doing so prevents the undue amplification of uncertainty that is caused by the pairing of extreme parameters. Instead of generating uncertainty bounds that represent only the worst- and best-possible scenarios, the Monte Carlo simulation uses random sampling of parameter distributions to generate uncertainty ranges that represent likely results.

Global warming potentials (GWPs) are used to convert GHG emissions to a common basis of carbon dioxide equivalents ($CO_2e$). The use of 20-year GWPs instead of 100-year GWPs amplifies scenarios that have high proportions of methane ($CH_4$) emissions. In the context of upstream natural gas, this amplification emphasizes key opportunities for reducing emissions from the natural gas supply chain. On 100- and 20-year time frames, the domestic mix of upstream natural gas has expected GHG emissions of 14.8 and 30.4 grams (g) of $CO_2e$ per MJ, respectively.

This analysis combines cradle-through-transmission natural gas data into a domestic natural gas mix that is used to model the environmental burdens from natural gas power systems with advanced and average fleet power plants. A functional unit of 1 megawatt-hour (MWh) of electricity delivered to the consumer is used as the basis for comparing the cradle-to-grave burdens of natural gas power systems. For scenarios without carbon capture and sequestration (CCS), $CO_2$ accounts for the majority of cradle-to-grave GHG emissions from natural gas-fired power, but the results for the natural gas power scenarios are still sensitive to the choice of GWP time frame. On 100- and 20-year time frames, the life cycle GHG emissions for baseload electricity from the existing fleet of natural-gas fired power plants are 514 and 613 kg $CO_2e$/MWh, respectively.

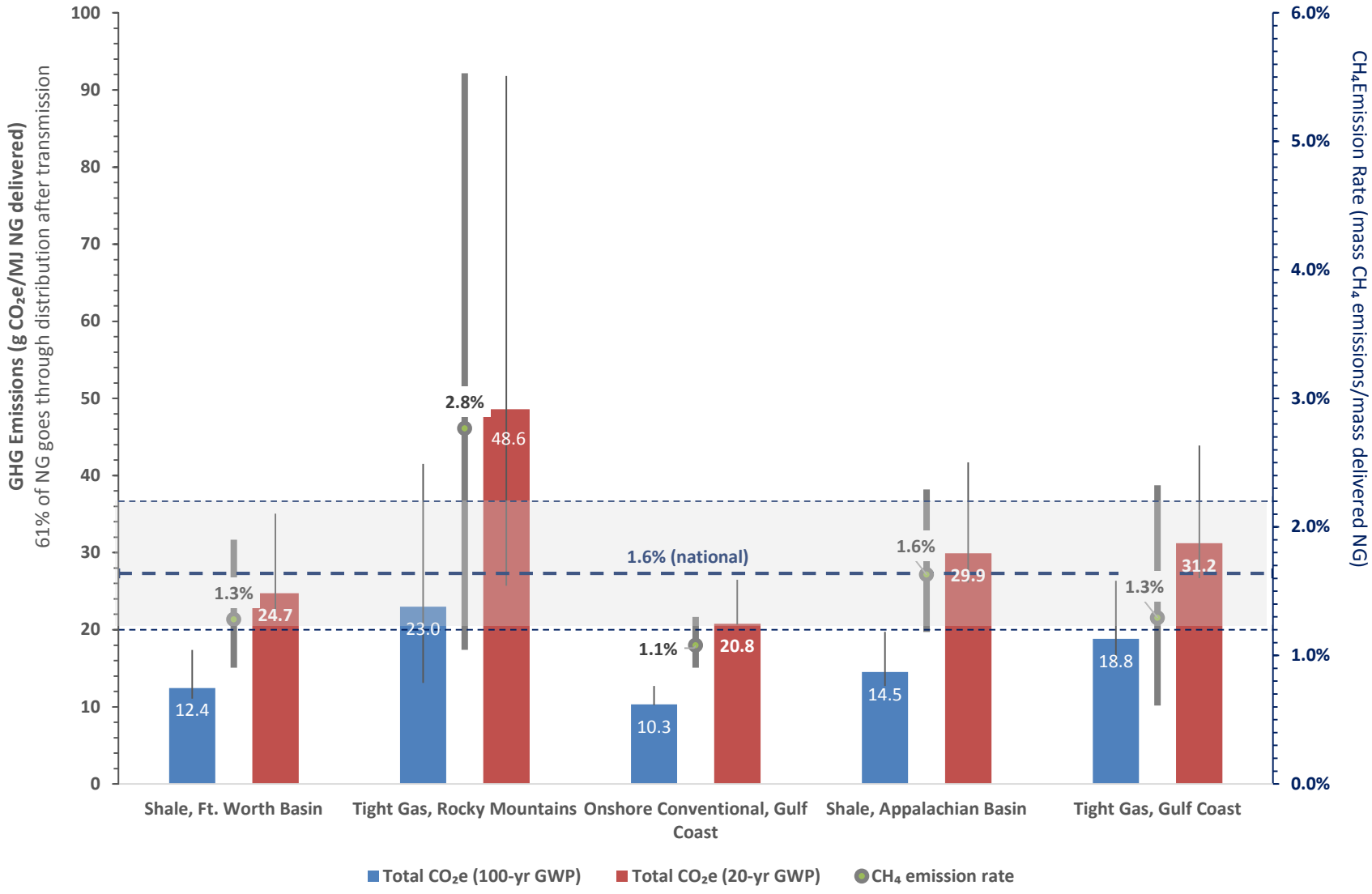
This analysis uses the latest version of the National Energy Technology Laboratory (NETL) natural gas model. NETL's natural gas model was updated and expanded from the previous 2014 natural gas life cycle GHG analysis:

- More details are used in calculating the fugitive, pneumatic, and liquid unloading emissions at extraction. Detailed calculations are made for five specific sources of fugitive emissions, account for variability in pneumatic bleed rates, and distinguish between wells with automatic and manual liquids unloading.

- Potential emissions (which represent the emissions that would be released if environmental controls were not in place) from unconventional completions (hydrofracking) are now calculated using the initial production rates of wells and the length (in days) of the flowback period. Unlike the legacy factor of 9,000 thousand cubic feet (Mcf) per completion event, this new episode ties together well performance and potential completion emissions.
- The domestic supply mix now includes natural gas produced in Alaska and also accounts for the technology profiles of 12 onshore and 3 offshore production regions. This supply mix is based on the latest data published by EIA and is representative of 2012 production. The resulting scenarios are thus a combination of technology and geography.
- Regional natural gas compositions are applied to the vent and flare streams from extraction and processing. This allows accurate speciation between $CH_4$, $CO_2$, and non-methane VOC emissions.
- The fifth version of IPCC's GHG guidelines are applied to the GHG inventory results. All instances in which results are shown in terms of $CO_2e$ use this latest version of the IPCC guidelines, wherein the 100- and 20-year GWP factors for fossil $CH_4$ are 36 and 87, respectively, and include climate change feedback (these factors were 25 and 78 in the previous version of IPCC's guidelines).

The emission rate of $CH_4$ from the natural gas supply chain (the emission of a mass of $CH_4$ per mass of natural gas delivered) not only represents a loss of product, but also represents the emission of a potent GHG. $CH_4$ emission rate is calculated from the outputs of the model and varies by extraction technologies and extraction regions. **Figure ES-1** shows the $CH_4$ emission rates and associated GHG emissions (using 100- and 20-year GWPs) for the top five producers (based on 2012 production volumes) of natural gas. The national $CH_4$ emission rate is 1.6 percent and ranges between 1.2 and 2.2 percent. This national emission rate is a production weighted composite of 31 different combinations of extraction technologies and regions (not all production scenarios are shown in **Figure ES-1**). Some combinations of production technologies and regions (such as tight gas extraction in the Rocky Mountains) may have wide bounds on $CH_4$ emission rate, but these wide bounds are diminished when all extraction technologies and regions are sampled to arrive at the national average.

**Figure ES-1: $CH_4$ Emission Rates and GHG Emissions for the Delivery of NG to Consumers**



The results in **Figure ES-1** represent a modification to the default cradle-to-gate boundary. Unlike the default cradle-to-gate boundary, in which 100 percent of natural gas is distributed to small scale consumers, the $CH_4$ emission rates in **Figure ES-1** represent a 39 percent delivery share to power plants that use natural gas immediately after transmission, and a 61 percent delivery share to smaller scale consumers who receive natural gas from local distribution systems. This 39/61 split is used only in the context of discussing $CH_4$ emission rates, thus providing a useful comparison point for ongoing natural gas research. All other results in this analysis are expressed in terms of the functional units defined above. **Table ES-1** shows how $CH_4$ emission rates change with changes to the upstream boundary.

**Table ES-1: $CH_4$ Emission Rates and GHG Emissions for Three Upstream Boundaries**

| Upstream boundary | Consumers | $CH_4$ Emission Rate | GHG Emissions (g $CO_2$e/MJ in 100-yr GWP) |
|---|---|---|---|
| Cradle through transmission | Large scale (power plants) | 1.4% | 12.7 |
| Cradle through transmission/ distribution | 39%/61% mix of large/small scale | 1.6% | 13.6 |
| Cradle through distribution | Small scale (industrial, commercial, residential) | 1.8% | 14.8 |

This analysis also includes non-GHG emissions, water quality, and water use metrics. These comprehensive metrics demonstrate the importance of evaluating the trade-offs among different environmental burdens.

# 1 Introduction

Natural gas (NG) is considered a cleaner burning and more flexible alternative to other fossil fuels today. It is used in residential, commercial, industrial, and transportation applications in addition to having an expanding role in power production. However, the primary component of natural gas is methane ($CH_4$), which is also a powerful greenhouse gas (GHG) that is 8 to 87 times as potent as carbon dioxide ($CO_2$) (Forster et al., 2007). Emissions of $CH_4$ during the extraction, transmission, and delivery of natural gas were 24 percent of United States' (U.S.) 2013 total $CH_4$ emissions and 2.4 percent of all GHGs when comparing GHGs on a 100-year time frame (EPA, 2015b)[1]. The $CH_4$ emission rate varies with the source of natural gas, due to the variability among geographic locations of natural gas formations and the different technologies used to extract natural gas.

This analysis expands upon previous life cycle analyses (LCA) of natural gas power generation technologies performed by the National Energy Technology Laboratory (NETL). It describes in detail the GHG emissions due to extracting, processing, and transporting various sources of natural gas to large end users, and the combustion of that natural gas to produce electricity. Emission inventories are created for the 2012 average natural gas production mix, and a scenario is created for the next natural gas well to be completed and put into production. This context allows an analysis of current and future emissions.

This analysis also includes an expanded system that compares the life cycle GHGs from advanced and fleet natural gas-fired power plants. The results for this expanded system are expressed in terms of a unit of electricity delivered to the end user and include all life cycle stages from fuel extraction through electricity transmission and distribution. This comparison provides perspective on the scale of fuel extraction and delivery emissions relative to subsequent emissions from power generation and electricity transmission.

Beyond presenting the inventory, the goal of this analysis is to provide a clear presentation of NETL's natural gas model, including documentation of key assumptions, data sources, and model sensitivities. Further, areas of large uncertainty in the inventory are highlighted, along with areas for potential improvement in both data collection and GHG reductions.

There are many opportunities to decrease the GHG emissions from natural gas extraction, delivery, and power production, including the reduction of fugitive $CH_4$ emissions at wells and the implementation of advanced combustion technologies and carbon capture and storage (CCS). GHGs are not the only factor that should be considered when comparing energy options, so this analysis also includes a full inventory of air emissions, water use and quality, and land use. The results for non-GHG emissions are presented in **Appendix C.**

# 2 Method and Assumptions

LCA is a systematic approach that calculates the environmental burdens of a product or system. The development of an LCA requires a basis for comparison, boundaries, and a modeling framework. The structure of a life cycle model and the data used by the model are also important aspects of performing an LCA.

[1] 2013 is the most recent data year in the EPA GHG inventory. The results of this analysis are reported in terms of 2012 natural gas production activity because that is the most recent year for most of the underlying parameters; EPA's emission inventory shows that natural gas systems emitted 24 percent of the 2012 U.S. $CH_4$ emissions.

## 2.1 Basis of Comparison (Functional Unit)

To establish a basis for comparison, the LCA method requires specification of a functional unit, the goal of which is to define an equivalent service provided by the systems of interest. Two functional units are used in this analysis: a cradle-to-gate functional unit that allows analysis of the natural gas supply chain, and a cradle-to-grave functional unit that allows analysis of electricity produced from natural gas. For the cradle-to-gate boundary, the functional unit is 1 MJ of natural gas delivered through local distribution companies. When the boundaries are expanded to include power production, the functional unit is the delivery of 1 megawatt-hour (MWh) of electricity to the consumer.

## 2.2 Boundaries

To be consistent with the two functional units defined above, the first portion of this analysis develops a detailed environmental profile of upstream natural gas. The second portion of this analysis applies a cradle-to-grave boundary that compares the environmental inventory from natural gas extraction and transport to those from electricity production and transmission.

Upstream natural gas comprises natural gas extraction, processing, and delivery. The upstream boundary begins with all construction and operation activities necessary to extract fuel from the earth, and ends after fuel is extracted, processed, transported by the natural gas transmission network to local distributors, and delivered via a distribution network to consumers. The functional unit for the upstream boundary is the delivery of 1 MJ of natural gas to the consumer.

The cradle-to-grave boundary for electricity produced from natural gas includes upstream natural gas, except for the distribution step; natural gas power plants are large-scale consumers of natural gas and are located near natural gas transmission networks. The cradle-to-grave boundary also comprises the operation of power plants and the transmission and distribution (T&D) of electricity to the consumer. The functional unit for the cradle-to-grave boundary is the delivery of 1 MWh of electricity to the consumer. (The types of consumer applications for electricity, and their associated efficiencies, are outside the scope of this analysis.)

## 2.3 Representativeness

This inventory uses data gathered from a variety of sources, each of which represents a particular temporal period, geographic location, and state of technology. Since the results of this analysis are the combination of each of those inventory sources, this section discusses the temporal, geographic, and regional representativeness of the results of this analysis.

### 2.3.1 Temporal

The temporal characteristics of this analysis include the vintage of data for the natural gas supply chain and power plants, as well as the lifetimes of natural gas wells, power plants, and associated infrastructure.

The natural gas upstream results best represent the year 2012, because the 2012 Energy Information Administration (EIA) natural gas production data are used to create the mix of natural gas sources in the domestic average result. The results for energy conversion facilities are based on advanced power plants modeled by NETL in 2010 (NETL, 2010a) and on 2010 operating data for U.S. power plants as reported in the latest version of Environmental Protection Agency's (EPA) Emissions & Generation Resource Integrated Database (eGRID) (EPA, 2012). Some data included in this analysis pre-dates these years, but were determined to be the latest or highest quality data available. The

upstream natural gas data are mostly representative of 2012, and the power plant data are mostly representative of 2010; however, these data represent mature technologies with established infrastructures, making it reasonable to expand the representativeness to a broader time frame, such as 2005 to 2015.

The study period is 30 years. This period is used to apportion one-time burdens (such as well construction, well completion, and power plant construction) to a unit of gas produced or electricity delivered. Assumptions are made about natural gas resource availability based on current estimated ultimate recovery (EUR) values and forecasts from the EIA. It is also assumed that the capacity factors of power plants, which affect the total amount of electricity that they produce in their lifetimes, are assumed to be constant over the study period.

### 2.3.2 Technological

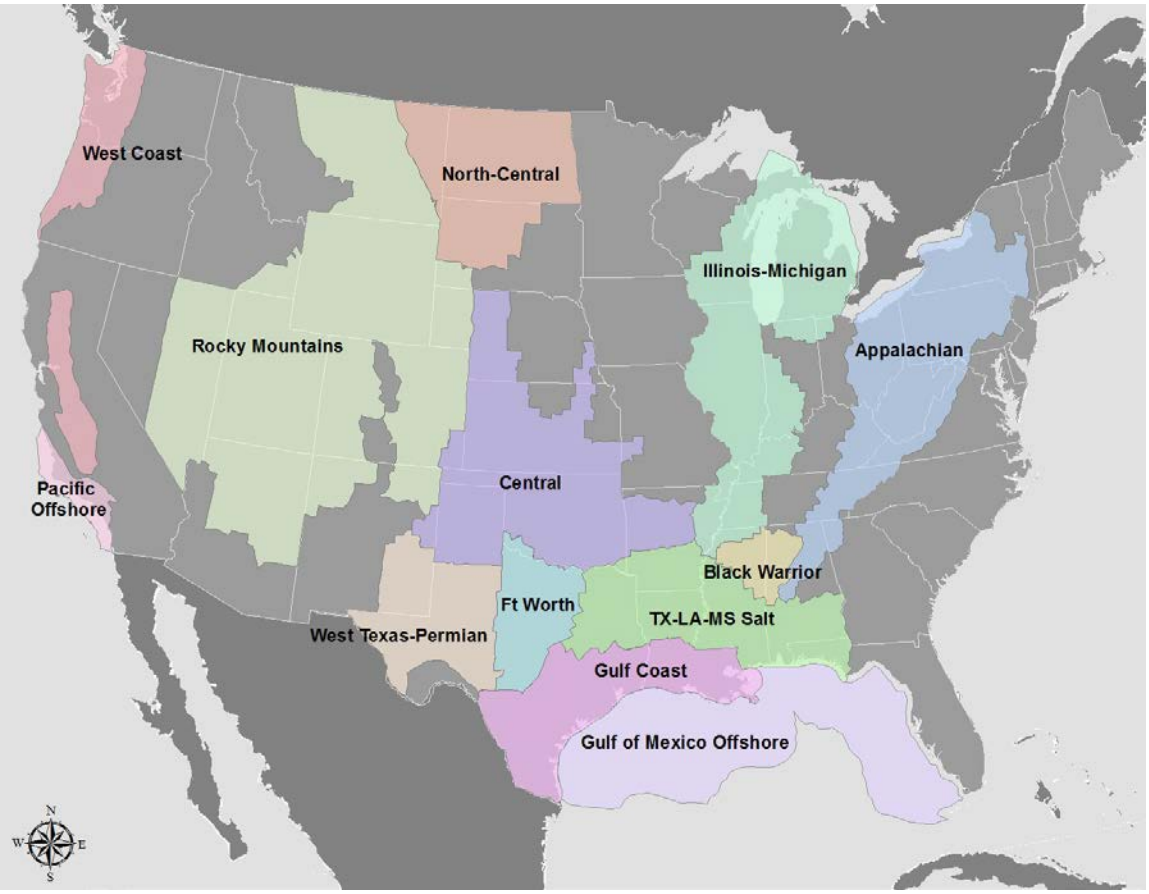
The natural gas upstream inventory results include two distinct technological representations. The first is a baseline result that represents average 2012 natural gas production, including production from older, less productive wells. Production data from that year is used to create an average domestic mix of natural gas sources, and the production rate of each source well is generally based on 2012 well count and production data.

The power plant results are a mix of current and advanced technologies. This analysis includes fleet power plants that are representative of installed technology as of 2009 and also includes advanced power plants – with and without $CO_2$ capture – that are representative of the latest technology but have not achieved broad commercialization.

### 2.3.3 Geographic

The location of an activity can affect its environmental performance, so this analysis accounts for geographic variability. For natural gas production sites, 12 onshore and 3 offshore regions are modeled and are shown in **Figure 2-1**. Unless noted otherwise, all natural gas production unit processes account for the variability among these 15 regions. Onshore and offshore sources of natural gas in Alaska are included in this analysis but are not shown in **Figure 2-1**. Additionally, only regions with offshore extraction are labeled as such; all other regions contain onshore extraction technologies only.

**Figure 2-1: NETL Natural Gas Production Regions (Alaska and Alaska Offshore not pictured)**




The above regions were defined by NETL based on the distribution of natural gas reservoirs in the U.S. as illustrated by the EIA's maps of natural gas plays (EIA, 2009). The regions that the EIA uses for their analyses are different than those defined here. Most regions comprise at least two extraction technologies, with the exceptions being the Fort Worth and West Texas-Permian shale basins, and the Black Warrior coal bed methane (CBM) basin. **Table 2-1** provides more definition on the geological provinces (i.e., regions or subregions with common geological characteristics) for each of the regions used in this analysis.

**Table 2-1: Geological Provinces that Compose Production Regions**

| Region | Geologic Province(s) |
|---|---|
| Alaska | Cook Inlet, North Slope |
| Alaska Offshore | Offshore Alaska |
| Appalachian Basin | Appalachian Basin |
| Black Warrior Basin | Black Warrior Basin |
| Central | Anadarko Basin, Arkoma Basin, Southern Oklahoma, Cherokee Platform, Sedgwick Basin, Nemaha Uplift |
| Fort Worth | Fort Worth Basin |
| Gulf Coast | Western Gulf |
| Gulf of Mexico Offshore | Gulf Coast Offshore Basin |
| Illinois/Michigan Basins | Michigan Basin, Illinois Basin |
| North-Central | Williston Basin |
| Pacific Offshore | Ventura Basin, Los Angeles Basin, Santa Maria Basin |
| Rocky Mountains | Greater Green River Basin, Uinta-Piceance Basin, San Juan Basin, Denver Basin, Wind River Basin, Powder River Basin, Raton Basin-Sierra Grande Uplift, Paradox Basin, Wyoming Thrust Belt, Big Horn Basin, Las Animas Arch, Northern Arizona, Eastern Great Basin |
| Texas-Louisiana-Mississippi Salt Basins | East Texas Basin, Louisiana-Mississippi Salt Basin |
| West Coast | San Joaquin Basin, Sacramento Basin, Western Oregon-Washington |
| West Texas | Permian Basin |

This analysis does not specify locations for natural gas power plants. The transport distance between natural gas processing facilities and processing plants are based on the U.S. average natural gas transmission distance, and the performance of natural gas power plants does not vary significantly among locations. Altitude and other geographically-specific factors may affect power plant performance (EPA, 2015a), but the influence of such factors is insignificant compared to non-geographic factors, such as power plant age, scale, and configuration of emission control equipment.

## 2.4 Impact Assessment

Impact assessment in this analysis is limited to the application of Global Warming Potential (GWP) to all of the inventoried GHGs. GHGs in this analysis are reported on a common mass basis of carbon dioxide equivalents ($CO_2e$) using the GWPs of each gas from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) (IPCC, 2013). The default GWP used is the 100-year time frame, but in some cases, results for the 20-year time frame are presented as well. All GHG results in this analysis are expressed as 100-year GWPs unless specified otherwise. **Table 2-2** shows the GWPs used for the GHGs that were inventoried.

**Table 2-2: IPCC Global Warming Potentials (IPCC, 2013)**

| GHG | 20-year | 100-year |
|---|---|---|
| $CO_2$ | 1 | 1 |
| $CH_4$ | 87 | 36 |
| $N_2O$ | 268 | 298 |
| $SF_6$ | 17,500 | 23,500 |

## 2.5 Monte Carlo Analysis

When data are available, high and low values are collected along with an expected value. These values are used to develop a triangular probability distribution (no parameters in the natural gas model have enough data points to represent distributions that are more informed than triangular distributions). The resulting distributions are used for running a Monte Carlo analysis. Monte Carlo analysis is a method that calculates the probability of an outcome; it works by taking random samples from probability distributions, calculating a result, and repeating this sampling and calculation process many times to arrive at the likelihood of a given outcome.

## 2.6 Summary of Key Model Parameters

Bottom-up unit processes rely heavily on parameterization because they use scientific principles and engineering concepts to calculate inputs and outputs. The primary unit processes of the model used for this analysis are based on data compiled by NETL. Secondary unit processes, such as production of construction materials, are based on third party data. The tables in **Appendix B** summarize the key parameters that affect the life cycle results for the extraction of natural gas. This includes the $CH_4$ emissions from routine activities, frequency and emission rates from non-routine operations, depths of different well types, flaring rates of vented gas, production rates, and domestic supply shares. **Appendix A** includes details on how these data are assembled in a model and references the detailed documentation in NETL's unit process library.

## 2.7 Model Structure

All results for this analysis were calculated by NETL's life cycle model for natural gas systems, which is a model of interconnected network of operation and construction blocks covering fuel extraction through electricity transmission. Each block in the model, referred to as a unit process, accounts for the key inputs and outputs of an activity. The inputs of a unit process include the purchased fuels, resources from nature (fossil feedstocks, biomass, or water), and man-made raw materials. The outputs of a unit process include air emissions, water effluents, solid waste, and product(s). A life cycle model calculates the values for all intermediate flows within a network of unit processes, and then scales the flows of all unit processes to a common basis, or functional unit.

The network of unit processes used for the modeling of natural gas systems is shown in **Figure 2-2**. Note that only the extraction, processing, transmission, and distribution portions of the model are necessary to determine the upstream environmental burdens of natural gas. A broader scope – from extraction through delivery of electricity – is necessary to determine the cradle-to-grave environmental burdens of natural gas power. The upstream natural gas supply chain is organized into the four aforementioned steps: extraction, processing, transmission, and distribution, each of which is described below.

- **Extraction:** A natural gas extraction site has a well pad that holds permanent equipment and also provides room for development and maintenance activities. The construction of natural gas wells requires a well casing that provides strength to the well bore and prevents contamination of the geological formations that surround the gas reservoir. In the case of offshore extraction, a large platform is also required. Well completions are the activities following well drilling and preceding production. Liquid unloading is a routine operation for gas wells affected by the accumulation of fluids in the well. Other sources of emissions include the gas that bleeds from pneumatically-controlled devices and fugitive emissions from flanges, connectors, open-ended lines, and valves. When vapor recover units are

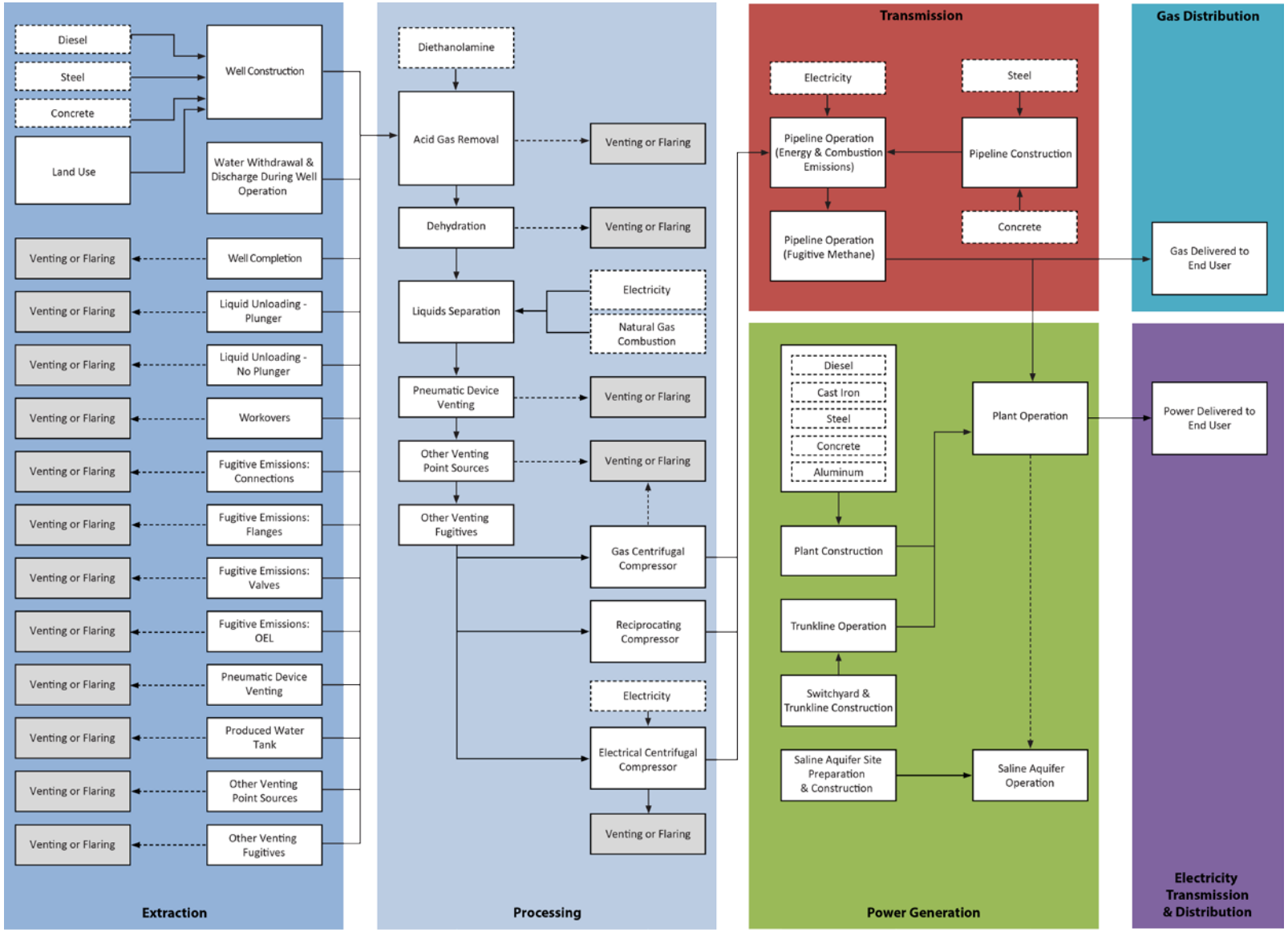
feasible, vented gas is captured and flared; otherwise, vented gas is released to the atmosphere.

- **Processing:** A natural gas processing facility removes impurities from natural gas, which improves its heating value and prepares it for pipeline transmission. Natural gas processing facilities include acid gas removal (AGR), dehydration, hydrocarbon liquids removal, and compression operations. When feasible, vapor recovery units capture vented gas and send it to flares. The size and complexity of processing plants are variable; in some cases, processing occurs near the extraction sites, while in other cases a central processing facility receives natural gas from multiple wells.
- **Transmission:** Natural gas transmission lines are large pipelines that transport natural gas from processing facilities to the city gate (the point at which natural gas can be consumed by large-scale consumers or transferred to local distribution companies). A typical natural gas transmission pipeline is 32 inches in diameter and is constructed of carbon steel. Transmission pipelines operate at 1,500 pounds per square inch of gauge pressure (psig). Compressor stations are located along natural gas transmission pipelines in order to boost the pressure of the natural gas. These stations consist of centrifugal and reciprocating compressors; most pipeline compressors are powered by natural gas, but some are powered by electricity.
- **Distribution:** Natural gas distribution networks transport natural gas from the city gate to commercial, residential, and some industrial consumers. Distribution pipelines operate at 3 psig. Unlike transmission pipelines, distribution pipelines do not use compressors to maintain system pressure. This analysis uses the distribution portion of the supply chain only for the upstream functional unit; distribution is not necessary for the functional unit of electricity in which natural gas power plants receive natural gas directly from transmission pipelines.

The cradle-to-grave boundary for electricity includes the extraction, processing, and transmission of natural gas (as summarized above), as well as power generation and electricity T&D.

- **Power Generation:** One of the primary uses of natural gas in the U.S. is to produce electricity. The natural gas power plant options in this analysis include natural gas combined cycle (NGCC), and fleet averages for baseload, load-following, and peaking power plants. The NGCC power plant is an advanced technology that includes options for carbon capture and saline aquifer sequestration. The NGCC power plant is a greenfield scenario, so its construction and installation is also modeled.
- **Electricity T&D:** The T&D of electricity from the power plant to the consumer results in an average energy loss of 7 percent. In addition to energy losses, the equipment used by T&D infrastructure are sources of sulfur hexafluoride ($SF_6$) emissions.

**Figure 2-2: Natural Gas Modeling Structure**



# 3 Data

The primary unit processes used in this analysis are based on data compiled by NETL. Secondary unit processes, such as production of construction materials, are based on third party data. **Appendix A** includes details on how these data are assembled in a model and also references the detailed documentation in NETL's unit process library.

## 3.1 Sources of Natural Gas

The environmental burdens for natural gas extraction are influenced by numerous factors, including drilling technology and type of reservoir stimulation processes. The properties of natural gas reservoirs, such as gas composition and volume of produced water, will also affect the level of environmental impact. These properties and their corresponding burdens vary geographically. The increase in domestic natural gas production within the last several years has garnered significant attention, and with that came an increase in the amount of data available. These data facilitate the consideration of the various combinations of extraction technologies and geographies.

The boundaries around natural gas production regions were developed with foresight on data availability and results interpretation. An insufficient number of regions could obscure hot spots of natural gas development or anomalous natural gas reservoir characteristics that could lend to the identification of key opportunities for improvement. Conversely, a high number of regions can lead to data limitations: data on specific extraction practices and geological characteristics are not available for every well, and in some cases, data are unavailable for entire clusters of wells.

EIA provides annual, state-level production data, which includes gross, marketed, and dry gas production (EIA, 2014). The regional distributions of shale gas, CBM, and offshore extraction technologies are clearly reported in EIA's data. However, EIA's data do not provide enough information to discern between conventional onshore and tight gas production within regions. EIA's maps of natural gas plays show where tight gas is produced (EIA, 2010a), but their state-level production data aggregate conventional and tight gas data into a single category ("gas wells"). NETL used the following criteria to split conventional onshore and tight gas production data:

- For recent growth in natural gas production, the growth in tight gas is assumed to outpace the growth in conventional onshore extraction. Six years of annual production data from EIA (EIA, 2014) were used to detect high-growth areas and label them as tight gas.
- In the case of Tennessee, the EIA maps show no conventional activity (EIA, 2009). All natural gas production other than CBM and shale gas in Tennessee is labeled as tight gas.

After applying the above criteria, NETL's stratification of production technologies and regions were aggregated to the national level and compared to EIA's national technology profile. NETL's and EIA's national technology profiles for natural gas production agree closely, which validates NETL's approach for distinguishing between conventional onshore and tight gas.

Regions are concentrated around the major natural gas plays in the lower 48 states and Alaska, resulting in 12 onshore regions and 3 offshore regions (**Table 3-1**). While there is substantial variation from one region to another, the ways in which regions differ are relatively similar. Using newly available data to add geographical and technological components to the upstream natural gas scenarios equips this model to characterize regional variability and isolate extraction technologies without overreaching the representativeness of underlying data.

**Table 3-1: Mix of U.S. Natural Gas Sources in 2012 (EIA, 2014)**

| Region | Technology | | | | | | Total |
|---|---|---|---|---|---|---|---|
| | CBM | Onshore Conventional | Offshore Conventional | Oil Wells | Shale | Tight Gas | |
| Alaska | - | 0.31% | - | 0.70% | - | - | 1.0% |
| Alaska Offshore | - | - | 0.14% | 0.31% | - | - | 0.44% |
| Appalachian | 0.44% | 2.8% | - | 0.050% | 9.1% | 0.32% | 13% |
| Black Warrior | 0.37% | - | - | - | - | - | 0.37% |
| Central | 0.41% | 5.4% | - | 0.21% | 6.0% | 1.6% | 14% |
| Fort Worth | - | - | - | - | 22% | - | 22% |
| Gulf of Mexico Offshore | - | - | 4.6% | 2.0% | - | - | 6.5% |
| Gulf Coast | - | 9.2% | - | 1.8% | - | 7.8% | 19% |
| Illinois-Michigan | - | 0.34% | - | 0.018% | 0.44% | 0.038% | 0.84% |
| North-Central | - | 0.087% | - | 0.40% | 0.75% | 0.026% | 1.3% |
| Pacific Offshore | - | - | 0.063% | 0.071% | - | - | 0.13% |
| Rocky Mountains | 4.7% | 4.6% | - | 0.093% | 0.89% | 10% | 21% |
| TX-LA-MS Salt | - | 0.15% | - | 0.049% | - | 0.21% | 0.41% |
| West Coast | - | 0.42% | - | 0.21% | 0.22% | - | 0.84% |
| West Texas-Permian | - | - | - | 0.21% | 0.25% | - | 0.46% |
| Total | 6.0% | 23% | 4.8% | 6.1% | 39% | 20% | 100% |

## 3.2 Composition of Production Natural Gas

The composition of natural gas varies regionally. This variability affects the GHG emissions and other environmental burdens of vented gas streams, as well as the resources expended to extract and process a unit of pipeline quality natural gas.

Composition data were obtained from EPA's Oil and Gas Emission Estimation Tool (O&G Tool), which contains county-level data for natural gas production, well counts, device counts, and various device characteristics (EPA, 2013b). The O&G Tool is a compilation of 49 data sources, including state and basin sampling studies and federal reports. For geographical areas where the 49 data sources are incomplete, the O&G Tool extends regional boundaries to fill data gaps. In regions where the extension of data from other regions is not appropriate, the O&G tool fills data gaps by using averages from Central States Air Resource Agencies (CenSARA). CenSARA data are a subcomponent of the O&G Tool database and represent oil and gas production in Texas, Louisiana, Arkansas, Oklahoma, Missouri, Kansas, and Nebraska. (EPA, 2013b). NETL aggregated data from the O&G Tool to generate basin level averages for 12 onshore basins of the 15 production regions shown in **Figure 2-1**.

There are data available within the O&G Tool to determine the emission rates of $CO_2$, $CH_4$, hydrogen sulfide ($H_2S$), and volatile organic compounds (VOC). The weight fractions, originally presented as a ratio to total organic compounds, were normalized to a basis of total natural gas emitted. The sum of total organic compound weight fractions is less than 100 percent of the total mass of extracted natural gas, so the remainder is classified as nitrogen and ethane in a ratio determined from a 2011 memorandum utilized in the development of the O&G Tool (Brown, 2011; Pring, 2014). Additionally, the molecular weight of the emitted gas that is used to determine the gas density is calculated using the extended gas composition rather than using the one provided in the O&G Tool. Due to the limited level of detail on VOC compounds with backbones of six or more carbons, the VOC weight fractions from the O&G Tool were further speciated using the SPECIATE database (EPA, 2011d).

For the purposes of modeling fugitive, venting, and flaring activity, each of which uses the expanded inventory detailed above, it is important to note the difference between the source of an emission and the emission's release point. Emissions that originate during liquids unloading, for example, may not be released during the unloading process. Instead, those emissions might be vented or flared. Failure to distinguish the source from the release point can lead to double counting, which will skew the impact assessment of a life cycle model. For this reason, this analysis tracks whole gas as it leaves a source unit process. Natural gas composition information is used within source unit processes to calculate the density of the natural gas. Density information is then used to determine the total mass of natural gas emitted. This tracked output is intended to be connected to the appropriate release point process, many of which contain regionally and device specific gas compositions as parameter scenarios to account for the specific gas species being emitted to the atmosphere.

**Table 3-2** shows the mass fractions of $CH_4$, $CO_2$, NMVOC, and $H_2S$ in production gas. As discussed above, the sum of mass fractions do not add up to 1 due to the omission of the weight fraction of $N_2$.

**Table 3-2: Natural Gas Composition on a Mass Basis (EPA, 2011d, 2013b)**

| **Region**<br>Technology | $CH_4$ | $CO_2$ | NMVOC | $H_2S$ |
|---|---|---|---|---|
| **Appalachian**<br>Conventional, CBM, Tight Gas, & Shale | 0.672 | 0.0327 | 0.00990 | 1.18E-05 |
| **Illinois-Michigan**<br>Conventional, Tight Gas, & Shale | 0.688 | 0.0329 | 0.00931 | 1.11E-05 |
| **Black Warrior**<br>CBM | 0.672 | 0.0327 | 0.00990 | 1.18E-05 |
| **Central**<br>Conventional, Tight Gas, & Shale | 0.743 | 0.0143 | 0.00851 | 4.40E-05 |
| **Central**<br>CBM | 0.820 | 0.0308 | 0.00433 | 6.55E-06 |
| **North-Central**<br>Conventional, Tight Gas, & Shale | 0.672 | 0.0327 | 0.0147 | 1.18E-05 |
| **TX-LA-MS Salt**<br>Conventional & Tight Gas | 0.741 | 0.0362 | 0.00719 | 7.06E-06 |
| **Gulf Coast**<br>Conventional & Tight Gas | 0.731 | 0.0253 | 0.00787 | 1.19E-05 |
| **Fort Worth**<br>Shale | 0.731 | 0.0253 | 0.00787 | 1.19E-05 |
| **West Texas-Permian**<br>Shale | 0.731 | 0.0253 | 0.00787 | 1.19E-05 |
| **Rocky Mountains**<br>Conventional, Tight Gas, & Shale | 0.691 | 0.0473 | 0.00711 | 2.38E-03 |
| **Rocky Mountains**<br>CBM | 0.820 | 0.124 | 0.00178 | 1.71E-04 |
| **West Coast**<br>Conventional & Shale | 0.672 | 0.0327 | 0.00990 | 1.18E-05 |
| **Alaska & Alaska Offshore**<br>Conventional | 0.672 | 0.0327 | 0.00990 | 1.18E-05 |
| **Gulf Offshore**<br>Conventional | 0.731 | 0.0253 | 0.00787 | 1.19E-05 |
| **Pacific Offshore**<br>Conventional | 0.672 | 0.0327 | 0.00990 | 1.18E-05 |

For the Central Basin and Rocky Mountain, the data in **Table 3-2** show different compositions for different extraction technologies. For example, the production gas in the Central Basins has a lower $CH_4$ fraction for conventional and tight gas than it does for CBM and shale gas. This does not mean that different extraction technologies cause different production gas compositions. Rather, it shows that production gas compositions vary within regions, and in some cases there are enough data to split gas compositions by region *and* extraction technology.

## 3.3 Production Rate

EUR, the projected amount of natural gas that will be recovered from a well, is used as the denominator for apportioning the one-time emissions from well completion to a unit of natural gas produced. This is necessary because, unlike other types of emissions that occur continuously over a well's life, completion emissions are a one-time impulse of emissions. From a life cycle perspective, these episodic emissions must be levelized over a well's operating life (every unit of natural gas produced by the well is assigned an equal fraction of the well's episodic emissions).

EUR values for the scenarios modeled in this analysis are shown in **Table 3-3**. For shale and tight gas plays, play-specific EURs are available in EIA's analyses of unconventional production (EIA, 2011e, 2013b). For conventional and CBM profiles, regional data were used to calculate technology-specific EUR values. The EUR for onshore conventional natural gas was calculated from EIA's performance profile for large energy producers (EIA, 2011d); for this particular calculation, 2008 production data were used to represent onshore conventional wells because 2008 was the last data year that did not include unconventional wells (shale gas, tight gas, and CBM). The EUR for offshore conventional wells was calculated by EIA production statistics for federal offshore wells in the Gulf of Mexico (EIA, 2011a). Finally, the EURs for CBM wells were calculated by applying production data for the four major CBM regions in the U.S. (Appalachia, Black Warrior, Powder River, and San Juan); these EURs vary among basins (EIA, 2010b). The EURs for Appalachian and Black Warrior CBM wells are a direct mapping to the Appalachian and Black Warrior regions defined herein; the average of Powder River and San Juan data are used to represent the EUR of Rocky Mountain CBM; the average of the four major CBM regions are used to estimate EUR of Central CBM.

**Table 3-3: EUR Values by Technology and Production Region**

| Technology | Region | EUR (Bcf) | | |
|---|---|---|---|---|
| | | Low | Expected | High |
| Conventional | Alaska Offshore, Gulf Offshore, Pacific Offshore | 23.1 | 19.3 | 15.4 |
| | Appalachian, Illinois-Michigan, Central, North-Central, TX-LA-MS Salt, Gulf, Rocky Mountains, West Coast, & Alaska | 1.81 | 1.51 | 1.21 |
| CBM | Appalachian | 0.180 | 0.120 | 0.080 |
| | Black Warrior | 0.210 | 0.210 | 0.080 |
| | Central | 0.220 | 0.170 | 0.060 |
| | Rocky Mountains | 1.51 | 0.230 | 0.060 |
| Tight Gas | Appalachian | 0.690 | 0.375 | 0.060 |
| | Illinois-Michigan | 0.690 | 0.375 | 0.060 |
| | Central | 1.72 | 1.31 | 0.900 |
| | North-Central | 0.610 | 0.330 | 0.210 |
| | TX-LA-MS Salt | 1.39 | 1.39 | 1.39 |
| | Gulf Coast | 2.36 | 1.60 | 0.440 |
| | Rocky Mountains | 4.06 | 0.820 | 0.240 |
| Shale | Appalachian | 2.38 | 1.59 | 0.795 |
| | Illinois-Michigan | 2.58 | 1.72 | 0.861 |
| | Central | 2.17 | 1.44 | 0.722 |
| | North-Central | 0.660 | 0.440 | 0.220 |
| | Fort Worth | 4.40 | 1.84 | 0.551 |
| | West Texas-Permian | 2.27 | 1.51 | 0.757 |
| | Rocky Mountains | 1.33 | 0.888 | 0.444 |
| | West Coast | 2.10 | 1.40 | 0.700 |

## 3.4 Venting and Flaring

Venting and flaring occur during both extraction and processing, and are necessary in situations where it is not feasible to recover natural gas and route it to the product stream. Venting and flaring may occur when a well is being prepared for operations and the wellhead has not yet been fitted with a valve manifold, when it is not financially preferable to recover the associated natural gas from an oil well, or during emergency operations when the usual systems for gas recovery are not available.

Venting is the direct release of an emission without the use of flaring or other environmental control equipment. For natural gas systems, vented gas contains $CH_4$, a GHG that has a higher GWP per unit mass than $CO_2$. From a GWP perspective, the flaring of vented natural gas, which converts $CH_4$ to $CO_2$, is preferable to venting. In order to understand the extent to which flaring equipment effects emissions, "potential emissions" must first be calculated. Potential emissions represent the emissions that would be released if environmental controls were not in place. The calculation of potential emissions from natural gas extraction and processing are discussed in following section. The way in which venting and flaring activity is assessed for each type of emission source is discussed below.

Accurate modeling of natural gas flaring requires an understanding of the difference between flaring "activity" and flaring "efficiency." Flaring activity is the portion of potential emissions that are flared, while flaring efficiency is the portion of gas that is combusted once it enters a flare.

The combustion products of flaring at natural gas extraction and processing sites include $CO_2$, $CH_4$, and nitrous oxide ($N_2O$). Processed natural gas has a higher share of $CH_4$ than production gas because it has been treated to remove acid gas, water, and natural gas liquids (in the form of NMVOCs) (EPA, 2011a). The mass composition of natural gas is used to calculate the composition of vented and flared gas. Flaring has a 98 percent destruction efficiency, meaning that 98 percent of carbon in the flared gas is converted to $CO_2$. The $CH_4$ emissions from flaring are equal to the 2 percent portion of gas that is not converted to $CO_2$; $N_2O$ emissions from flaring are based on EPA AP-42 emission factors for stationary combustion sources (API, 2009; EPA, 1998).

Flaring activity data are based on three data sources: EIA's natural gas database (EIA, 2015), EPA's Envirofacts database (EPA, 2014b), and the flaring data provided by a partnership between the National Oceanic and Atmospheric Administration (NOAA) and the World Bank-led Global Gas Flaring Reduction Partnership (GGFRP) (GGFRP, 2014; NOAA, 2011).

Data from EIA and the NOAA and GGFRP, when combined, provides an understanding of the flaring practices associated with well development (i.e. completions and workovers). First, NOAA flaring data were divided by EIA's aggregated venting and flaring data to get annual flaring activity factors. Historical natural gas production data from EIA, which shows the growth and decline trends of major gas types, was used to calculate the annual growth and the decline in production for each general gas type. These annual growth and decline patterns, as well as the known time frames of Barnett and Marcellus shale development, can be used to select "windows of development" for each gas type. For example, recent (i.e. 2008 and later) well construction has been concentrated in the Appalachian basin, while the majority of conventional onshore well completions occurred during the late 1990s and early 2000s. Flaring activity factors were generated for each gas type by calculating the average, minimum, and maximum values for flaring activity within the period of well completion for each gas type. There is consensus (Burnham et al., 2011; Jiang et al., 2011; NETL, 2014) that unconventional well completions, unconventional well workovers, and liquids unloading are key sources of episodic emissions from natural gas extraction. The flaring activity factors derived from this method are applicable to well completions and workovers only and are shown in **Table 3-4**.

These factors are not applied to liquids unloading; it is not currently economically or technically feasible to capture and flare natural gas that is vented by liquids unloading (EPA, 2014e).

**Table 3-4: Flaring Activity for Well Completions and Workovers**

| **Technology**<br>*Region* | **Low** | **Expected** | **High** |
|---|---|---|---|
| **Conventional**<br>Gulf of Mexico Offshore & Pacific Offshore | 53% | 44% | 39% |
| **Conventional**<br>Alaska Offshore | 53% | 47% | 41% |
| **Conventional**<br>Alaska | 53% | 47% | 41% |
| **Conventional**<br>Appalachian, Central, Gulf Coast, Illinois-Michigan, North-Central, Rocky Mountains, TX-LA-MS Salt, & West Coast | 94% | 59% | 39% |
| **CBM**<br>Appalachian, Black Warrior, Central, & Rocky Mountains | 95% | 69% | 39% |
| **Tight Gas**<br>Appalachian, Illinois-Michigan, Central, North-Central, TX-LA-MS Salt, Gulf Coast, & Rocky Mountains | 95% | 65% | 39% |
| **Shale**<br>Central, West Texas-Permian, Fort Worth, & West Coast | 95% | 69% | 65% |
| **Shale**<br>Appalachian, Illinois-Michigan, North-Central, & Rocky Mountains | 51% | 46% | 43% |

**Table 3-5** shows the flaring activity factors for other upstream natural gas processes. It comprises processes other than completions and workovers. These parameters are set at either 0 percent or 100 percent and are based on the following principles:

- Liquids unloading events, pneumatic devices, and compressors do not have vapor recovery units, so they vent gas directly to the atmosphere without flaring (EPA, 2014e, 2014f).
- Fugitive emissions, regardless of technology or location, are unintentional releases that are released directly to the atmosphere without flaring.
- Tight confines of offshore extraction platforms make capture and control a safety measure in addition to an environmental control measure, so vent streams from offshore point sources have 100 percent flaring activity.

**Table 3-5: Flaring Activity Factors for Other Processes**

| Process | Flaring Activity |
|---|---|
| **Extraction** | |
| Liquids Unloading: Plunger and Non-Plunger | 0% |
| Fugitives: Connections, Flanges, Open-ended Lines, Valves, Pneumatics | 0% |
| Offshore: Other Point Source Emissions | 100% |
| Offshore: Other Venting Fugitives | 0% |
| Produced Water Tank | 0% |
| **Processing** | |
| AGR & Dehydration | 100% |
| Pneumatics | 0% |
| All Regions: Other Venting Point Source | 100% |
| All Regions: Other Venting Fugitives | 0% |
| Compression | 0% |
| **Transmission & Distribution** | |
| Transmission | 0% |
| Distribution | 0% |

## 3.5 Extraction of Natural Gas

Natural gas extraction includes the construction and development of wells, steady-state operations, and intermittent maintenance activities.

### 3.5.1 Extraction Land Use

Natural gas extraction occurs within the production stage of NETL's life cycle model. A natural gas extraction site has a well pad that holds permanent equipment and also provides room for development and maintenance activities.

The land area for natural gas wells ranges from 0.25 to 5.0 acres (1,000 to 20,200 $m^2$) per well (**Table 3-6**). CBM wells are on the low end of this range, shale wells are on the high end of this range, with two exceptions. First, tight gas wells in the TX-LA-MS Salt basin and Central basin have been assigned a land use value of 20,200 $m^2$. This assignment is due to the recent development of these areas and the wells within them, whereas other tight gas plays are typically built around conventional wells or the conversion of a conventional well to a tight gas well. Converting a conventional well to a tight gas well does not require additional land, so only newly developed tight gas wells have been assigned a land use area value. The second exception is the assignment of 6,000 $m^2$ to Appalachian shale wells, an area that is much smaller than that of other shale wells. This

decrease in area is due to new technologies that minimize the land use requirements of a shale well (Arthur & Cornum, 2010). The data show that Appalachian wells fall within a later period of well completion, discussed in **Section 3.4**, and for this reason they are assigned a land use value that better represents the technology of that timeframe. To calculate life cycle results, the life cycle model apportions these land areas according to the total lifetime production of each well type. Natural gas extraction sites are permanently converted to an industrial land application. This permanent conversion is accounted for in NETL's model, which includes long-term carbon balances for permanent and temporary conversion.

**Table 3-6: Land Use Area by Technology and Production Region**

| Technology | Region | Land Use Area ($m^2$) |
|---|---|---|
| Conventional | All Regions | 10,100 |
| CBM | All Regions | 1,000 |
| Tight Gas (new wells) | TX-LA-MS Salt & Central | 20,200 |
| Tight Gas (converted wells) | Appalachian, Illinois-Michigan, North-Central, Gulf Coast, & Rocky Mountains | 0 |
| Shale | Appalachian | 6,000 |
| | Illinois-Michigan, Central, North-Central, Fort Worth, West Texas-Permian, Rocky Mountains, & West Coast | 20,200 |

The land use metrics used for this analysis quantify the land area that is transformed from its original state due to the production of electricity, including supporting facilities. The transformation of land causes the direct emission of GHG emissions due to changes in above-ground biomass and soil carbon. GHG emissions are also caused from the indirect consequences of land use change, specifically, the displacement of agriculture. Calculations are based on a 30-year study period, or as relevant for the natural gas life cycle. NETL's land use model requires the input of land area ($m^2$) and land type (grassland, forest, and cropland).

GHG emissions due to land use change were evaluated based on EPA's method for the quantification of GHG emissions, in support of the Renewable Fuel Standards (RFS) (EPA, 2010c). EPA's analysis quantifies GHG emissions that are expected to result from land use changes from forest, grassland, savanna, shrubland, wetland, perennial, or mixed land use types to agricultural cropland, grassland, savanna, or perennial land use types. Relying on an evaluation of historic land use change completed by Winrock (Harris, Grimland, & Brown, 2009), EPA calculated a series of GHG emission factors for the following criteria: change in biomass carbon stocks, lost forest sequestration, annual soil carbon flux, $CH_4$ emissions, $NO_X$ emissions, annual peat emissions, and fire emissions. All of these criteria would result from land conversion over a range of timeframes. EPA's analysis also includes calculated reversion factors for the reversion of land use from agricultural cropland, grassland, savanna, and perennial to forest, grassland, savanna, shrub, wetland, perennial, or mixed land uses. Emission factors considered for reversion were change in biomass carbon stocks, change in soil carbon stocks, and annual soil carbon uptake over a variety of timeframes. Each of these emission factors, for land conversion and reversion, was included for a total of 756 global countries and regions within countries, including the 48 contiguous states. Based on the land use categories (forest, grassland, and agriculture/cropland) that were affected by study facilities, EPA's emission factors

were applied on a regional basis. The direct $CO_2$ emission factors from land use change are shown in **Table 3-7**.

**Table 3-7: $CO_2$ Emission Factors by Production Region and Technology**

| Region | Technology | Direct Land Use Emission Factor (kg $CO_2/m^2$) | |
|---|---|---|---|
| | | Forest | Grassland |
| Appalachian Basin | CBM | 54.7 | 3.92 |
| | Conventional & Tight Gas | 55.3 | 4.70 |
| | Shale | 56.7 | 4.63 |
| Illinois/Michigan Basin | Conventional & Tight Gas | 46.6 | 2.56 |
| | Shale | 45.8 | 3.65 |
| Black Warrior | CBM | 40.2 | 3.81 |
| Central | Conventional & Tight Gas | 30.0 | 2.91 |
| | CBM | 29.9 | 3.06 |
| | Shale | 37.7 | 2.60 |
| North-Central | Conventional & Tight Gas | 31.8 | 3.69 |
| | Shale | 34.6 | 3.73 |
| TX-LA-MS Salt Basin | Conventional & Tight Gas | 48.6 | 3.58 |
| Gulf Coast | Conventional | 27.9 | 2.31 |
| | Tight Gas | 28.9 | 2.34 |
| Ft. Worth Basin | Shale | 26.3 | 2.26 |
| West Texas-Permian | Shale | 22.0 | 1.27 |
| Rocky Mountains | Conventional & Tight Gas | 30.6 | 1.77 |
| | CBM | 29.4 | 1.69 |
| | Shale | 30.7 | 1.92 |
| West Coast | Conventional | 70.8 | 3.34 |
| | Shale | 70.7 | 3.32 |
| Alaska[1] | Conventional | 70.8 | 3.34 |

[1] Land use emission factors are not available for Alaska, so it is assumed that Alaskan factors are the same as those for the West Coast.

**Table 3-7** shows the emission factors for forest and grassland conversion, but does not show emission factors for agricultural conversion. Our land use method does not calculate direct land use change emissions for agricultural conversion, but does calculate a net change from indirect effects (i.e., displacement of agricultural land to another region). The emission factor for displaced agricultural land is 24.6 kg $CO_2$ per $m^2$ of displaced agriculture. This is the only emission factor used by the indirect land use calculations because the exact location of replaced agricultural land is unknown.

The type of land (forest, grassland, or cropland) that is transformed depends on the location of the natural gas infrastructure. The location of transformation and type of conversion varies across natural gas sources and technologies, as shown in **Table 3-8**. Specific natural gas extraction sources include Marcellus Shale (Pennsylvania, West Virginia, and Ohio) and Barnett Shale (Texas). CBM is extracted in the Western U.S. (Colorado, Montana, New Mexico, Oklahoma, and Wyoming) and Illinois. Other natural gas extraction technologies (conventional onshore and tight gas) occur in many

states. Offshore natural gas does not incur any land transformation at the point of extraction. These land use fractions are based on state-level profiles developed by the United States Department of Agriculture (USDA, 2006), factored by the state production profiles that were used to develop **Table 3-1**.

**Table 3-8: Land Use Fractions by Production Region and Technology**

| Region | Technology | Fraction of Land Use | | |
|---|---|---|---|---|
| | | Agriculture | Forest | Grassland |
| Appalachian | Conventional & Tight Gas | 0.157 | 0.754 | 0.0888 |
| | CBM | 0.154 | 0.729 | 0.117 |
| | Shale | 0.224 | 0.723 | 0.0532 |
| Illinois-Michigan | Conventional & Tight Gas | 0.505 | 0.409 | 0.0861 |
| | Shale | 0.279 | 0.662 | 0.0591 |
| Black Warrior | CBM | 0.115 | 0.793 | 0.0923 |
| Central | Conventional & Tight Gas | 0.366 | 0.201 | 0.433 |
| | CBM | 0.413 | 0.149 | 0.438 |
| | Shale | 0.291 | 0.478 | 0.231 |
| North-Central | Conventional & Tight Gas | 0.591 | 0.025 | 0.384 |
| | Shale | 0.632 | 0.0360 | 0.332 |
| TX-LA-MS Salt | Conventional & Tight Gas | 0.198 | 0.725 | 0.077 |
| Gulf Coast | Conventional | 0.222 | 0.187 | 0.591 |
| | Tight Gas | 0.221 | 0.235 | 0.544 |
| Fort Worth | Shale | 0.223 | 0.112 | 0.665 |
| West Texas-Permian | Shale | 0.0341 | 0.216 | 0.750 |
| Rocky Mountains | Conventional & Tight Gas | 0.0819 | 0.223 | 0.695 |
| | CBM | 0.0864 | 0.225 | 0.688 |
| | Shale | 0.194 | 0.312 | 0.494 |
| West Coast | Conventional | 0.149 | 0.422 | 0.430 |
| | Shale | 0.149 | 0.421 | 0.430 |
| Alaska | Conventional | 0.0045 | 0.702 | 0.294 |

### 3.5.2 Well Construction and Installation

The average well depths by region and technology are shown in **Table 3-9**. These parameters are based on industry and government documents that discuss the technologies and trends for natural gas well development (EIA, 1993; Halliburton, 2009; Reum, Dahlem, & Pollock, 2008).

**Table 3-9: Drill Depth (m) by Production Region and Technology**

| Region | Technology | Drill Depth (m) | | |
|---|---|---|---|---|
| | | Low | Expected | High |
| Appalachian | CBM, Tight Gas, & Shale | 762 | 1,460 | 2,130 |
| | Conventional | 1,030 | 1,040 | 1,050 |
| Illinois-Michigan | Conventional | 1,030 | 1,040 | 1,050 |
| | Shale & Tight Gas | 762 | 1,460 | 2,130 |
| Black Warrior | CBM | 2,590 | 3,800 | 4,880 |
| Central | Conventional | 1,300 | 2,110 | 2,900 |
| | CBM, Tight Gas, & Shale | 1,190 | 2,280 | 3,140 |
| North-Central | Conventional | 1,300 | 2,110 | 2,900 |
| | Tight Gas & Shale | 2,260 | 3,150 | 3,400 |
| TX-LA-MS Salt | Conventional | 1,000 | 1,000 | 1,000 |
| | Tight Gas | 2,590 | 3,800 | 4,880 |
| Gulf Coast | Conventional | 1,000 | 1,000 | 1,000 |
| | Tight Gas | 2,590 | 3,800 | 4,880 |
| Gulf of Mexico Offshore | Conventional | 2,000 | 2,000 | 2,000 |
| Fort Worth | Shale | 2,070 | 2,370 | 2,660 |
| West Texas-Permian | Shale | 2,070 | 2,370 | 2,660 |
| Rocky Mountains | Conventional | 1,000 | 1,000 | 1,000 |
| | CBM, Tight Gas, & Shale | 2,260 | 3,150 | 3,400 |
| West Coast | Conventional | 1,000 | 1,000 | 1,000 |
| | Shale | 2,260 | 3,150 | 3,400 |
| Pacific Offshore | Conventional | 2,000 | 2,000 | 2,000 |
| Alaska & Alaska Offshore | Conventional | 2,000 | 2,000 | 2,000 |

The construction and installation of natural gas wells requires a well casing that provides strength to the well bore and prevents contamination of the geological formations that surround the gas reservoir. In the case of offshore extraction, a large platform is also required. A well is lined with a carbon steel casing that is held in place with concrete. The total weight of materials for the construction of a well bore is calculated by factoring the total well length by the linear weight of carbon steel and concrete. The drilling energy is based on the average power rating of drilling equipment, well depth, and drilling speed. The average power rating of drilling equipment is 0.45 megawatts (MW) (600 horsepower), and the average drilling speed is 18 meters per hour. Theses parameters are based on industry and government documents for natural gas well development (EIA, 1993; Halliburton, 2009; Reum et al., 2008)

Horizontal drilling is used for unconventional natural gas reserves where hydrocarbons are dispersed throughout a matrix of shale or coal. Construction and material requirements are apportioned to a unit of natural gas production by dividing them by the lifetime production of the well. Most wells produce a combination of natural gas, oil, and other hydrocarbons, so when apportioning well construction requirements per unit of production, this analysis uses the total mass of hydrocarbons that are expected to be produced by the well. The amount of total hydrocarbons produced by wells are based on reported data for oil and gas ratios, with further calculations that use oil and gas densities to convert barrels of oil and cubic feet of natural gas to a mass basis.

### 3.5.3 Well Completions and Workovers

Well completions are the activities following well drilling and preceding production. A well completion is an episodic emission; it is not part of daily, steady-state well operations, but represents a potential emission from an event that occurs one time in the life of a well. The output of the completion unit process is a flow of potential emissions that is sent to another unit process where conditions for venting and flaring are applied.

Shale gas and tight gas wells are developed by hydraulic fracturing (hydrofracking) of a reservoir, which stimulates the reservoir to liberate natural gas and other hydrocarbons from otherwise trapped pockets (or microscopic pores). This process includes flowback water that contains natural gas. Due to the high reservoir pressures created by hydrofracking, shale gas and tight gas wells have high initial production rates that quickly decline. If production infrastructure is not immediately installed, these wells have the potential to emit high levels of $CH_4$ and other hydrocarbons. For shale gas wells, which have an immediate peak in production followed by a sharp decline and then a gradual decrease in production, the unit process uses initial production rates factored by the flowback period as a proxy for the volume of potential emissions generated by well completions. For this analysis, the expected flowback period for both tight gas and shale wells is 7 days, with the low and high emissions scenarios based on a 3- and 10-day flowback period, respectively. Initial production rates are also used as a proxy for the potential completion emissions from tight gas wells, with one additional step: the initial production rates for tight gas wells are divided by two to account for the gradual breakthrough of natural gas in flowback water (Abbasi, 2014).

Data on initial production rates are available for the Hayneville-Bossier Shale and Barnett Shale plays (EIA, 2013b). The initial production rates for other shale and tight gas plays were calculated using decline curve analysis (DCA). DCA uses the initial production rates, decline rates, and assumptions about long-term performance to estimate the total volume of natural gas ultimately recovered from a well. Instead of using DCA to calculate EUR, however, DCA is used to back calculate initial production rates from play-specific EURs. While it is assumed that these decline curve parameters can be used to represent shale gas and tight gas wells, the curves are based on projections of future production. Future production is uncertain, and thus the factors for completion

emissions are also uncertain. To account for this uncertainty, the expected values for initial production rate, shown in **Table 3-10**, are accompanied by low and high values.

**Table 3-10: Initial Production (scf/day) of Tight Gas and Shale Wells**

| Technology | Region | Initial Production (scf/day) | | |
|---|---|---|---|---|
| | | Low | Expected | High |
| Tight Gas | Appalachian | 41,000 | 41,300 | 64,000 |
| | Illinois-Michigan | 97,700 | 98,400 | 153,000 |
| | Central | 648,000 | 652,000 | 1,010,000 |
| | North-Central | 76,500 | 77,000 | 119,000 |
| | Gulf Coast | 32,800 | 33,000 | 51,200 |
| | TX-LA-MS Salt | 1,000,000 | 1,010,000 | 1,570,000 |
| | Rocky Mountains | 124,000 | 125,000 | 194,000 |
| Shale | Appalachian | 2,170,000 | 2,190,000 | 3,390,000 |
| | Illinois-Michigan | 2,350,000 | 2,370,000 | 3,670,000 |
| | Central | 1,970,000 | 1,990,000 | 3,080,000 |
| | North-Central | 601,000 | 605,000 | 938,000 |
| | Fort Worth | 1,410,000 | 2,530,000 | 4,200,000 |
| | West Texas-Permian | 2,070,000 | 2,080,000 | 3,230,000 |
| | Rocky Mountains | 1,210,000 | 1,220,000 | 1,890,000 |
| | West Coast | 1,910,000 | 1,930,000 | 2,990,000 |

When compared to shale and tight gas wells, conventional wells (onshore and offshore) and CBM wells have lower potential emissions during well completion. This difference can be attributed to the combined effects of stimulation techniques and the pressure of the well, which, for conventional and CBM wells, is lower than the pressures found in shale and tight gas wells. The volume of natural gas that escapes from conventional and CBM wells during completion operations is based on factors that EPA developed from Gas Research Institute (GRI) research conducted in 1996 (EPA, 2010a). These factors, shown in **Table 3-11**, are organized by technology (i.e. stimulation technique) since EPA's data are not available on a regional basis.

**Table 3-11: Conventional (onshore & offshore) and CBM Completion Emission Factors (EPA, 2010a)**

| Technology | Completion Emissions (scf/episode) |
|---|---|
| Conventional | 37,000<br>(3,700-370,000) |
| CBM | 49,600<br>(4,960-496,000) |

Well workovers are necessary for cleaning wells, and, unlike well completions, workovers occur more than one time during the life of a well. The workover of a well is an episodic emission; it is not a part of daily, steady-state well operations, but rather represents a significant emission from the occasional maintenance of a well. In EPA's technical support document of the petroleum and natural gas industry (EPA, 2011a), EPA assumes that the emissions from unconventional well workovers are equal to the emission factors for unconventional well completion. Thus, for unconventional wells, this analysis uses the same emission factors for well completion (discussed above) and well workovers (**Table 3-12**). In the case of conventional and CBM wells, workovers represent more of a disruption in production rather than a re-stimulation effort. For this reason, the volume of natural gas that escapes from conventional and CBM wells during workover operations is also based on factors that EPA developed from Gas Research Institute (GRI) research conducted in 1996 (EPA, 2010a).

**Table 3-12: Workover Episodes by Technology and Workover Emission Factors for Conventional (onshore and offshore) and CBM Wells (EPA, 2010a)**

| Technology | Lifetime Workovers | Workover Emissions (scf/day) |
|---|---|---|
| Conventional | 0.0750<br>(0.0600-0.0900) | 2,450<br>(245-24,500) |
| CBM | 0.125<br>(0.100-0.150) | 49,600<br>(4,960-496,000) |
| Tight Gas | 0.0750<br>(0.0600-0.0900) | Calculated |
| Shale | 0.125<br>(0.100-0.150) | Calculated |

## 3.5.4 Liquids Unloading

Liquids unloading is a routine operation for natural gas wells that are affected by the accumulation of fluids in the well, which can impede gas production. To maintain gas flow, fluids are removed by several treatment methods, including venting the well to the atmosphere. These fluid removal practices can result in substantial $CH_4$ emissions to the atmosphere (EPA, 2006). For this reason, some operators install plunger lift systems that use gas pressure buildup in a well to lift a column of accumulated fluid out of the well, which helps maintain gas production and reduce $CH_4$ emissions. While vented $CH_4$ emissions during liquid unloading events vary as a result of the use of a plunger lift system, other factors include local geology, hydrology, and state law. The EPA's *Greenhouse Gas Reporting Rule: Revisions and Confidentiality Determinations for Petroleum and Natural Gas Systems* provides a method for calculating emissions from each sub-basin venting to the atmosphere for liquids unloading with or without plunger lift assist (EPA, 2014c). **Equation 3-1** and **Equation 3-2** are used for calculating emissions without a plunger lift system and with a plunger lift system, respectively. The variables used in this calculation are described in **Table 3-13**.

**Equation 3-1: Emissions without Plunger Lift Assist (EPA, 2014c)**

$$E_{s,n} = \sum_{p=1}^{W} \left[ V_p \cdot \left( (0.37 \cdot 10^{-3}) \cdot CD_p^2 \cdot WD_p \cdot SP_p \right) + \sum_{q=1}^{V_p} (SFR_q \cdot \left( HR_{p,q} - 1.0 \right) \cdot Z_{p,q} \right]$$

**Equation 3-2: Emissions with Plunger Lift Assist (EPA, 2014c)**

$$E_{s,n} = \sum_{p=1}^{W} \left[ V_p \cdot \left( (0.37 \cdot 10^{-3}) \cdot TD_p^2 \cdot WD_p \cdot SP_p \right) + \sum_{q=1}^{V_p} (SFR_q \cdot \left( HR_{p,q} - 0.5 \right) \cdot Z_{p,q} \right]$$

**Table 3-13: Parameters for Calculation of Potential Emissions from Liquids Unloading**

| Parameter | Definition | Units |
|---|---|---|
| V | Total number of unloading events per well | Events/well |
| TD | Tubing internal diameter for each well | in |
| CD | Casing internal diameter for each well | in |
| WD | Well depth | ft |
| SP | Shut-in pressure or surface pressure for wells with tubing production, or casing pressure for each well with no packers | psia |
| SFR | Average flow-line rate of NG for well | $ft^3/hr$ |
| HR | Hours of unloading event | hr |
| Z | If HR is less than 0.5 then Z is equal to 0. If HR is greater than or equal to 0.5 then Z is equal to 1 | dimensionless |
| E | Annual NG emissions for each sub-basin at standard conditions | $ft^3/yr$ |

The model uses two instances of the liquid unloading unit process: one instance is used to represent wells without plunger lifts, while the other instance is used to represent wells with plunger lifts. The volume of natural gas vented by unloading events is calculated by the liquid unloading unit process, but the air emissions from liquid unloading are accounted for by a venting and flaring unit process that receives the volume of vented gas from the liquid unloading unit process and speciates it into the hydrocarbon and other compounds that compose natural gas. Liquids unloading events, pneumatic devices, and compressors do not have vapor recovery units, so they vent gas directly to the atmosphere without flaring (EPA, 2014e, 2014f). (More information on the venting and flaring unit process is provided in **Section 3.4**.)

The technological and geographical variability in liquids unloading is based on a report by American Petroleum Institute (API) and America's Natural Gas Alliance (ANGA). (The API/ANGA report is based on a survey of member companies and stratifies results into five regions (Northeast, Mid-Continent, Southwest, Gulf Coast, and Rocky Mountains), four extraction technologies (conventional, shale, CBM, and tight gas), and whether or not plunger lifts are used (API/ANGA, 2012). **Table 3-14** through **Table 3-17** show the API/ANGA data organized into the scenarios of this analysis.

**Table 3-14: Liquid Unloading Data by Production Region and Technology**

| Property (Units) | Appalachian | | Illinois-Michigan | | Black Warrior |
|---|---|---|---|---|---|
| | Conventional | CBM, Tight Gas, & Shale | Conventional | Tight Gas & Shale | CBM |
| Wells Requiring Liquids Unloading | 10.0% | | 10.0% | | 10.4% |
| **Liquids Unloading: Plunger** | | | | | |
| Well Depth (m) | 1,040 (1,030-1,050) | 1,550 (762-2,130) | 1,040 (1,030-1,050) | 1,550 (762-2,130) | 4,060 (2,590-4,880) |
| Tubing: Internal Diameter (in) | 2.24 (2.00-2.38) | 2.38 | 2.24 (2.00-2.38) | 2.38 | 2.38 |
| Shut-in or Surface Pressure (psia) | 77.0 (64.7-99.7) | 148 (136-215) | 77.0 (64.7-99.7) | 148 (136-215) | 484 (29.7-555) |
| Average Flow-line Rate (scf/hr) | 382 (300-535) | 7,230 (625-26,200) | 382 (300-535) | 7,230 (625-26,200) | 258,000 (3,460-354,000) |
| Unloading Event Duration (hrs) | 0.545 (0.300-1.00) | 0.170 (0.0500-0.221) | 0.545 (0.300-1.00) | 0.170 (0.0500-0.221) | 0.672 (0.300-2.00) |
| Total Unloading Events (events/well life) | 38.6 (38.6-38.7) | 229 (38.8-730) | 38.6 (38.6-38.7) | 229 (38.8-730) | 2.36 (1.00-52.0) |
| Fraction of Production from Wells with Plunger Lifts | 11.4% | 55.2% | 11.4% | 55.2% | 24.3% |
| **Liquids Unloading: No Plunger** | | | | | |
| Well Depth (m) | 1,040 (1,030-1,050) | 1,480 | 1,040 (1,030-1,050) | 1,480 | 4,080 (1,830-4,880) |
| Casing: Internal Diameter (in) | 4.63 (4.50-5.00) | 4.50 | 4.63 (4.50-5.00) | 4.50 | 9.04 (4.50-10.8) |
| Shut-in or Surface Pressure (psia) | 74.1 (64.7-99.7) | 136 | 74.1 (64.7-99.7) | 136 | 521 (29.7-555) |
| Average Flow-line Rate (scf/hr) | 364 (300-535) | 1,083 | 364 (300-535) | 1,083 | 280,000 (1,040-354,000) |
| Unloading Event Duration (hrs) | 1.73 (1.00-2.00) | 1.36 | 1.73 (1.00-2.00) | 1.36 | 1.36 (0.688-5.30) |
| Total Unloading Events (events/well life) | 37.8 (22.8-43.3) | 82.3 | 37.8 (22.8-43.3) | 82.3 | 1.56 (0.600-52.0) |

**Table 3-15: Liquid Unloading Data by Production Region and Technology**

| Property (Units) | Rocky Mountains | | North-Central | | Central | |
|---|---|---|---|---|---|---|
| | Conventional | CBM, Tight Gas, & Shale | Conventional | Tight Gas & Shale | Conventional | CBM, Tight Gas, & Shale |
| Wells Requiring Liquids Unloading | 10.4% | 29.4% | 5.17% | 29.4% | 5.17% | |
| **Liquids Unloading: Plunger** | | | | | | |
| Well Depth (m) | 0 | 3,180 (2,260-3,400) | 1,340 (1,300-2,900) | 3,180 (2,260-3,400) | 1,340 (1,300-2,900) | 2,250 (1,190-3,140) |
| Tubing: Internal Diameter (in) | 0 | 2.30 (1.92-2.38) | 2.00 (1.99-2.38) | 2.30 (1.92-2.38) | 2.00 (1.99-2.38) | 3.62 (2.38-4.11) |
| Shut-in or Surface Pressure (psia) | 0 | 249 (165-305) | 84.5 (40.2-515) | 249 (165-305) | 84.5 (40.2-515) | 107 (89.4-113) |
| Average Flow-line Rate (scf/hr) | 0 | 13,200 (1,920-18,900) | 3,440 (1,250-3,500) | 13,200 (1,920-18,900) | 3,440 (1,250-3,500) | 29,600 (10,400-36,500) |
| Unloading Event Duration (hrs) | 0 | 1.53 (0.407-2.10) | 0.0729 (0.0670-0.750) | 1.53 (0.407-2.10) | 0.0728 (0.0670-0.750) | 1.97 (0.0833-2.99) |
| Total Unloading Events (events/well life) | 0 | 16.2 (2.24-1,152) | 2,920 (11.5-2,990) | 16.2 (2.24-1,150) | 2,920 (11.5-2,990) | 480 (2.40-3,250) |
| Production from Wells with Plunger Lifts | 0% | 90.3% | 81.9% | 90.3% | 81.9% | 21.5% |
| **Liquids Unloading: No Plunger** | | | | | | |
| Well Depth (m) | 4,540 (3,050-5,890) | 3,390 (3,310-3,540) | 1,320 (1,300-2,140) | 3,390 (3,300-3,540) | 1,320 (1,300-2,140) | 2,240 (1,190-3,350) |
| Casing: Internal Diameter (in) | 4.53 (3.65-5.50) | 4.11 (2.38-4.70) | 4.01 (4.00-4.83) | 4.11 (2.38-4.70) | 4.01 (4.00-4.83) | 5.19 (4.92-5.50) |
| Shut-in or Surface Pressure (psia) | 163 (79.9-239) | 261 (213-491) | 74.9 (40.2-75.5) | 261 (213-491) | 74.9 (40.2-75.5) | 121 (94.7-215) |
| Average Flow-line Rate (scf/hr) | 20,500 (12,500-27,700) | 5,630 (1,730-18,000) | 3,480 (2,440-3,500) | 5,630 (1,730-18,000) | 3,480 (2,440-3,500) | 26,500 (4,170-36,500) |
| Unloading Event Duration (hrs) | 1.79 (1.00-2.50) | 1.77 (0.750-3.18) | 4.87 (0.250-4.95) | 1.77 (0.750-3.18) | 4.87 (0.250-4.95) | 1.89 (0.500-2.50) |
| Total Unloading Events (events/well life) | 10.9 (10.0-12.0) | 68.1 (2.00-378) | 63.2 (1.00-64.3) | 68.1 (2.00-378) | 63.2 (1.00-64.3) | 3.77 (2.26-12.0) |

**Table 3-16: Liquid Unloading Data by Production Region and Technology**

| Property (Units) | TX-LA-MS Salt | | Gulf Coast | | Fort Worth | West Texas-Permian |
|---|---|---|---|---|---|---|
| | Conventional | Tight Gas | Conventional | Tight Gas | Shale | Shale |
| Wells Requiring Liquids Unloading | 10.4% | | 10.4% | | 14.2% | 14.2% |
| **Liquids Unloading: Plunger** | | | | | | |
| Well Depth (m) | 0 | 4,060 (2,590-4,880) | 0 | 4,060 (2,590-4,880) | 2,630 (2,070-2,660) | 2,630 (2,070-2,660) |
| Tubing: Internal Diameter (in) | 0 | 2.38 | 0 | 2.38 | 2.02 (2.00-2.38) | 2.02 (2.00-2.38) |
| Shut-in or Surface Pressure (psia) | 0 | 484 (29.7-555) | 0 | 484 (29.7-555) | 509 (125-531) | 509 (125-531) |
| Average Flow-line Rate (scf/hr) | 0 | 258,000 (3,460-354,000) | 0 | 258,000 (3,460-354,000) | 59,300 (1,040-62,500) | 59,300 (1,040-62,500) |
| Unloading Event Duration (hrs) | 0 | 0.672 (0.300-2.00) | 0 | 0.672 (0.300-2.00) | 0.484 (0.200-0.500) | 0.484 (0.200-0.500) |
| Total Unloading Events (events/well life) | 0 | 2.36 (1.00-52.0) | 0 | 2.36 (1.00-52.0) | 1.37 (1.00-1.39) | 1.37 (1.00-1.39) |
| Production from Wells with Plunger Lifts | 0% | 24.3% | 0% | 24.3% | 24.8% | 24.8% |
| **Liquids Unloading: No Plunger** | | | | | | |
| Well Depth (m) | 4,540 (3,050-5,890) | 4,080 (1,830-4,880) | 4,540 (3,050-5,890) | 4,080 (1,830-4,880) | 2,660 (2,440-4,570) | 2,660 (2,440-4,570) |
| Casing: Internal Diameter (in) | 4.53 (3.65-5.50) | 9.04 (4.50-10.8) | 4.53 (3.65-5.50) | 9.04 (4.50-10.8) | 9.62 (5.00-9.63) | 9.62 (5.00-9.63) |
| Shut-in or Surface Pressure (psia) | 163 (79.9-239) | 521 (29.7-555) | 163 (79.9-239) | 521 (29.7-555) | 530 (64.7-531) | 530 (64.7-531) |
| Average Flow-line Rate (scf/hr) | 20,500 (12,500-27,700) | 280,000 (1,040-354,000) | 20,500 (12,500-27,700) | 280,000 (1,040-354,000) | 62,400 (500-62,500) | 62,400 (500-62,500) |
| Unloading Event Duration (hrs) | 1.79 (1.00-2.50) | 1.36 (0.688-5.30) | 1.79 (1.00-2.50) | 1.36 (0.688-5.30) | 1.01 (0.500-6.67) | 1.01 (0.500-6.67) |
| Total Unloading Events (events/well life) | 10.9 (10.0-12.0) | 1.56 (0.600-52.0) | 10.9 (10.0-12.0) | 1.56 (0.600-52.0) | 0.968 (0.333-1.00) | 0.968 (0.333-1.00) |

**Table 3-17: Liquid Unloading Data by Production Region and Technology**

| Property (Units) | West Coast | | Alaska |
|---|---|---|---|
| | Conventional | Shale | Conventional |
| Wells Requiring Liquids Unloading | 10.4% | 29.4% | 10.4% |
| **Liquids Unloading: Plunger** | | | |
| Well Depth (m) | 0 | 3,180 (2,260-3,400) | 0 |
| Tubing: Internal Diameter (in) | 0 | 2.30 (1.92-2.38) | 0 |
| Shut-in or Surface Pressure (psia) | 0 | 249 (165-305) | 0 |
| Average Flow-line Rate (scf/hr) | 0 | 13,200 (1,920-18,900) | 0 |
| Unloading Event Duration (hrs) | 0 | 1.53 (0.407-2.10) | 0 |
| Total Unloading Events (events/well life) | 0 | 16.2 (2.24-1,150) | 0 |
| Production from Wells with Plunger Lifts | 0% | 90.3% | 0% |
| **Liquids Unloading: No Plunger** | | | |
| Well Depth (m) | 4,540 (3,050-5,890) | 3,390 (3,310-3,540) | 4,543 (3,048-5,893) |
| Casing: Internal Diameter (in) | 4.53 (3.65-5.50) | 4.11 (2.38-4.70) | 4.53 (3.65-5.50) |
| Shut-in or Surface Pressure (psia) | 163 (79.9-239) | 261 (213-491) | 163 (79.9-239) |
| Average Flow-line Rate (scf/hr) | 20,500 (12,500-27,700) | 5,630 (1,730-18,000) | 20,500 (12,500-27,700) |
| Unloading Event Duration (hrs) | 1.79 (1.00-2.50) | 1.77 (0.750-3.18) | 1.79 (1.00-2.50) |
| Total Unloading Events (events/well life) | 10.9 (10.0-12.0) | 68.1 (2.00-378) | 10.9 (10.0-12.0) |

### 3.5.5 Pneumatic Devices (Extraction)

Natural gas production sites use pneumatic devices for the opening and closing of valves and actuation of other control equipment.

The unit process for pneumatic devices uses EPA's O&G Tool, which contains county-level data on natural gas production, well counts, device counts, and emission rates. A more detailed description of the O&G Tool can be found in **Section 3.2.**

For the development of a unit process for pneumatic devices at natural gas production sites, this analysis aggregates the O&G tool's county data to represent regional averages. Most pneumatic devices operate continuously and are characterized as no, low, and high bleed devices with individual bleed rates (EPA, 2013b). There are also intermittent pneumatic devices that are not in continuous operation. For this unit process, the limited operating time of intermittent devices is accounted for in a decreased average bleed rate rather than an adjustment to the actual operating time (ENVIRON, 2012). Pneumatic device data are shown in **Table 3-18** through **Table 3-21**. **Appendix A** includes details on how these data are assembled in a model and references the detailed documentation in NETL's unit process library.

Most of the parameters in **Table 3-18** through **Table 3-21** have low and high values in addition to a central, expected value. However, in some instances, only and expected value is shown. The sample sizes for some regions are not large enough to calculate low and high uncertainty bounds. This demonstrates a trade-off between specificity and sample size; as geographical boundaries are narrowed to represent specific regions with low production activity, fewer data points are available. In particular, this is demonstrated by the parameters in **Table 3-21**, which are representative of regions (West Coast and Alaska) with relatively low natural gas production volumes.

**Table 3-18: Pneumatic Device Data by Production Region and Technology**

| Property (Units) | | Appalachian | | Illinois-Michigan | Black Warrior |
|---|---|---|---|---|---|
| | | Conventional, Tight Gas, & Shale | CBM | Conventional, Tight Gas, & Shale | CBM |
| Pneumatic Vent Rate (scf/hr) | High | 37.3 (32.1-37.3) | | 36.9 (32.1-37.3) | 37.3 (32.1-37.3) |
| | Intermittent | 13.5 (8.58-13.5) | | 13.5 (8.58-13.5) | 13.5 (8.58-13.5) |
| | Low | 1.39 (1.39-3.15) | | 1.52 (1.39-3.15) | 1.39 (1.39-3.15) |
| | Zero | 0 | | 0 | 0 |
| Pneumatic Device Count | High | 0.595 (0.222-3.00) | 0.244 (0.222-3.00) | 0.278 (0.222-3.00) | 0.318 (0.318-1.33) |
| | Intermittent | 0.104 (0-0.718) | 0.137 (0-0.718) | 0.199 (0-1.20) | 0.171 (0.171-0.717) |
| | Low | 0.125 (0-0.865) | 0.159 (0-0.865) | 0.206 (0-1.00) | 0.206 (0.206-0.865) |
| | Zero | 0.330 | | 0.306 (0-0.330) | 0.330 |

**Table 3-19: Pneumatic Device Data by Production Region and Technology**

| Property (Units) | | Central | | Rocky Mountains | | North-Central |
|---|---|---|---|---|---|---|
| | | Conventional, Tight Gas, & Shale | CBM | Conventional, Tight Gas, & Shale | CBM | Conventional, Tight Gas, & Shale |
| Pneumatic Vent Rate (scf/hr) | High | 32.1 | | 27.8 (0-38.9) | 37.2 (0-38.9) | 38.9 |
| | Intermittent | 7.36 (4.01-13.1) | 11.3 (4.01-13.1) | 8.37 (0-23.7) | 13.9 (0-23.7) | 23.7 |
| | Low | 3.02 (2.28-3.15) | 3.15 (2.28-3.15) | 1.99 (0.313-6.00) | 1.26 (0.313-6.00) | 4.62 |
| | Zero | 0 | | 0 | | 0 |
| Pneumatic Device Count | High | 0.844 (0-1.33) | 1.13 (0-1.33) | 0.829 (0-4.75) | 0.575 (0-4.75) | 1.37 |
| | Intermittent | 0.868 (0.438-1.20) | 1.00 (0.438-1.20) | 0.140 (0-1.19) | 0.296 (0-1.19) | 1.19 |
| | Low | 0.871 (0-1.11) | 0.936 (0-1.11) | 2.68 (0.336-5.27) | 1.61 (0.336-5.27) | 0.336 |
| | Zero | 0.604 (0-0.990) | 0.137 (0-0.990) | 0.111 (0-0.495) | 0.0649 (0-0.495) | 0 |

**Table 3-20: Pneumatic Device Data by Production Region and Technology**

| Property (Units) | | TX-LA-MS Salt | Gulf Coast | Fort Worth | West Texas-Permian |
|---|---|---|---|---|---|
| | | Conventional & Tight Gas | Conventional & Tight Gas | Shale | Shale |
| Pneumatic Vent Rate (scf/hr) | High | 32.1 (32.1-37.3) | 32.1 | 32.1 | 32.1 |
| | Intermittent | 8.58 (8.58-13.5) | 8.58 | 8.58 | 8.58 |
| | Low | 3.15 (1.39-3.15) | 3.15 | 3.15 | 3.15 |
| | Zero | 0 | 0 | 0 | 0 |
| Pneumatic Device Count | High | 0.845 (0.318-1.33) | 0.159 (0.110-1.33) | 0.180 (0.180-1.33) | 0.0600 (0.0600-3.00) |
| | Intermittent | 0.421 (0-0.717) | 2.26 (0.717-2.32) | 1.09 (0.717-1.09) | 0.910 (0-0.91) |
| | Low | 0.585 (0.206-1.00) | 0.975 (0.865-0.980) | 2.40 (0.865-2.40) | 0.220 (0-0.865) |
| | Zero | 0.198 (0-0.330) | 0.330 | 0.330 | 0.0000128 (0– 0.330) |

**Table 3-21: Pneumatic Device Data by Production Region and Technology**

| Property (Units) | | West Coast | Alaska |
|---|---|---|---|
| | | Conventional & Shale | Conventional |
| Pneumatic Vent Rate (scf/hr) | High | 37.3 | 37.3 |
| | Intermittent | 13.5 | 13.5 |
| | Low | 1.39 | 1.39 |
| | Zero | 0 | 0 |
| Pneumatic Device Count | High | 0.458 | 0.458 |
| | Intermittent | 0.247 | 0.247 |
| | Low | 0.297 | 0.297 |
| | Zero | 0.330 | 0.330 |

The pneumatics unit process does not show emissions of $CH_4$ and other natural gas components to the air. In reality, pneumatic devices are a direct source of these types of emissions; however, as a modeling convention, an intermediate flow of vented natural gas is sent to a specialized venting and flaring unit process that separates the bulk flow of the vented natural gas stream into its component hydrocarbons and other species. The venting and flaring unit process, described in more detail in **Section 3.4**, accounts for the regional variability in natural gas composition and, when appropriate, calculates the combustion emissions from the flaring of natural gas. Pneumatic devices are often dispersed across production sites, making it infeasible to install vapor recovery equipment on pneumatic devices. Since vapor recovery equipment is not installed on pneumatic devices, the gas vented by pneumatic devices is released directly to the atmosphere without being flared.

### 3.5.6 Fugitive Emissions (Extraction)

The infrastructure at natural gas production sites has connectors and valves that are designed to have zero emissions, but aging or improperly operated equipment can be sources of fugitive emissions (EPA, 2014d). The model used for this analysis has four unit processes for fugitive emissions: flanges, connectors, valves, and open-ended lines (OEL):

- **Flanges** are a specific type of connector that use bolted-on fittings to ensure tight seals that join pipes or interface pipes with other equipment.
- **Connectors** (other than flanges) include threaded unions, tees, plugs, and caps.
- **Valves** can emit natural gas through the stem that is used to open and close the valve.
- **OELs** occur when a plug or cap are missing (EPA, 2014d)

The unit process for fugitive emissions uses EPA's O&G Tool, which contains county-level data on natural gas production, well counts, device counts, and emission rates. A more detailed description of the O&G Tool can be found in **Section 3.2.**

To develop the four unit processes for fugitive emissions from natural gas extraction, this analysis aggregated the O&G Tool's county data into regional averages. The data for these sources of natural gas extraction fugitives are shown in **Table 3-22** through **Table 3-25**, and refer to components located only at the wellhead, not to large transmission pipeline and other midstream sources.

This fugitive unit processes do not show emissions of $CH_4$ and other natural gas components to the air. In reality, fugitive devices are indeed a direct source of these types of these emissions; however, as a modeling convention, an intermediate flow of vented natural gas is sent to a specialized venting and flaring unit process that separates the bulk flow of the vented natural gas stream into its component hydrocarbons and other species. The venting and flaring unit process, described in more detail in **Section 3.4**, accounts for the regional variability in natural gas composition and, when appropriate, calculates the combustion emissions from the flaring of natural gas.

**Table 3-22: Fugitive Emissions Data by Production Region and Technology**

| Property (Units) | | Appalachian | | Illinois-Michigan | Black Warrior |
|---|---|---|---|---|---|
| | | Conventional, Tight Gas, & Shale | CBM | Conventional, Tight Gas, & Shale | CBM |
| Mass Leak Rate (kg/device hr) | Connections | 0.000207 | | 0.000207 | 0.000207 |
| | Flanges | 0.000403 | | 0.000403 | 0.000403 |
| | OEL | 0.00207 | | 0.00207 | 0.00207 |
| | Valves | 0.00465 | | 0.00465 | 0.00465 |
| Device Count | Connections | 38.5 (35.0-39.1) | 39.1 (35.0-39.1) | 38.8 (35.0-39.1) | 39.1 |
| | Flanges | 18.8 (0-21.7) | 21.7 (0-21.7) | 21.4 (0-21.7) | 21.7 |
| | OEL | 4.66 (1.00-5.23) | 5.23 (1.00-5.23) | 5.29 (1.00-6.00) | 5.23 |
| | Valves | 13.6 (12.0-13.8) | 13.8 (12.0-13.8) | 13.7 (12.0-13.8) | 13.8 |
| Hours of Operation (hr/yr) | | 7,620 (260-8,760) | 8,760 (260-8,760) | 8,760 (260-8,760) | 8,760 |
| Regional Production Rate (Bcf/yr): Used to scale fugitive emission factors[1] | | 0.0138 (0.0000-1.8084) | 0.0222 (0.0010-0.1148) | 0.0120 (0.0009-0.2991) | 0.0163 (0.0056-0.0231) |

[1]Values are used for Other Fugitive Emissions as well as Pneumatic Device Venting.

**Table 3-23: Fugitive Emissions Data by Production Region and Technology**

| Property (Units) | | Central | | Rocky Mountains | | North-Central |
|---|---|---|---|---|---|---|
| | | Conventional, Tight Gas, & Shale | CBM | Conventional, Tight Gas, & Shale | CBM | Conventional, Tight Gas, & Shale |
| Mass Leak Rate (kg/device hr) | Connections | 0.000203 | 0.000206 | 0.000210 | 0.000228 | 0.000207 |
| | Flanges | 0.000396 | 0.000402 | 0.000410 | 0.000445 | 0.000403 |
| | OEL | 0.00203 | 0.00206 | 0.00210 | 0.00228 | 0.00207 |
| | Valves | 0.00457 | 0.00464 | 0.00474 | 0.00514 | 0.00465 |
| Device Count | Connections | 36.2 (35.0-47.9) | 36.7 (35.0-47.9) | 47.5 (8.90-90.1) | 30.1 (13.1-90.1) | 90.1 |
| | Flanges | 18.9 (18.0-25.4) | 19.5 (18.0-25.4) | 38.1 (0.592-143) | 20.6 (0.592-143) | 21.6 |
| | OEL | 5.86 (5.14-6.00) | 5.68 (5.14-6.00) | 7.26 (0.237-31.0) | 2.35 (0.000267-31.0) | 2.27 |
| | Valves | 12.4 (12.0-14.6) | 12.8 (12.0-14.6) | 29.6 (8.98-85.8) | 13.3 (8.98-85.8) | 27.0 |
| Hours of Operation (hr/yr) | | 8,760 | | 8,760 (7,250-8,760) | | 8,760 |
| Regional Production Rate (bcf/yr): Used to scale fugitive emission factors[1] | | 0.0426 (0.0000-0.6386) | 0.0091 (0.0004-0.1418) | 0.0637 (0.0002-0.7248) | 0.0581 (0.0001-0.1890) | 0.0185 (0.0000-0.2605) |

[1]Values are used for Other Fugitive Emissions as well as Pneumatic Device Venting.

**Table 3-24: Fugitive Emissions Data by Production Region and Technology**

| Property (Units) | | TX-LA-MS Salt | | Gulf Coast | | Fort Worth | West Texas-Permian |
|---|---|---|---|---|---|---|---|
| | | Conventional | Tight Gas | Conventional | Tight Gas | Shale | Shale |
| Mass Leak Rate (kg/device hr) | Connections | 0.000208 | | 0.000205 | | 0.000205 | 0.000209 |
| | Flanges | 0.000405 | | 0.000400 | | 0.000400 | 0.000408 |
| | OEL | 0.00208 | | 0.00205 | | 0.00205 | 0.00209 |
| | Valves | 0.00467 | | 0.00462 | | 0.00462 | 0.00471 |
| Device Count | Connections | 37.4 (35.0-39.1) | | 39.1 | | 39.1 | 42.5 (39.1-42.5) |
| | Flanges | 20.2 (18.0-21.7) | | 21.7 | | 21.7 | 29.0 (21.7-29.0) |
| | OEL | 5.54 (5.23-6.00) | | 5.23 | | 5.23 | 3.00 (3.00-5.23) |
| | Valves | 13.1 (12.0-13.8) | | 13.8 | | 13.8 | 18.5 (13.8-18.5) |
| Hours of Operation (hr/yr) | | 8,760 | | 8,760 | | 8,760 | 8,760 |
| Regional Production Rate (Bcf/yr): Used to scale fugitive emission factors[1] | | 0.1129 (0.0007-3.0201) | | 0.0889 (0.0014-1.7526) | | 0.165 (0.165-0.0625) | 0.0667 (0.0741-0.0181) |

[1]Values are used for Other Fugitive Emissions as well as Pneumatic Device Venting.

**Table 3-25: Fugitive Emissions Data by Production Region and Technology**

| Property (Units) | | West Coast | | Alaska |
|---|---|---|---|---|
| | | Conventional | Shale | Conventional |
| Mass Leak Rate (kg/device hr) | Connections | 0.000207 | | 0.000200 |
| | Flanges | 0.000403 | | 0.000390 |
| | OEL | 0.00207 | | 0.00200 |
| | Valves | 0.00465 | | 0.00450 |
| Device Count | Connections | 39.1 | | 39.1 |
| | Flanges | 21.7 | | 21.7 |
| | OEL | 5.23 | | 5.23 |
| | Valves | 13.8 | | 13.8 |
| Hours of Operation (hr/yr) | | 8,760 | | 8,760 |
| Regional Production Rate (scf/yr): Used to scale fugitive emission factors [1] | | 0.0605 (0.0018-0.3848) | | 0.144 (0.144-0.0412) |

[1] Values are used for Other Fugitive Emissions as well as Pneumatic Device Venting.

### 3.5.7 Produced Water Tanks

A common by-product of natural gas is produced water, which is a brine solution that condenses out of the gas or is cleared of the well during liquid unloading. A separator at the extraction site separates the produced water from the gas and pipes it to a produced water storage tank. Often, produced water tanks are at atmospheric pressure and vented directly to the atmosphere. Emission types from produced water tanks include flashing, working, and breathing losses. Flashing losses are emissions due to the volatilization of the lightest end liquids as the produced water enters the atmospheric tank from the slightly more pressurized separator. Working losses occur as the tank is filled and make up the volume of residual gas in the tank as it is displaced by liquid produced water. Breathing losses are due to the slow volatilization of the produced water while it is stored in the tank, which is a function of the daily temperature fluctuation of the region in which the water is produced. The data for produced water tanks (**Table 3-26**) were obtained from the O&G Tool, which is discussed in **Sections 3.2**, **3.5.5**, and **3.5.6**.

**Table 3-26: Produced Water Tank Data for all Production Regions**

| Property (units) | Value |
|---|---|
| $CH_4$ Emission Factor (kg/bbl) | 0.0508 |
| NG Produced (mcf/well) | 16,300 |
| Water Produced (bbl/well) | 9,630 |

This unit process for produced water tanks does not show emissions of $CH_4$ and other natural gas components to the air. In reality, produced water tanks are indeed a direct source of these types of emissions; however, as a modeling convention, an intermediate flow of vented natural gas is sent to a specialized venting and flaring unit process that separates the bulk flow of the vented natural gas stream into its component hydrocarbons and other species. The venting and flaring unit process, described in more detail in **Section 3.4**, accounts for the regional variability in natural gas composition and, when appropriate, calculates the combustion emissions from the flaring of natural gas.

### 3.5.8 Point Source and Fugitive Emissions from Offshore Extraction

Routine emissions from natural gas extraction include gas that is released from the wellhead and gathering equipment. The data for onshore wells allow attribution to specific activities (liquid unloadings) and equipment (valves, flanges, connectors, open ended lines, and pneumatic devices); the scope of these onshore unit processes are described in **Section 3.5.1** through **Section 3.5.7** of this analysis. The data for offshore wells is not as detailed as it is for onshore wells. Two general categories – other point sources and other fugitives – are used to account for routine emissions from offshore natural gas extraction. (The word “other” is used here to distinguish these emission sources from completions, workovers, and other specific emission sources for offshore extraction.)

For offshore extraction, other point sources comprise heating equipment, engines, mud degassing, and storage tanks. It is possible to install vapor recovery units (VRU) on these emission sources and send potential emissions to flares (EPA, 2009). The data for other point source emissions from offshore extraction, located in **Table 3-27**, are based on EPA data representative of 2006 natural gas production (EPA, 2011b).

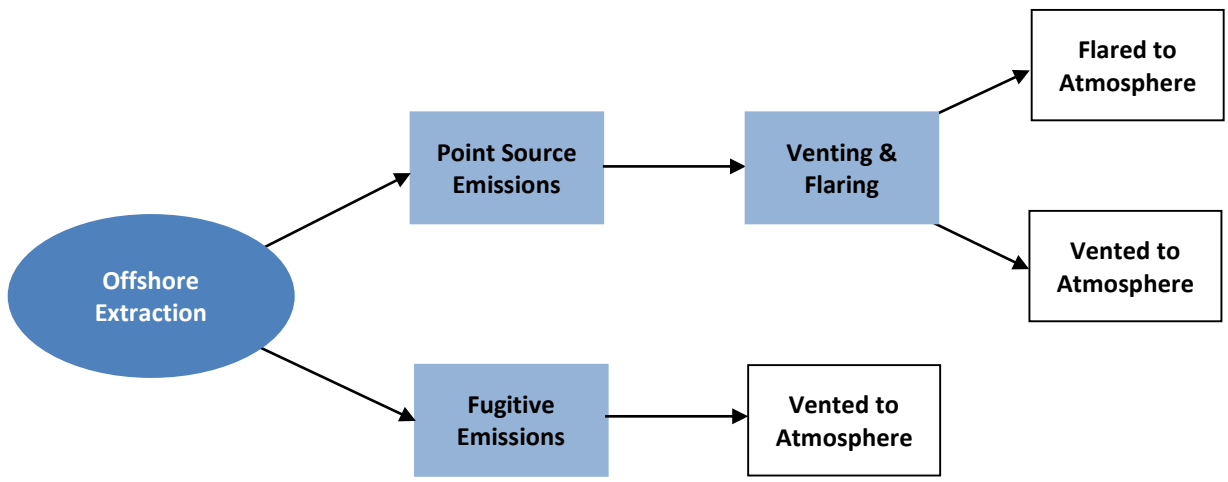
For offshore extraction, fugitive emission sources comprise connectors, flanges, open-ended lines, pumps, and valves. Data for other fugitive emissions from offshore extraction. **Table 3-27** is based on EPA data for onshore and offshore natural gas wells (EPA, 2011a).

**Table 3-27: Point Source and Fugitive Emissions Data for Offshore Conventional Production**

| Property (Units) | Alaska Offshore | Gulf of Mexico Offshore | Pacific Offshore |
|---|---|---|---|
| **Extraction: Venting Other Point Source** | | | |
| Point Source Emission Factor (fraction of *potential* NG emissions per unit of NG produced) | 0.0000708 | 0.0000651 | 0.0000708 |
| **Extraction: Venting Other Fugitives** | | | |
| Fugitives Emission Factor (fraction of NG emissions per unit of NG produced) | 0.00354 | 0.00326 | 0.00354 |

The key difference between point source and fugitive emission sources is that it is practical to apply VRUs to point sources, allowing the flaring of natural gas and thus reducing the GWP and other impacts of extraction emissions. In contrast, fugitive emissions are released directly to the atmosphere without the use of flares or other environmental control devices. The difference between point source and fugitive emissions is shown in **Figure 3-1**.

**Figure 3-1: Emissions Pathways for Offshore Extraction**




## 3.6 Processing of Natural Gas

The processing of natural gas comprises AGR, dehydration, hydrocarbon liquids removal, and compression.

### 3.6.1 Acid Gas Removal

AGR, also called natural gas sweetening, is the removal of $H_2S$ from raw natural gas. Raw natural gas contains varying levels of $H_2S$, a toxic gas that reduces the heat content of natural gas and causes fouling when combusted in equipment. The $H_2S$ concentration used in this analysis is based on raw gas composition data compiled by the Gas Processors Association (Foss, 2004).

The scrubbing columns in AGR systems bring natural gas in contact with amine-based solvents that have an affinity for $H_2S$ and $CO_2$. The acid gases are then separated from the solvent in a stripping

column. Stripping columns have reboilers that drive off acid gases and regenerate the amine-based solvents. Reboiler heat is generated by the combustion of natural gas and accounts for the majority of energy consumed by the AGR process. Reboiler energy consumption is a function of the amine flow rate, which, in turn, is related to the amount of $H_2S$ removed from natural gas. This analysis applies an emission factor for industrial boilers to the energy consumption rate to estimate the combustion emissions from amine reboilers (EPA, 1995). The chemistry, energy requirements, and efficiency of the amine reboiler are the factors used in this analysis to calculate the energy requirements per unit of natural gas treated.

Raw natural gas contains naturally occurring $CO_2$ that contributes to the acidity of natural gas. Most of this $CO_2$ is absorbed by the amine solution during the sweetening of natural gas and is ultimately released to the atmosphere when the amine is regenerated. This analysis calculates the mass of naturally occurring $CO_2$ emissions from the AGR unit by balancing the composition of production gas (natural gas that has been extracted but has not undergone significant processing) and pipeline-quality gas.

AGR is a source of vented natural gas emissions. In addition to absorbing $H_2S$, the amine solution absorbs a portion of natural gas. This natural gas is released to the atmosphere during amine solvent regeneration. The venting of natural gas from acid gas removal is based on emission factors developed by the Gas Research Institute (API, 2009). Natural gas processing facilities have VRUs that recover the gas vented from AGR units; the way in which the model accounts for venting and flaring, including the variability in regional natural gas compositions, is described in more detail in **Section 3.4**.

### 3.6.2 Dehydration

Dehydration is necessary to remove water from raw natural gas, which makes it suitable for pipeline transport and increases its heating value. The configuration of a typical dehydration process includes an absorber vessel in which glycol-based solution comes into contact with a raw natural gas stream, followed by a stripping column in which the rich glycol solution is heated in order to drive off the water and regenerate the glycol solution. The regenerated glycol solution (the lean solvent) is recirculated to the absorber vessel. The emissions from dehydration operations include combustion and venting emissions.

The fuel requirements of dehydration are a function of the reboiler duty. Due to the heat integration of the absorber and stripper streams, the reboiler, which is heated by natural gas combustion, is the only equipment in the dehydration system that consumes fuel. The reboiler duty (the heat requirements for the reboiler) is a function of the flow rate of glycol solution, which, in turn, is a function of the difference in water content between raw and dehydrated natural gas.

In addition to absorbing water, the glycol solution also absorbs natural gas, which is lost to evaporation during the regeneration of glycol in the stripper column. The rate of natural gas venting from glycol dehydration is based on emission factors developed by the Gas Research Institute (API, 2009). Natural gas processing facilities have VRUs that recover the gas vented from dehydration units; the way in which the model accounts for venting and flaring, including the variability in regional natural gas compositions, is described in more detail in **Section 3.4**.

### 3.6.3 Liquids Separation

In addition to removing impurities from natural gas, processing facilities also remove fractions of higher hydrocarbons as natural gas liquids (NGL). These NGLs should not be confused with the hydrocarbon condensates that more freely separate from natural gas at the wellhead.

Separators use propane refrigeration to chill natural gas, allowing the separation of natural gas from NGLs (Vargas, 2010). The electrical and heat requirements and the process yields for this process are dependent on the various flow rates through the system and thus the chemical composition of the inlet gas. For simplicity, the unit process for natural gas liquids separation scales the electrical and heat requirements and yields based on the mass flow rate of output natural gas, rather than accounting for changes in gas composition and the non-linear changes in loads that would accompany changes in flow rates.

NGLs are a marketable product that can be used as a material feedstock or an energy source. The relative masses of natural gas and NGL after the point at which the co-products are separated are used as a basis for splitting all emissions based on mass that occur from extraction through AGR.

### 3.6.4 Pneumatic Devices (Processing)

The processing of natural gas uses pneumatic devices for the opening and closing of valves and other control systems. When a pneumatic device is in action, a small amount of natural gas leaks through the valve stem and is released to the atmosphere.

Data for the pneumatic emissions at processing facilities are based on EPA data for gas processing plants (EPA, 2011a). The EPA data are based on 2006 production (EPA, 2011a) and show the annual $CH_4$ emissions for specific processing activities. This analysis translates EPA's annual data to a unit production basis by dividing the $CH_4$ emissions by the natural gas processed in 2006. (More recent data are available for the annual natural gas processing rate – the volume of gas processed in a year – but the data for pneumatic emissions from processing were the latest data point available when the life cycle model was developed, making it necessary to use 2006 as the data year for both $CH_4$ emissions and natural gas throughput. Using a single data year for this calculation ensures that the resulting emission rate is not confounded by temporal variability.)

It is not feasible to install vapor recovery equipment on all pneumatics emission sources. In reality, these emission sources are released directly to the atmosphere, but the model augments these emission sources with a venting and flaring unit process that speciates the natural gas emissions into $CH_4$, a detailed profile of NMVOCs, and other compounds. These species are then reported as emissions to air. In the case of pneumatic and fugitive emissions the venting and flaring unit process is set at 100 percent venting (0 percent flaring). The venting and flaring unit process, described in more detail in **Section 3.4**, accounts for the regional variability in natural gas composition.

### 3.6.5 Other Point Source Emissions (Processing)

Routine emissions from natural gas processing include gas that is released from processing equipment not accounted for elsewhere in NETL's model. These emissions are referred to as "other point source emissions." VRUs are feasible for the other point source emissions, so this analysis assigns a 100 percent flaring rate to other point source emissions from natural gas processing.

Data for the other point source emissions from natural gas processing are based on EPA data for 2006 (EPA, 2011a) and show the annual emissions for specific gas processing activities. The EPA data are converted from an annual basis to a unit of production basis by dividing the natural gas emission rate by the amount of natural gas processed in the same data year. (As discussed above, in **Section 3.6.4**, the 2006 data year was the latest data available when the life cycle model was developed.) A venting and flaring unit process, described in more detail in **Section 3.4**, accounts for the regional variability in natural gas composition and, when appropriate, calculates the combustion emissions from the flaring of natural gas.

### 3.6.6 Fugitive Emissions (Processing)

Routine emissions from natural gas processing include fugitive emissions from processing equipment not accounted for elsewhere in the model. Fugitive emissions are another source of natural gas emissions. Fugitive emissions pass through valve stems, connections, and other processing equipment. These emissions cannot be captured for flaring.

Data for the fugitive emissions from natural gas processing are based on EPA data that are based on 2006 production (EPA, 2011a) and show the annual emissions for specific gas processing activities. (As discussed above, in **Section 3.6.4**, the 2006 data year was the latest data available when the life cycle model was developed.) This analysis translates the EPA data from an annual basis to a unit of production basis by dividing the annual emission rate by the amount of natural gas processed in the same data year. A venting and flaring unit process, described in more detail in **Section 3.4**, accounts for the regional variability in natural gas composition.

The unit processes for acid gas removal, dehydration, liquids separation, other point source emissions, and fugitive emissions calculate a complete list of energy and material flows. **Appendix A** provides links to the documentation for these unit processes. **Table 3-28** summarizes the energy requirements and potential emissions (vent streams prior to flaring) for these processes. (Most of the material flows in the natural gas model are on a mass basis, so **Table 3-28** expresses the flows of natural gas in kg.)

**Table 3-28: Summary of NG Processing Energy and Potential Emissions**

| Parameter | Unit Process | Value | Units |
|---|---|---|---|
| Processing Energy | Acid Gas Removal | 2.26E-05 | kg NG combusted/kg NG (post AGR) |
| | Dehydration | 1.48E-04 | kg NG combusted/kg NG (post dehydration) |
| | Liquid Separation | 1.45E-06 | kg NG combusted/kg NG (post liquid separation) |
| | | 1.38E-05 | MWh electricity/kg NG (post liquid separation) |
| Potential Emissions (prior to flaring) | Acid Gas Removal | 1.39E-03 | kg NG/kg NG (post AGR) |
| | Dehydration | 8.63E-06 | kg NG/kg NG (post dehydration) |
| | Other Point Sources | 3.68E-04 | kg NG/kg NG (post other point sources) |
| | Pneumatic Devices | 6.33E-06 | kg NG/kg NG (post pneumatic devices) |
| | Other Fugitives | 1.02E-03 | kg NG/kg NG (post other fugitives) |

### 3.6.7 Natural Gas Compression

Compressors are used to increase the gas pressure for pipeline distribution. This analysis assumes that the inlet pressure to compressors at the natural gas extraction and processing site is 50 psig and the outlet pressure is 800 psig. The inlet pressure depends on the pressure of the natural gas reservoir and pressure drop during gas processing and thus introduces uncertainty to the model. The outlet pressure of 800 psig is a standard pressure for pipeline transport of natural gas. The energy required for compressor operations is based on manufacturer data that compares power requirements to compression ratios (the ratio of outlet to inlet pressures).

The two types of compressors used for natural gas operations are reciprocating compressors and centrifugal compressors. Although they are not as efficient as centrifugal compressors, reciprocating compressors account for most onshore wellhead compression because they are used for small-scale extraction operations that do not justify the increased capital requirements of centrifugal compressors. The natural gas fuel requirements for a gas-powered, reciprocating compressor used for

natural gas extraction are based on a compressor survey conducted for natural gas production facilities in Texas (Burklin & Heaney, 2006). In addition to $CO_2$ emissions from diesel fuel combustion, reciprocating compressors have $CH_4$ emissions as a result of leaks in compressor rod packing systems. These emissions are based on measurements conducted by the EPA on a sample of 22 compressors (EPA, 1995).

Centrifugal compressors use a rotating disk or impeller to compress gas. There are two types of centrifugal compressors: gas-powered and electrically powered. Gas-powered centrifugal compressors use natural gas as a fuel and are commonly used at offshore natural gas extraction sites. If the natural gas extraction site is near a source of electricity, it is financially preferable to use electrically powered equipment instead of gas-powered equipment. This is the case for extraction sites for Barnett Shale located near Dallas-Fort Worth. The use of electric equipment is also an effective way of reducing the noise of extraction operations, which is encouraged when an extraction site is near a city. An electric centrifugal compressor uses the same compression principles as a gas-powered centrifugal compressor, but its shaft energy is provided by an electric motor instead of a gas-fired turbine. Electric compressors have negligible $CH_4$ emissions because they do not require a fuel line for the combustion of product natural gas; incomplete combustion of natural gas is not an issue (EPA, 2011c). Electric compressors are recommended by EPA's Natural Gas STAR program (a voluntary partnership between EPA and industry) as a strategy for reducing system emissions of $CH_4$ (EPA, 2011c).

The unit processes for compression at natural gas processing facilities calculate a complete list of energy and material flows. **Appendix A** provides links to the documentation for these unit processes. **Table 3-29** summarizes the energy requirements and potential emissions (vent streams prior to flaring) for compression at processing facilities. (Most of the material flows in the natural gas model are on a mass basis, so **Table 3-29** expresses natural gas flows in kg.)

**Table 3-29: Summary of NG Processing Compression Energy and Potential Emissions**

| Parameter | | Unit Process | Value | Units |
|---|---|---|---|---|
| Energy | Compressor Shaft Energy | Centrifugal Compressor (gas powered) | 1.76E-04 | MWh shaft energy/ kg NG compressed |
| | | Centrifugal Compressor (electrically powered) | | |
| | | Reciprocating Compressor | | |
| | NG Combusted as Fuel | Centrifugal Compressor (gas powered) | 201 | kg NG combusted/ MWh shaft energy |
| | | Reciprocating Compressor | 217 | |
| | Electric Motor Efficiency | Centrifugal Compressor (electrically powered) | 95% | dimensionless |
| Potential Emissions (prior to flaring) | Wet Seal Emissions | Centrifugal Compressor (gas powered) | 6.90E-03 | kg $CH_4$/ kg NG compressed |
| | | Centrifugal Compressor (electrically powered) | | |
| | Rod Packing Emissions | Reciprocating Compressor | 1.53E-03 | |

## 3.7 Transmission of Natural Gas

Natural gas transmission lines are large pipelines that transport natural gas from processing facilities to the city gate (the point at which natural gas can be consumed by large-scale consumers or

transferred to local distribution companies). This analysis includes the key construction and operation activities for pipeline transmission.

### 3.7.1 Natural Gas Transport Construction

The construction of a natural gas pipeline is based on the linear density, material requirements, and length for pipeline construction. A typical natural gas transmission pipeline is 32 inches in diameter and is constructed of carbon steel. The mass of pipeline per unit length was determined using an online calculator (Tubes, 2009). The weight of valves and fittings were estimated at an additional 10 percent of the total pipeline weight. The pipeline was assumed to have a life of 30 years. The mass of pipeline construction per kg of natural gas was determined by dividing the total pipeline weight by the total natural gas flow through the pipeline for a 30-year period.

Construction is a one-time activity that is apportioned to each unit of natural gas transport by dividing all construction burdens by total production over the study period.

### 3.7.2 Natural Gas Transport Operations

The U.S. has an extensive natural gas pipeline network that connects natural gas supplies and markets. Compressor stations are located along natural gas transmission pipelines to boost the pressure of the natural gas. These stations consist of centrifugal and reciprocating compressors, most of which are powered by natural gas. When electricity is available, however, electrically powered compressors are used. The average power of electrically driven compressors for U.S. natural gas transmission is assumed to be the same as the average power of all compressors on the transmission network.

The use rate of natural gas for fuel in transmission compressors was calculated from the Federal Energy Regulatory Commission (FERC) Form 2 database, which is based on an annual survey of gas producers and pipeline companies (FERC, 2010). This fuel use rate was converted to a basis of kg of natural gas consumed per kg of natural gas transported by multiplying it by the total natural gas delivered by the transmission network in 2008 (EIA, 2011c) and dividing it by the annual tonne-km of pipeline transmission in the U.S. (Dennis, 2005). More recent transportation data are not available, so this analysis assumes the same tonne-km rate for 2008 as shown from 1995 through 2003.

The air emissions from the combustion of natural gas by compressors are estimated by applying EPA emission factors to the natural gas consumption rate of the compressors (EPA, 1995). Specifically, the emission profile of gas-powered, centrifugal compressors is based on emission factors for gas turbines; the emission profile of gas-powered, reciprocating compressors is based on emission factors for 4-stroke, lean burn engines. For electrically powered compressors, this analysis assumes that the indirect emissions are representative of the U.S. average fuel mix for electricity generation.

In addition to air emissions from combustion processes, fugitive venting from pipeline equipment results in the $CH_4$ emissions to air. The fugitive emission rate for natural gas pipeline operations is based on data published by the Bureau of Transportation Statistics (BTS) (Dennis, 2005) and EPA (EPA, 2010b). The 2003 data are the most recent data point in the BTS reference, and thus EPA's inventory data for the years 2000 and 2005 were interpolated to arrive at a year 2003 value.

## 3.8 Distribution of Natural Gas

The distribution system leaks natural gas, resulting in $CH_4$ emissions and product losses. This analysis models the distribution of natural gas by characterizing key operation activities for natural gas distribution at a high level. This process is used only for the cradle-to-gate boundary described in

this analysis. It is not included in the cradle-to-grave boundary of delivered electricity, as it assumed that the power plant will connect directly to the high-capacity transmission network.

The natural gas distribution process accounts for the loss of natural gas during distribution, all of which are assumed to be due to leaks. The $CH_4$ emissions from distribution are not inventoried explicitly in this process, but rather this process sends a value for total natural gas distribution losses to a venting and flaring unit process that has zero percent flaring and allows parameterization of the gas composition.

The loss rate is calculated by dividing total $CH_4$ emissions from distribution by the total natural gas distributed and adjusting for the non-$CH_4$ content in distributed gas.

No energy use for motive force is modeled; unlike the transmission network, the distribution network does not rely on compressors to move natural gas. Transmission pipelines operate at 1,500 pounds per square inch (psi), but distribution pipelines operate at much lower pressures – 3 psi or lower (NaturalGas.org, 2010).

## 3.9 Electricity Generation from Natural Gas

One of the primary uses of natural gas in the U.S. is to produce electricity. In this analysis, five different natural gas power plant options are modeled: two plants using advanced technology and three plants representing different fleet applications.

### 3.9.1 Advanced Natural Gas Power

The advanced natural gas power plants are natural gas combined cycle (NGCC) technologies as characterized by NETL's baseline study. The NGCC power plant is a thermoelectric generation facility with a net capacity of 555 MW. It has two parallel, advanced F-Class gas-fired combustion turbines, and each combustion turbine is followed by a heat recovery steam generator that produces steam that is fed to a single steam turbine. The NGCC plant consumes natural gas at a rate of 75,900 kg/hr and has an 85 percent capacity factor (NETL, 2010b).

The carbon capture scenario for NGCC is the same power generation technology described above, but is configured with a Fluor Econamine FG Plus$^{SM}$ carbon capture system that recovers 90 percent of the $CO_2$ in the flue gas. The NGCC power plant with carbon capture has the same fuel input rate as the plant without carbon capture (75,900 kg/hr), but the addition of a carbon capture system reduces the net capacity to 474 MW (NETL, 2010b).

In the carbon capture scenario, $CO_2$ is sent by pipeline to a saline aquifer sequestration site. Saline aquifers are geological formations that are saturated with brine water. In the United States (U.S.), saline aquifers have a broader geographical distribution than oil and gas reservoirs and have a large capacity potential for long-term carbon dioxide ($CO_2$) storage. The sequestration technology modeled herein comprises the energy and emissions from site preparation, well construction, $CO_2$ sequestration operations, site monitoring, brine management, well closure, and land use. It is assumed that a maximum of one percent of stored $CO_2$ eventually migrates to the surfaces and is released to the atmosphere over a 100-year monitoring period (a conservative assumption that is based on other NETL reports that bracket the potential sequestration losses until better, long-term data are available). The gate-to-grave emissions (where the gate is capture of $CO_2$ at a power plant and the grave is the disposition of $CO_2$ at a sequestration site) are 13.9 kg of $CO_2$ and 0.031 kg of $CH_4$ per sequestration of one metric ton of $CO_2$. Small amounts of $N_2O$ and $SF_6$ (accounting for less than 0.5% of gate-to-grave emissions) are also emitted by the $CO_2$ sequestration life cycle. More data

on the details of our modeling of $CO_2$ sequestration in saline aquifers is available in *Gate-to-Grave Life Cycle Analysis of Saline Aquifer Sequestration of Carbon Dioxide* (NETL, 2013).

### 3.9.2 Fleet Natural Gas Power

Each region of the U.S. has baseload generation capacity with load following and peaking plants that are brought online to respond to variations in demand. Demand levels rise throughout the day and are typically higher during the summer and winter than in fall and spring (EIA, 2011b). When demand exceeds baseload capacity, the most efficient (i.e. least costly on a per MWh basis) plants are typically brought online first. With each subsequent demand increase, the next most efficient plant is brought online (EIA, 2013c).

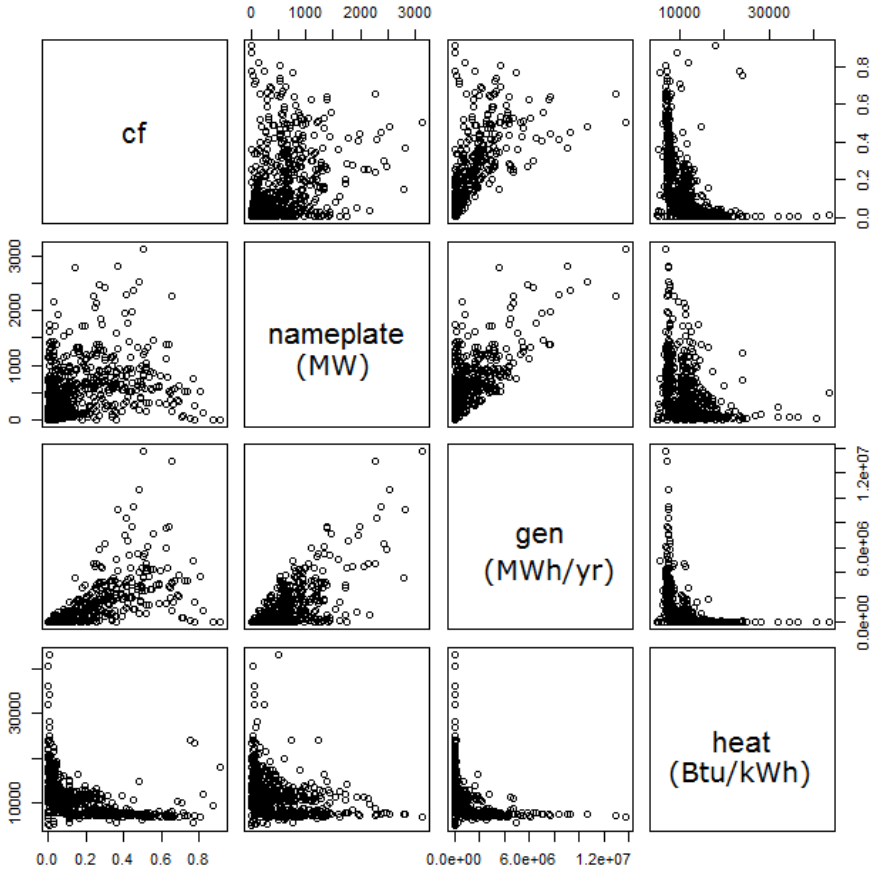
This analysis uses the Emissions and Generation Resource Integrate Database (eGRID) (2010) to characterize the heat rates and emissions from fleet power plants; however, additional filtering was necessary. The eGRID database provides regional emission profiles for natural gas power plants, but does not categorize plant by application (baseload, load following, or peaking). To develop regional fleet profiles, the eGRID data were filtered by capacity factors, heat rate, and nameplate capacity. The capacity factor of a power plant is the ratio of its actual output to its maximum possible output, typically on an annual basis. This ratio characterizes a plant based on how often it is being run during the year in order to meet electricity demand. Heat rate is essentially the power plant efficiency, expressed in this analysis in units of Btu/kWh (where 100 percent efficiency is 3,412 Btu/kWh), and thus potentially characterizes a plant for when it would be brought online to meet demand. The nameplate capacity is the designed full-load sustained output, expressed in this analysis in units of MW. The expected characteristics for natural gas plant types are categorized and shown in **Table 3-30**.

**Table 3-30: Expected Qualitative Characteristics for U.S. Natural Gas Power Plant Types**

| PlantType | Capacity Factor | Heat Rate | Nameplate Capacity |
|---|---|---|---|
| Baseload | High | Low | High |
| Load-Following | Medium | Medium | Medium/High |
| Peaking | Low | High | Low/Medium |

A multi-box scatterplot (**Figure 3-2**) was generated to show the relationships among primary parameters (capacity factor, heat rate, and nameplate capacity) as well as the total generation for each power plant. The scatter plots indicate positive correlations between capacity factor and nameplate capacity, capacity factor and annual net generation, and nameplate capacity and annual net generation. The scatter plots indicate negative correlations between heat rate and capacity factor, heat rate and nameplate capacity, and heat rate and annual net generation.

**Figure 3-2: Multi-box Scatterplot for Fleet Natural Gas Power Plants**




To evaluate the strengths of the correlations indicated by the above scatterplots (**Figure 3-2**) a Pearson product-moment correlation coefficient was computed to assess the relationship between capacity factor and nameplate capacity, and capacity factor and heat rate (Btu/kWh). Results show a weak positive correlation between capacity factor and nameplate capacity variables, and a moderate negative correlation between capacity factor and heat rate variables. Given the small p-values for both tests, it can be concluded that the correlation between these variables is not due to random sampling. An additional Pearson product-moment correlation coefficient was computed to assess the relationship between capacity factor and percent net annual generation, as well as capacity factor and cumulative net annual generation (MWh/yr). Results show a strong positive correlation between capacity factor and percent net annual generation, and a strong positive correlation between capacity factor and cumulative net annual generation. Given the small p-values for both tests, we conclude that the correlation between these variables is not due to random sampling.

**Figure 3-3** shows the cumulative net annual generation as a function of capacity factor and uses bubble size to represent the magnitudes of heat rate (left) and nameplate capacity (right), where an increase in turquoise bubble size represents a more inefficient plant and an increase in green bubble size represents a larger plant. Similarly, **Figure 3-4** shows percent net annual generation as a function of capacity factor and uses bubble size to represent the magnitudes of heat rate (left) and nameplate capacity (right), where an increase in turquoise bubble size represents a more inefficient plant and an increase in green bubble size represents a larger plant. These figures show that natural gas peaking

and load-following plants (plants with relatively low capacity factors) contribute more to cumulative net annual generation for U.S. natural gas fleet compared to natural gas baseload plants (plants with high capacity factors). Similarly, plants with low capacity factors are a large percent contribution to annual generation. As expected, **Figure 3-3** and **Figure 3-4** show plant efficiency to generally increase as capacity factor increases and the capacity of the plant to generally have a weak correlation with an increase in capacity factor. Therefore, larger natural gas plants are not necessarily utilized for baseload. Ultimately, results from data and statistical analysis show that the majority of U.S. natural gas fleet generation is utilized for peaking and load-following with a small portion being utilized for baseload, where capacity factor and heat rate parameterization have the strongest capability in discerning between natural gas fleet types in 2010.

**Figure 3-3: Capacity Factor vs. Cumulative Net Annual Generation, Natural Gas**

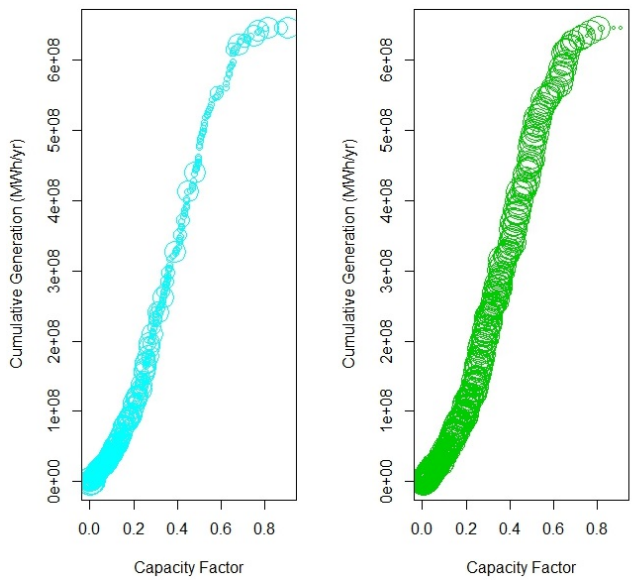
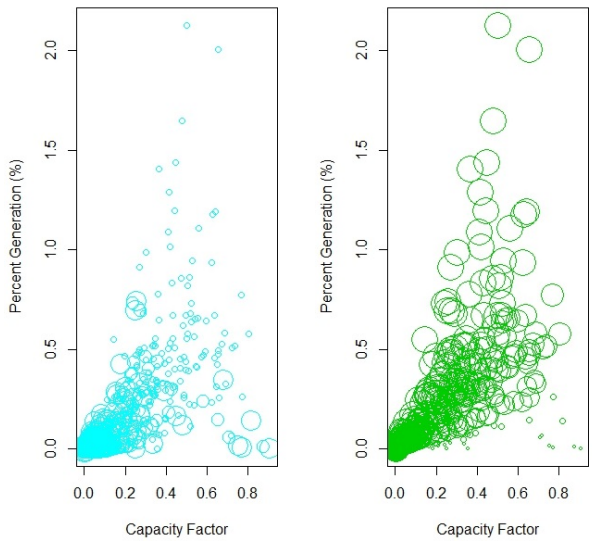



**Figure 3-4: Capacity Factor vs. Percent Net Annual Generation, Natural Gas**



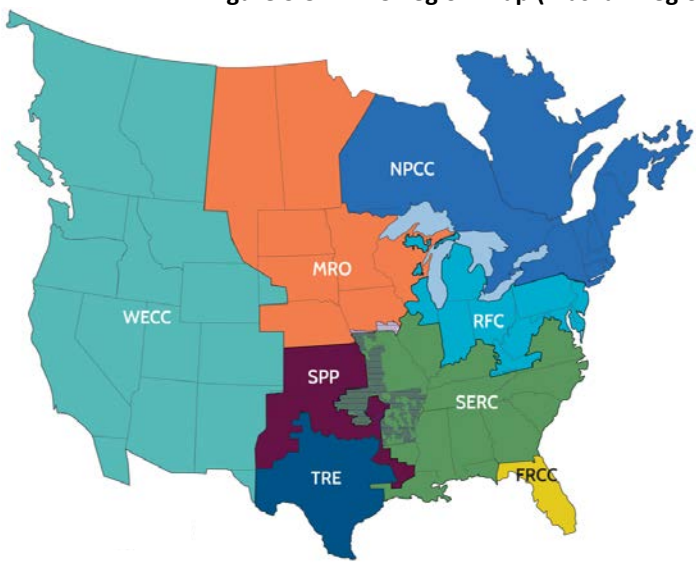
The above statistical analysis shows that the majority of U.S. natural gas power is used for load-following and peaking applications, and capacity factor and heat rate have the strongest correlations with natural gas power plant applications. Based on these findings and the available data, capacity factor was applied to the eGRID data to stratify power plant by application (baseload, load following, and peaking). According to the EIA, average capacity factors for U.S. natural gas turbines, which are generally used to meet peak electricity demand, were 0.5 in 2012, except for the Texas Reliability Entity (TRE) and Northeast Power Coordinating Council (NPCC) regions, where they were approximately 0.2 (EIA, 2013a). Using this information as a guide, eGRID (2010) facilities were filtered into three categories using the capacity factor ranges in **Table 3-31**.

**Table 3-31: Capacity Factor Filters for Plant Categorization**

| Plant Type | Capacity Factor |
|---|---|
| Baseload | ≥ 0.6 |
| Load-Following | 0.2 ≤ n < 0.6 |
| Peaking | < 0.2 |

The capacity factor relationship is also used to determine percent generation and emissions from each power plant application. Inventories were filtered by NERC category before percent generation for each plant was calculated. This percentage was used to calculate weighted fleet emission factors for each region based on its percent contribution to total net annual generation for the respective NERC region. This was done for the entire U.S. to generate emission factors for the U.S. fleet based on each plant's percent contribution to total net annual generation for the U.S. The nine NERC regions that compose the U.S. fleet emission profile shown in **Figure 3-5**.

**Figure 3-5: NERC Region Map (Alaskan Region Not Shown) (ERCOT, 2015)**




ASCC (Alaska Systems Coordinating Council)
FRCC (Florida Reliability Coordinating Council)
MRO (Midwest Reliability Organization)
NPCC (Northeast Power Coordinating Council)
RFC (Reliability First Corporation)
SERC (Southeastern Electric Reliability Council)
SPP (Southwest Power Pool)
TRE (Texas Reliability Entity)
WECC (Western Electricity Coordinating Council)

*Graphic used with permission from ERCOT.*

The emission profile results for natural gas fleet type and NERC region averages, as well as natural gas fleet type and U.S. average derived from EPA's eGRID 2010 data are shown in **Table 3-32**.

**Table 3-32: Emission Profile Results for Natural Gas Fleet Type and NERC Region Averages (EPA, 2014a)**

| Fleet Type | Region | Capacity Factor | Nameplate Capacity (MW) | Heat Rate (Btu/kWh) | $CO_2$ (kg/MWh) | $CH_4$ (kg/MWh) | $N_2O$ (kg/MWh) |
|---|---|---|---|---|---|---|---|
| Baseload | NPCC | 0.73 | 518 | 7,130 | 385 | 7.52E-03 | 7.54E-04 |
| | SERC | 0.91 | 2.50 | 17,900 | 949 | 1.89E-02 | 4.24E-03 |
| | SPP | 0.82 | 125 | 11,900 | 643 | 1.26E-02 | 1.26E-03 |
| | TRE | 0.77 | 724 | 5,990 | 322 | 6.32E-03 | 6.33E-04 |
| | WECC | 0.79 | 395 | 7,270 | 391 | 7.67E-03 | 7.68E-04 |
| Load-Following | ASCC | 0.61 | 340 | 10,500 | 558 | 1.11E-02 | 1.11E-03 |
| | FRCC | 0.45 | 2,150 | 7,460 | 403 | 8.30E-03 | 8.95E-04 |
| | NPCC | 0.51 | 936 | 7,340 | 396 | 7.74E-03 | 7.75E-04 |
| | RFC | 0.39 | 1,040 | 7,580 | 409 | 7.99E-03 | 8.01E-04 |
| | SERC | 0.38 | 1,310 | 8,000 | 432 | 8.44E-03 | 8.45E-04 |
| | SPP | 0.31 | 903 | 8,620 | 464 | 9.09E-03 | 9.11E-04 |
| | TRE | 0.39 | 971 | 7,640 | 412 | 8.06E-03 | 8.07E-04 |
| | WECC | 0.46 | 925 | 7,450 | 402 | 7.86E-03 | 7.87E-04 |
| Peaking | ASCC | 0.05 | 94.2 | 14,400 | 766 | 1.53E-02 | 1.55E-03 |
| | FRCC | 0.15 | 477 | 9,860 | 533 | 1.04E-02 | 1.04E-03 |
| | MRO | 0.10 | 567 | 8,720 | 470 | 9.21E-03 | 9.24E-04 |
| | NPCC | 0.14 | 577 | 10,500 | 567 | 1.12E-02 | 1.14E-03 |
| | RFC | 0.09 | 845 | 9,440 | 509 | 9.96E-03 | 9.98E-04 |
| | SERC | 0.11 | 893 | 10,200 | 551 | 1.07E-02 | 1.08E-03 |
| | SPP | 0.14 | 850 | 11,800 | 635 | 1.24E-02 | 1.25E-03 |
| | TRE | 0.12 | 1,030 | 10,500 | 566 | 1.11E-02 | 1.11E-03 |
| | WECC | 0.12 | 1,170 | 9,070 | 488 | 9.57E-03 | 9.59E-04 |

### 3.9.3 Power Plant and $CO_2$ Sequestration Land Use

This analysis models land use change for advanced power plants, which are greenfield installations. Modeling assumptions for land use change can be found in **Table 3-33**. Land use change is not modeled for fleet power plants, which are existing installations.

The area of a typical NGCC facility is 40,500 $m^2$ (10 acres). This land area is increased by 10 percent to account for the land used by an NGCC power plant *with* $CO_2$ capture. Power plant sites are permanently converted to an industrial land application with no reversion to the original land type.

The NGCC with CCS scenario includes the land used by a saline aquifer sequestration sites. There are a total of 47 wells required for the modeled saline aquifer. Each well footprint of 0.25 acres (NETL, 2012). The sequestration site has a water treatment facility with a footprint of 6,400 $m^2$. $CO_2$ injection equipment was assumed to require 400 $m^2$. Roads are used to access injection wells; the required road area was estimated by assuming that the wells are laid out in a square grid with equal spacing. The total footprint for the saline aquifer sequestration site is 497,800 $m^2$ (NETL, 2013).

**Table 3-33: Land Use Area Assumptions for Electricity Generation**

| Process | Property | Units | Value |
|---|---|---|---|
| Power Plant | NGCC | acres/facility | 10 |
| | | $m^2$/facility | 40,500 |
| | NGCC with $CO_2$ capture | acres/facility | 11 |
| | | $m^2$/facility | 44,600 |
| | Fleet NGCC | acres/facility | n/a |
| | | $m^2$/facility | n/a |
| Saline Aquifer | Injection, monitoring, and disposal wells | acres/well | 0.25 |
| | | $m^2$/well | 1,010 |
| | | wells/facility | 47 |
| | Water treatment | acres/facility | 1.6 |
| | | $m^2$/facility | 6,400 |
| | Access roads | acres/facility | 110 |
| | | $m^2$/site | 444,000 |
| | Storage capacity | tonne $CO_2$/facility-day | 10,000 |
| | Operating life | years | 100 |

## 3.10 Electricity Transmission and Distribution

Electricity transmission and distribution systems transport energy from suppliers to demand sites. Transmission systems facilitate the bulk transfer of electric power from the power plant to the demand center substations, while distribution systems transfer power to the end user. Distribution is sub-grouped based on the end user; primary distribution transports electricity from transmission to industrial users, while secondary distribution transports electricity from transmission to commercial or residential consumers. Transmission and distribution losses can be sub-grouped as transmission, sub-transmission, and distribution losses.

In total, transmission and distribution incur a 7 percent loss of energy. The data for transmission and distribution (primary and secondary) processes are representative of 2011 conditions. Data sources for transmission losses are utilities that own transmission infrastructure and regional transmission organizations (RTO) (PPL Corporation, 2012; FERC, 2012; AEP, 2012b). Data are limited for distribution losses because utilities are not obligated to make the distribution loss factor data publicly available. Data sources for primary and secondary distribution losses are the actual hourly distribution loss factors used in the Electric Reliability Council of Texas (ERCOT) settlement process (ERCOT, 2013) and the actual hourly distribution loss factors calculated by San Diego Gas and Electric (San Diego Gas and Electric, 2012).

In addition to electricity losses, transmission and distribution systems are also have equipment that emit $SF_6$. EPA's GHG inventory is used to calculate the $SF_6$ emissions from electricity transmission and distribution (EPA, 2013a). The $SF_6$ emission factor for transmission and distribution is 0.143 grams of $SF_6$ per MWh delivered, which was calculated from EPA's GHG inventory by filtering out non-applicable sectors and dividing by the annual amount of delivered electricity (EPA, 2013a).

# 4 Results

The GHG results for two functional units, upstream natural gas and electricity generated from natural gas, are discussed below. Full inventory results are provided in **Appendix C**.

## 4.1 Delivered Natural Gas

The cradle-to-gate boundary for delivered natural gas includes extraction, processing, transmission, and distribution, with a final output of a 1 MJ of natural gas delivered to consumer. This boundary is referred to as "upstream natural gas."

**Figure 4-1** shows the upstream natural gas GHGs for 15 gas regions, associated natural gas, and the 2012 mix of domestic natural gas production (as shown in **Table 3-1**). Each result includes average GHG emissions, interquartile ranges ($25^{th}$ and $75^{th}$ percentiles), a 5/95 confidence interval ($5^{th}$ and $95^{th}$ percentiles), and minimum and maximum values. A legend of the symbols used to represent these statistics is provided in the figure.

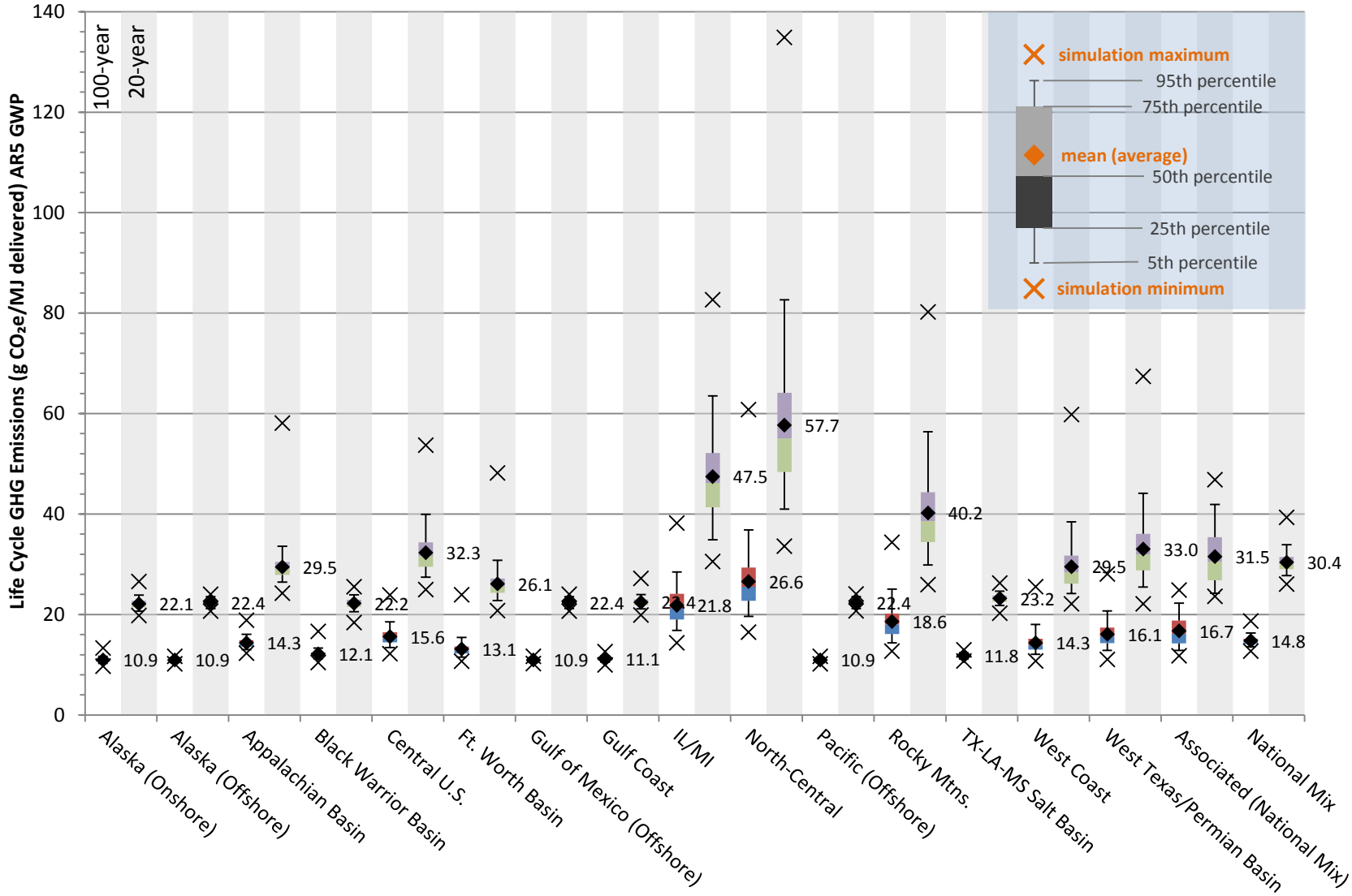
The results in **Figure 4-1** are expressed with two GWP timeframes (100 and 20 years) as prescribed by Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) and including fossil $CH_4$ decomposition and climate change feedback (IPCC, 2013). Converting the GHGs from 100- to 20-year GWPs, which increases the methane GWP from 36 to 87, magnifies the differences between systems that have different proportions of $CH_4$ emissions. In other words, as the ratio of $CH_4$ to $CO_2$ in an emission inventory increases, the percent change in GHG impacts when changing from 100- to 20-year GWPs also increases. The use of 20-year GWPs also emphasizes the importance of reducing $CH_4$ emissions as a strategy for reducing the GHG impacts from natural gas systems.

As the average values of the upstream GHG results increases, the uncertainty ranges also increase. Most of the uncertainty in this analysis is directly related to $CH_4$ emissions or parameters that are used to apportion $CH_4$ emissions. The scenarios with high GHG results have higher ratios of $CH_4$ to $CO_2$ than scenarios with low expected GHG results. Since most uncertainty is associated with $CH_4$, as the share of $CH_4$ emissions increases, so does the contribution of uncertainty.

The national average for associated gas is shown here to provide a complete profile of the U.S. natural gas supply. It represents the portion of the natural gas supply that comes from oil wells. The associated gas result is generated using a separate model for oil production and represents fundamentally different types of resource extraction technologies. Unlike the other scenarios in this analysis, it does not account for regional variability, but is an accurate depiction of the different oil production technologies used in the U.S.

The average GHG emissions from the national mix of natural gas are 15.4 g $CO_2$e/MJ (using 100-year GWPs). This average value, and its uncertainty, was generated using an additional Monte Carlo simulation in which the results from all component regions were sampled and used to generate the national mix. This additional sampling step uses each region's supply contribution to the national supply mix **(Table 3-1)** to weight the corresponding likelihood of each region's GHG contributions to the national average GHG scenario. By sampling from the results for each regional scenario and weighting uncertainty by supply contributions, the uncertainty around the national mix scenario is reduced.

**Figure 4-1: Upstream Cradle-to-Gate Natural Gas GHG Emissions by Source**



The offshore natural gas scenarios have lower GHG emissions than the onshore scenarios. One explanation for these lower results is that offshore wells have higher production rates than other types of natural gas wells, which reduces the inventory of methane emissions per unit of gas produced. Another explanation is that offshore platforms must control methane emissions for safety and risk-mitigation reasons. This second explanation (safety and risk-mitigation) should be considered within the context of data quality; the data for point source and fugitive emissions from offshore wells are older and less detailed than the data for onshore wells. While this analysis ensures that consistent boundaries are used when comparing natural gas sources, the point source and fugitive emission data for onshore and offshore natural gas production are not directly comparable.

Understanding the differences among the results in **Figure 4-1** requires an understanding of the ways in which extraction parameters vary among scenarios. Variability among natural gas extraction sources account for the majority of differences among scenarios.[1] Upstream GHG results are high for scenarios that have the following extraction characteristics:

- High proportions of unconventional wells, which are completed by hydrofracking
- High initial production rates, which are used to represent the amount of potential emissions from completions with hydrofracking
- High concentrations of $CH_4$ in production gas
- Low lifetime well productivities (the lower a well's EUR, the greater the amount of life cycle emissions that are apportioned to each unit of natural gas produced)
- Low flaring activities (flaring converts $CH_4$ to $CO_2$, reducing its GHG impact)
- High liquids unloading emissions
- High pneumatic device emissions

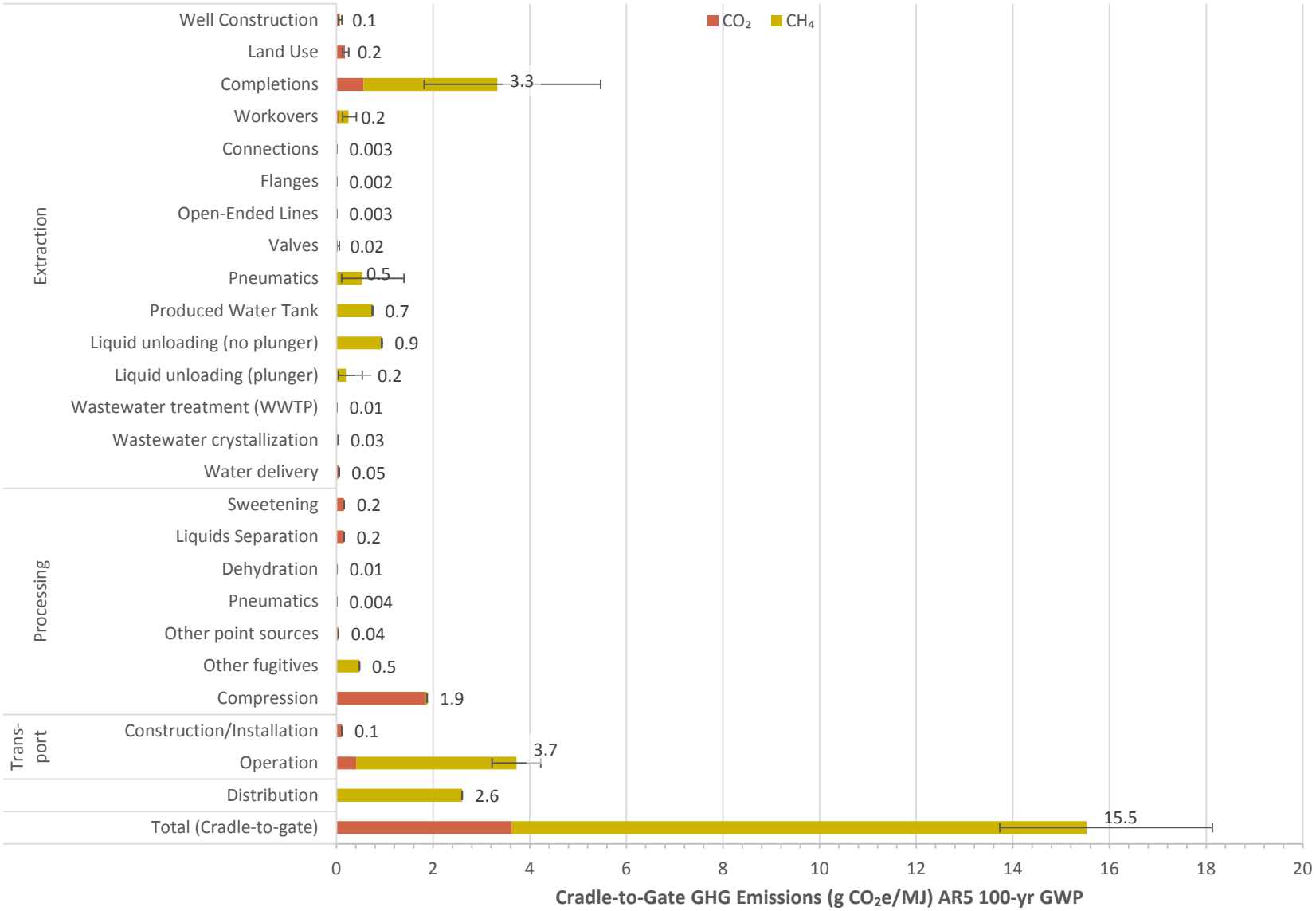
The North-Central region, the scenario with the highest upstream GHG emissions, exemplifies most of the above characteristics. The North-Central region has a relatively large share of unconventional wells, with shale gas wells that account for 58 percent of the regional natural gas supply. Further, these shale gas wells have a low average EUR of 0.44 Bcf. The North-Central region also has low flaring activity, with an expected value of 46 percent (the range of expected flaring activities for all scenarios in this analysis is from 44 to 69 percent). For liquids unloading and pneumatic devices, the GHG emissions are driven by multiple factors, making it difficult to ascertain the emissions for a particular scenario by looking only at the parameter tables. However, the detailed results (not shown here) for the North-Central scenario have high contributions from liquids unloading and pneumatics. The North-Central region contributes only 1.3 percent to the domestic natural gas supply, but is used here to exemplify how combinations of key parameters (as documented in **Section 3**) can affect life cycle results.

[1] Due to variability in natural gas compositions, processing emissions vary across scenarios, but not to the same extent that variability in extraction characteristics affects emissions. Once natural gas is processed and meets pipeline specifications, it is a commodity with no discernable source characteristics; transmission and distribution burdens are identical across all scenarios.

A better understanding of the key contributors to natural gas emissions can be achieved by expanding the results so individual unit processes and gas species are shown. **Figure 4-2** shows upstream GHG emissions for natural gas from Appalachian shale wells. In many energy systems carbon dioxide is the primary concern, but for upstream natural gas, $CH_4$ drives the GHG results and most of the uncertainty. **Figure 4-2** also shows how one-time or occasional activities such as completions, workovers, and liquids unloading can be significant contributors to total GHG emissions. This is an unusual conclusion for energy systems; steady-state operating emissions are usually the only significant contributors to total GHG emissions.

For upstream Appalachian shale gas, the key contributors to GHG emissions are fugitive emissions from transport and distribution systems, episodic emissions from completion, and fuel combusted by processing compressors. Transmission pipeline operation is the most GHG intensive upstream process, with fugitive emissions contributing 24 percent to total upstream GHG emissions. Completions are the second highest contributor, accounting for 21 percent of the upstream GHG emissions. Processing compressors, which prepare processed gas for pipeline transport, contribute 12 percent to the total. Since all sources of natural gas use processing, transmission, and distribution infrastructure, the conclusions about the contributions of these activities can be extended to other sources of natural gas. (The percent contributions will vary among scenarios, but the absolute values of processing emissions will be similar among scenarios, and the absolute values of transmission and distribution emissions will be identical among scenarios.)

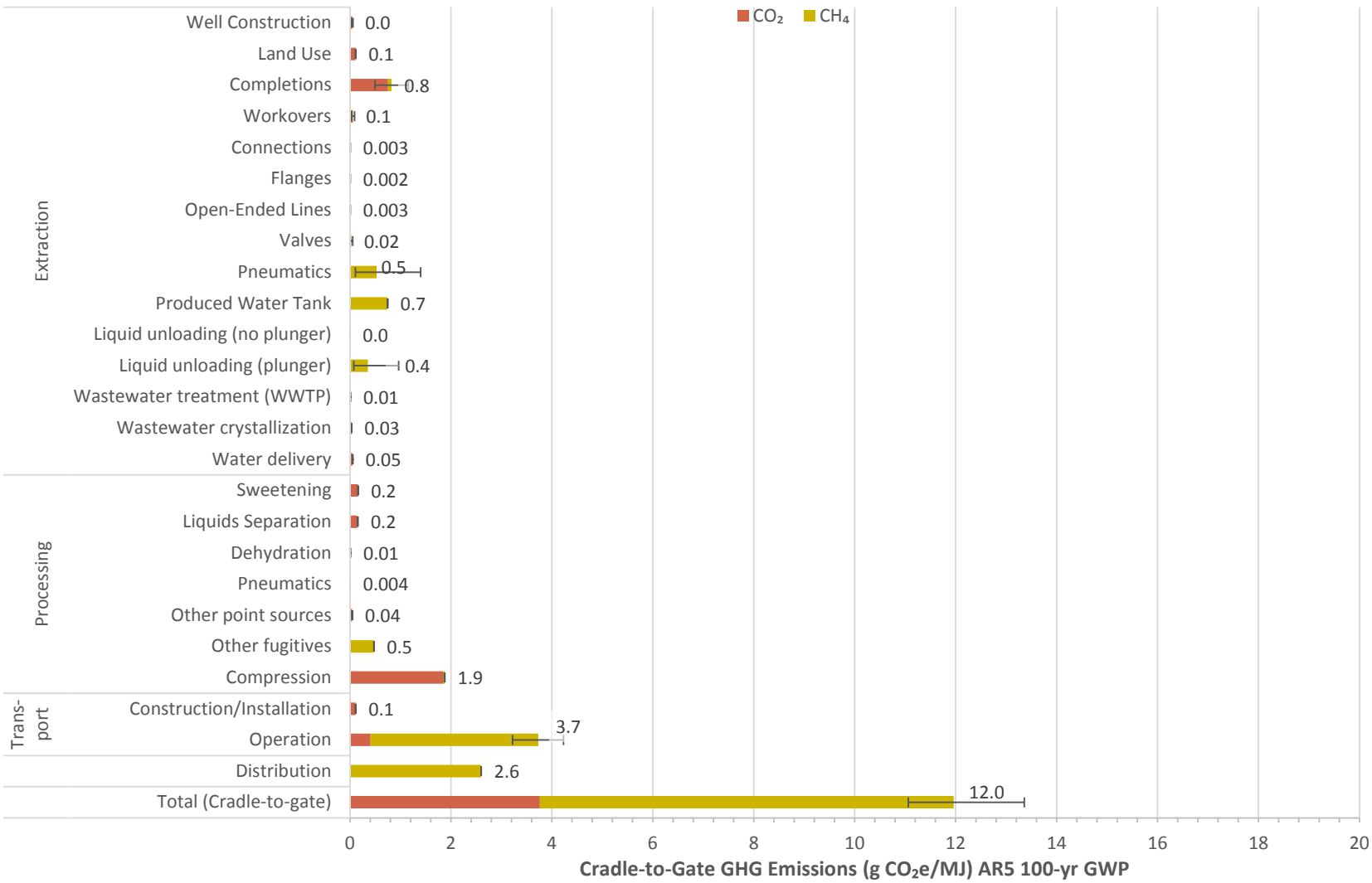
**Figure 4-2: Expanded Greenhouse Gas Results for Appalachian Shale Gas**



The scenarios in this analysis use historical data to represent prevailing technologies for natural gas systems. Over time, however, the implementation of new technologies and adoption of new practices will change the environmental burdens of natural gas systems. For this reason, this analysis includes an evaluation of the next natural gas well. To model the life cycle burdens of this hypothetical well, the parameters are adjusted to reflect likely emission reduction technologies (e.g., plunger lifts), preferred practices (e.g., increased flaring activity), and high recovery rates (e.g., high EURs). Since most of the recent growth in natural gas production has occurred within the Marcellus shale, Appalachian shale gas well parameters are used as the basis for this next well scenario.

**Figure 4-3** shows the cradle-to-gate GHG emissions for natural gas extracted from the next natural gas well. In this instance, the next well scenario has GHG emissions that are 23 percent lower than historical practices, with all emission reductions occurring at the extraction stage.

**Figure 4-3: Expanded Greenhouse Gas Results for the Next Appalachian Shale Well**



### 4.1.1 Sensitivity and Uncertainty Analysis

This analysis uses a parameterized model that allows the alteration and analysis of key variables. Doing so allows the identification of variables that have the greatest effect on results. The sensitivity analysis was performed by increasing each parameter by 100 percent while holding all other parameters constant. The 100 percent increase is an arbitrary change – the sensitivity analysis is valid as long as all parameters are changed by the same scale. The percent change to Appalachian shale upstream GHG emissions with respect to each parameter were graphed using the tornado graph shown in **Figure 4-4**.

Positive results in **Figure 4-4** indicate that an increase in a parameter increases the result. Conversely, negative results indicate inverse relationships, where an increase in a parameter decreases the overall result. For example, a 100 percent increase in completion flowback days *increases* the upstream GHG emissions by 21 percent, but a 100 percent increase in production rate *decreases* the upstream GHG emissions by 20.2 percent. The lower portion of **Figure 4-4** can be equally informative with respect to the model; these parameters have a minimal impact on model results, even if they are off by 100 percent.

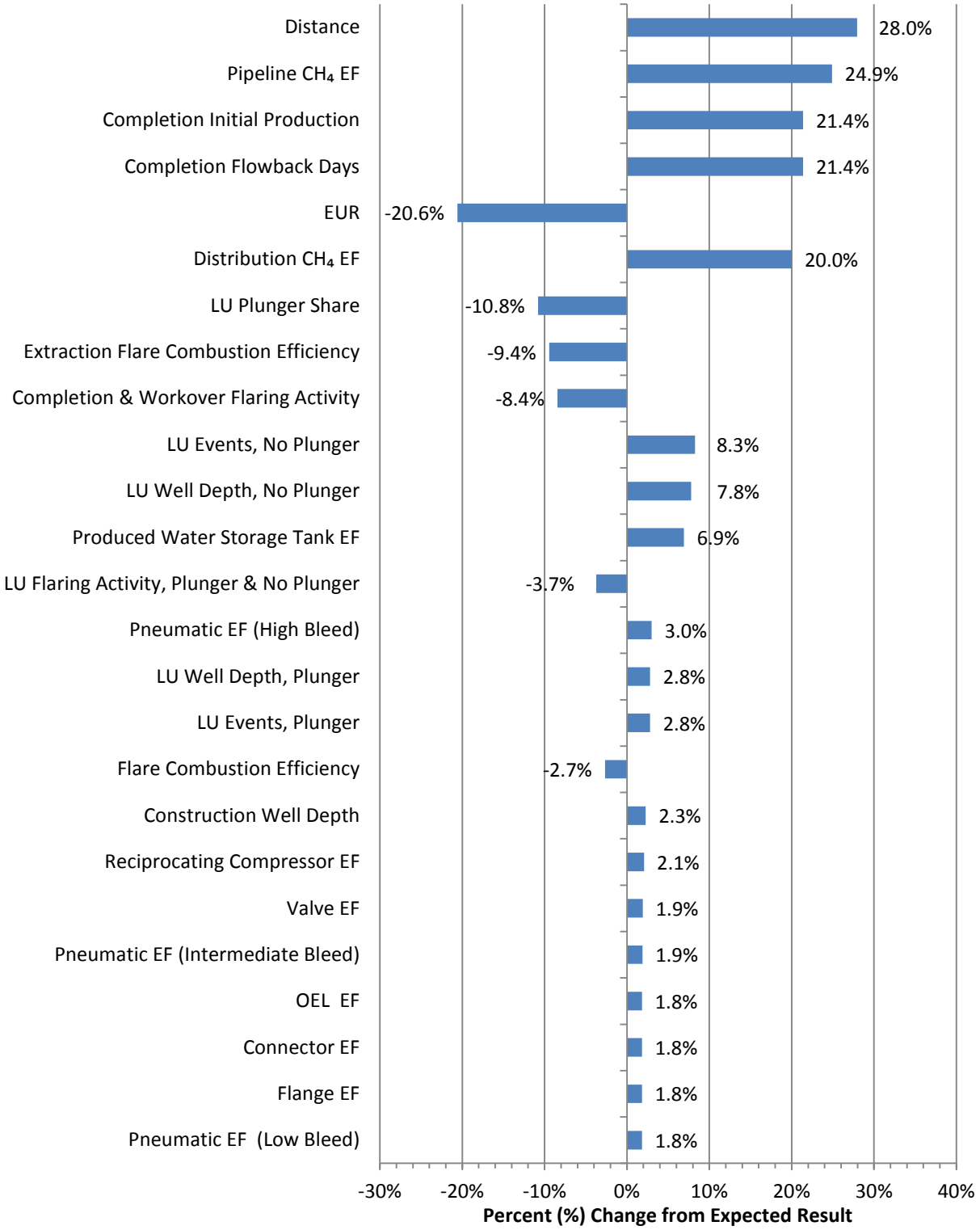
The top two bars in **Figure 4-4** pertain to pipeline transmission of natural gas. The top bar (Distance) accounts for the effect of pipeline transport distance with respect to $CH_4$ emitted by pipelines and $CO_2$ emissions from combustion activities (e.g. compression). Upstream natural gas GHG emissions are sensitive to changes in pipeline distance, which is modeled with an expected value of 971 km (604 miles) for all natural gas sources. The pipeline transport of natural gas is inherently energy intensive because compressors are required to continuously alter the physical state of the natural gas in order to maintain adequate pipeline pressure. Further, the majority of compressors on the U.S. pipeline transmission network are powered by natural gas that is withdrawn from the pipeline.

GHG results are sensitive to production rate because it is a parameter used as the denominator for apportioning episodic emissions (completions, workovers, and liquid unloading) to a unit of natural gas produced. The results in **Figure 4-4** show that, in addition to EUR, there are two main areas of sensitivity: transmission and distribution of natural gas, and completion activities.

Other key sensitivities include parameters for completion, including initial production, flowback days, and flaring activity. As discussed in **Section 3.5.3**, the high reservoir pressures of unconventional (hydrofracked) wells can lead to high initial production rates that quickly decline. If production infrastructure is not immediately installed, hydrofracked wells can produce high potential emissions of $CH_4$ and other hydrocarbons. Completion parameters are large sources of $CH_4$ emissions, so they are key drivers of GHG sensitivity.

These sensitivity results can be used to gauge the effect of parameters on model results, but they are less prescriptive when it comes to prioritizing opportunities for improvement. Increases in per well production rates and reductions in transport distance would lead to significant reduction in upstream natural gas emissions, but in reality it may not be practical (or possible) to change these variables.

**Figure 4-4: Sensitivity of Appalachian Shale Natural Gas GHG Emissions to Changes in Parameters**

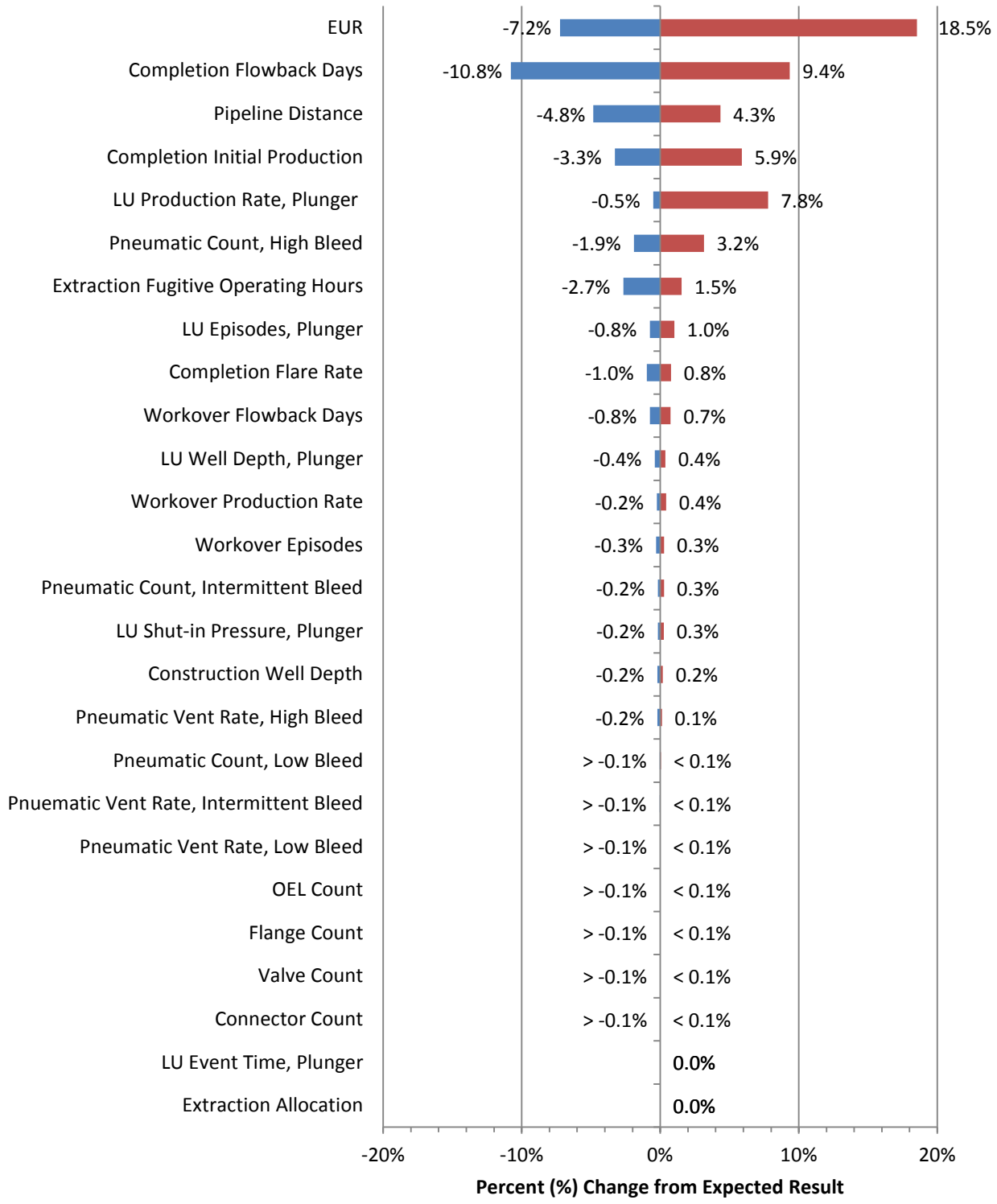



*Emission factor (EF), liquid unloading (LU)

The above sensitivity tornado is useful because it demonstrates how GHG results respond to changes in parameters. However, while a sensitivity analysis effectively demonstrates how the model behaves, it does not represent likely parameter ranges. As discussed in **Section 3**, many of the parameters used in this model comprise expected, minimum, and maximum values. The uncertainty analysis is performed by entering the minimum value of a given parameter while holding all other parameters constant, and then performing the same activity with the maximum value. In doing so, the uncertainty analysis illustrates the extent to which the minimum and maximum values can affect results. **Figure 4-5** shows an uncertainty tornado for Appalachian shale gas.

The key contributors to the uncertainty in Appalachian shale gas GHG emissions are parameters related to the scale of completion emissions (EUR, completion flowback days, completion initial production), transmission pipeline distance, the production rate used to calculated liquids unloading emissions, and count of high bleed pneumatic devices.

**Figure 4-5: Uncertainty Contributions to Marcellus Shale GHGs**

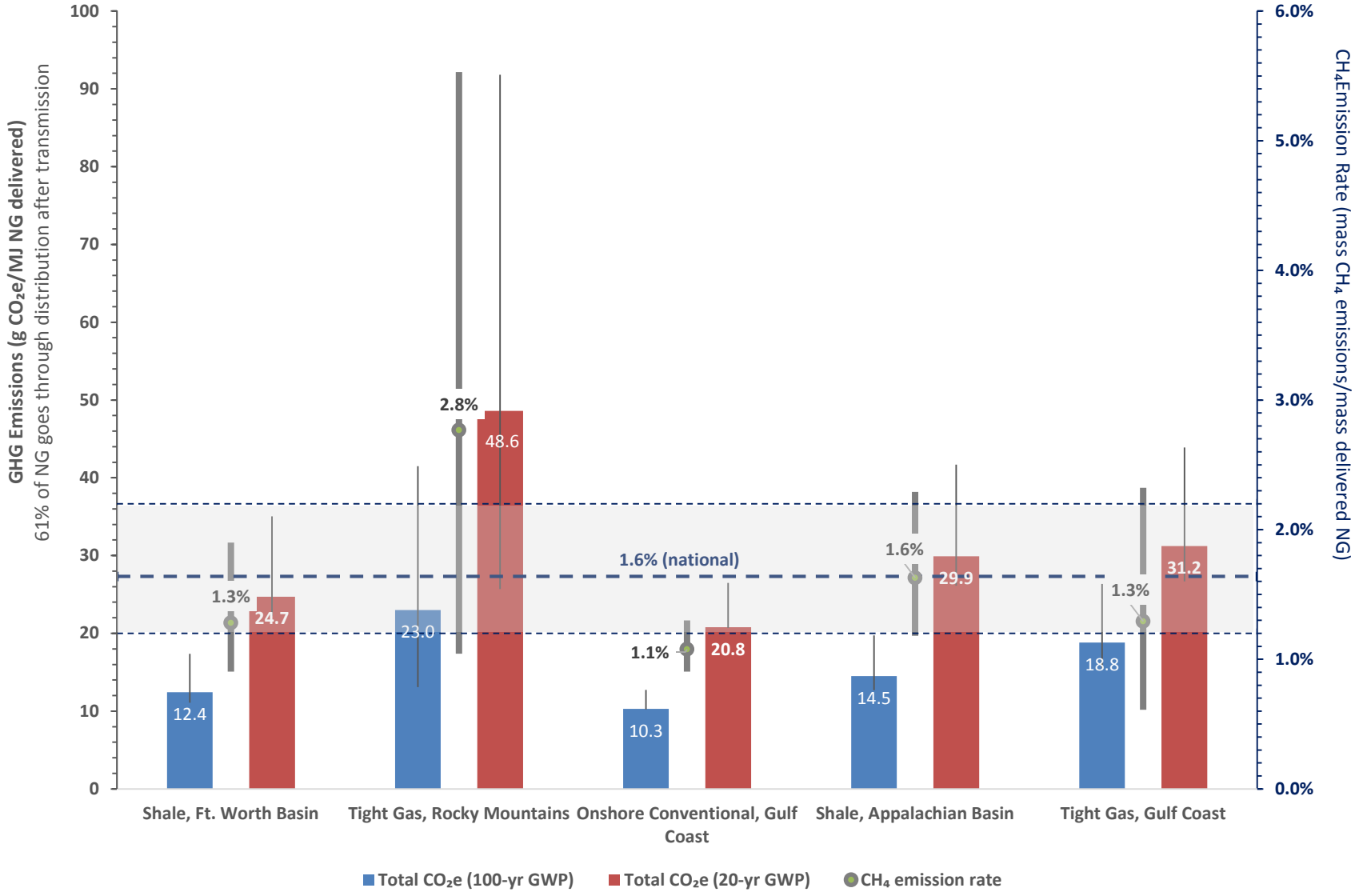



*Emission factor (EF), liquid unloading (LU)

## 4.2 $CH_4$ Emission Rate

The emission rate of $CH_4$ from the natural gas supply chain (the mass emissions of $CH_4$ per mass of natural gas delivered) not only represents a loss of product, but also represents the emission of a potent GHG. $CH_4$ emission rate is calculated from the outputs of our model and varies by extraction technologies and extraction regions. **Figure 4-6** shows the $CH_4$ emission rates and associated GHG emissions (using 100- and 20-year GWPs) for the top five producers (based on 2012 production volumes) of natural gas. The national $CH_4$ emission rate is 1.6 percent and ranges between 1.2 and 2.2 percent. This national emission rate is a production weighted composite of 31 different combinations of extraction technologies and regions (not all production scenarios are shown in **Figure 4-6**). Some combinations of production technologies and regions (such as tight gas extraction in the Rocky Mountains) may have wide bounds on $CH_4$ emission rate, but these wide bounds are diminished when all extraction technologies and regions are sampled to arrive at the national average.

**Figure 4-6: $CH_4$ Emission Rates and GHG Emissions for the Delivery of NG to Consumers**



The results in **Figure 4-6** represent a modification to the default cradle-to-gate boundary. Unlike the default cradle-to-gate boundary, in which 100 percent of natural gas is distributed to small scale consumers, the $CH_4$ emission rates in **Figure 4-6** represent a 39 percent delivery share to power plants that use natural gas immediately after transmission, and a 61 percent delivery share to smaller scale consumers who receive natural gas from local distribution systems. This 39/61 split is used only in the context of discussing $CH_4$ emission rates, thus providing a useful comparison point for ongoing natural gas research. **Table 4-1** shows how $CH_4$ emission rates change with changes to the upstream boundary.

**Table 4-1: $CH_4$ Emission Rates and GHG Emissions for Three Upstream Boundaries**

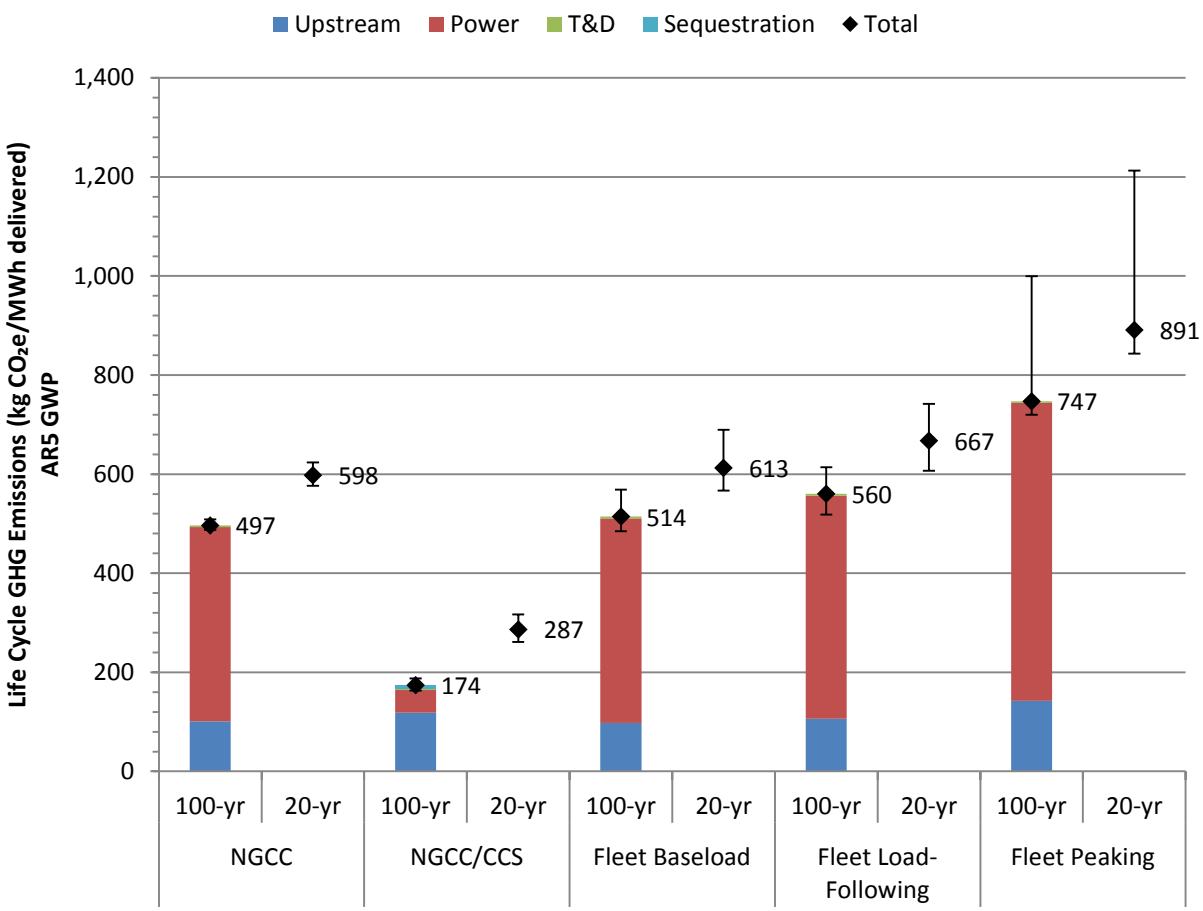
| Upstream boundary | Consumers | $CH_4$ Emission Rate | GHG Emissions (g $CO_2$e/MJ in 100-yr GWP) |
|---|---|---|---|
| Cradle through transmission | Large scale (power plants) | 1.4% | 12.7 |
| Cradle through transmission/ distribution | 39%/61% mix of large/small scale | 1.6% | 13.6 |
| Cradle through distribution | Small scale (industrial, commercial, residential) | 1.8% | 14.8 |

The above discussion on $CH_4$ emission rates requires a modified basis for comparison (a 39/61 split between end users). All other results in this analysis are expressed in terms of the two functional units defined earlier: a cradle-to-gate functional unit where all natural gas goes through distribution, and a cradle-to-grave functional unit in which 1 MWh of electricity is delivered to consumers.

## 4.3 Delivered Natural Gas-fired Electricity

For this portion of analysis, upstream data for the U.S. domestic mix (from cradle-through-transmission) are fed to power generation facilities to calculate the life cycle results for electricity from natural gas-fired power plants. In addition to the NETL advanced NGCC plants with and without CCS, these results include scenarios for fleet average natural gas plants, as described in **Section 3.9. Figure 4-7** shows the GHG emissions results for natural gas power plants on the basis of 1 MWh of electricity delivered to the consumer.

**Figure 4-7: Life Cycle GHG Emissions for Electricity Production from Natural Gas**




The results shown in **Figure 4-7** illustrate two major trends. First, as with the upstream comparison of life cycle GHGs scaled to 20-year and 100-year GWPs, application of the 20-year GWP results in a significant increase in life cycle GHG emissions for all plant types. Second, by extending the life cycle through power generation, the life cycle GHG profiles for natural gas power are comprised mostly of $CO_2$ from power plant operation. Using 100-year GWPs, upstream natural gas (which has cradle-through-transmission boundaries when used for power generation) accounts for 20 to 22 percent of life cycle GHG emissions. The NGCC with CCS scenario is the only scenario in which upstream natural gas accounts for the majority of life cycle GHG emissions.

Comparison of NGCC plants with and without CCS illustrates a trade-off caused by environmental controls. CCS-equipped plants require energy to capture and compress $CO_2$. This energy demand reduces the overall efficiency of the power plant. Compared to the other power plant scenarios, the NGCC with CCS scenario has significantly lower $CO_2$ emissions at the power plant, but has higher upstream emission because it requires more natural gas to deliver the same amount of electricity as the other scenarios. Even so, on a 100-year GWP time frame, the expected life cycle GHG emissions from the NGCC with CCS scenario are 64 percent lower than the NGCC (without CCS) scenario.

When comparing the life cycle GHG emissions from natural gas-fired power, it is important to consider the applicability of each power plant. Peaking plants are less efficient than baseload plants, but the higher cost of peak power on a per MWh basis justifies this inefficiency. Conversely, fleet baseload plants are expected to provide continuous power and must operate more efficiently than peaking or load following power plant to be economically viable. A functional unit of 1 MWh is used to compare natural gas power scenarios, but, due to the different applications of power plants, their life cycle GHG emissions are not directly comparable.

# 5 References

Abbasi, M. A., Ezulike, D. O., Dehghanpour, H., & Hawkes, R. V. . (2014). A comparative study of flowback rate and pressure transient behavior in multifractured horizontal wells completed in tight gas and oil reservoirs. *Journal of Natural Gas Science and Engineering, 17*, 82-93.

API. (2009). *Compendium of Greenhouse Gas Emissions for the Oil and Natural Gas Industry*. American Petroleum Institute. Retrieved from http://www.api.org/ehs/climate/new/upload/2009_GHG_COMPENDIUM.pdf.

API/ANGA. (2012). *Characterizing Pivotal Sources of Methane Emissions from Natural Gas Production*. American Petroleum Institute & America's Natural Gas Alliance.

Arthur, D., & Cornum, D. (2010). Technologies Reduce Pad Size, Waste. *The American Oil & Gas Reporter*.

Brown, H. P. (2011). Composition of Natural Gas for use in the Oil and Natural Gas Sector Rulemaking: ECR Incorporated.

Burklin, C. E., & Heaney, M. (2006). Natural Gas Compressor Engine Survey for Gas Production and Processing Facilities *Houston Advanced Research Center*. Houston, Texas.

Burnham, A., Han, J., Clark, C. E., Wang, M., Dunn, J. B., & Palou-Rivera, I. (2011). Life-cycle greenhouse gas emissions of shale gas, natural gas, coal, and petroleum. *Environmental science & technology, 46*(2), 619-627.

Dennis, S. M. (2005). Improved Estimates of Ton-Miles. *Journal of Transportation and Statistics, 8*(1).

EIA. (1993). *Drilling Sideways -- A Review of Horizontal Well Technology and Its Domestic Application*. (DOE/EIA-TR-0565). U.S. Department of Energy Retrieved from http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/drilling_sideways_well_technology/pdf/tr0565.pdf.

EIA. (2009). *Gas Production in Conventional Fields, Lower 48 States*. Energy Information Administration Retrieved from http://www.eia.gov/oil_gas/rpd/conventional_gas.pdf.

EIA. (2010a). *Major Tight Gas Plays, Lower 48 States*. Retrieved from http://www.eia.gov/oil_gas/rpd/tight_gas.pdf.

EIA. (2010b). *Oil and Gas Lease Equipment and Operating Costs 1994 through 2009*. U.S. Energy Information Administration Retrieved from

http://www.eia.gov/pub/oil_gas/natural_gas/data_publications/cost_indices_equipment_production/current/coststudy.html.

EIA. (2011a). *Distribution and Production of Oil and Gas Wells by State*. U.S. Energy Information Administration Retrieved from http://www.eia.gov/pub/oil_gas/petrosystem/petrosysog.html.

EIA. (2011b). *Electricity demand changes in predictable patterns*. Retrieved from http://www.eia.gov/todayinenergy/detail.cfm?id=4190.

EIA. (2011c). *Natural Gas Gross Withdrawals and Production*. U.S. Department of Energy, Energy Information Administration. Retrieved from http://www.eia.doe.gov/dnav/ng/ng_prod_sum_a_EPG0_VRN_mmcf_a.htm.

EIA. (2011d). *Performance Profiles of Major Energy Producers 2009*. Energy Information Administration Retrieved from http://www.eia.gov/finance/performanceprofiles/pdf/020609.pdf.

EIA. (2011e). Review of emerging resources: US Shale gas and shale oil plays. *Government. US Energy Information Administration. http://205.254, 135*.

EIA. (2013a). Natural gas-fired combustion turbines are generally used to meet peak electricity load. Washington, DC: U.S. Energy Information Administration.

EIA. (2013b). *NEMS Model Documentation 2013: Oil and Gas Supply Module*. U.S. Energy Information Administration Retrieved from http://www.eia.gov/forecasts/aeo/nems/documentation/ogsm/pdf/m063%282013%29.pdf.

EIA. (2013c). Rapid increases in electricity demand challenge both generating unit and system operators. Washington, DC: U.S. Energy Information Administration.

EIA. (2014). Natural Gas Gross Withdrawals and Production. from U.S. Department of Energy, Energy Information Administration http://www.eia.gov/dnav/ng/ng_prod_sum_a_EPG0_FGS_mmcf_a.htm

EIA. (2015). *Natural Gas Gross Withdrawals and Production*. Retrieved from http://www.eia.gov/dnav/ng/ng_prod_sum_a_epg0_vgv_mmcf_a.htm.

ENVIRON, E. R. G. (2012). 2011 Oil and Gas Emission Inventory Enhancement Project for CenSARA States. Retrieved August 8, 2014, from www.censara.org/filedepot_download/56064/14

EPA. (1995). *Compilation of Air Pollutant Emission Factors, Volume I: Stationary Point and Area Sources*. (AP-42.). Research Triangle Park, North Carolina: U.S. Environmental Protection Agency Retrieved from http://www.epa.gov/ttnchie1/ap42.

EPA. (1998). *Emissions Factors and AP 42, Compilation of Air Pollutant Emission Factors; Natural Gas Combustion*. (AP-42.). Research Triangle Park, North Carolina: U.S. Environmental Protection Agency Retrieved from http://www.epa.gov/ttnchie1/ap42/ch01/final/c01s04.pdf

EPA. (2006). Installing Plunger Lift Systems in Gas Wells: Lessons Learned from Natural Gas STAR Partners.

EPA. (2009). *Installing Vapor Recovery Units*. U.S Environmental Protection Agency Retrieved from http://www.epa.gov/gasstar/documents/workshops/billings2009/05_vru.pdf.

EPA. (2010a). *Greenhouse Gas Emissions Reporting from the Petroleum and Natural Gas Industry: Background Technical Support Document*. Washington, DC.: U.S. Environmental Protection Agency Retrieved from http://www.epa.gov/ghgreporting/documents/pdf/2010/Subpart-W_TSD.pdf.

EPA. (2010b). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008*. Washington, DC.: U.S. Environmental Protection Agency Retrieved from http://www.epa.gov/climatechange/emissions/downloads10/508_Complete_GHG_1990_2008.pdf.

EPA. (2010c). *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis*. (EPA-420-R-10-006). U.S. Environmental Protection Agency Retrieved from http://www.epa.gov/oms/renewablefuels/420r10006.pdf.

EPA. (2011a). *Background Technical Support Document - Petroleum and Natural Gas Industry*. Washington, D.C.: U.S. Environmental Protection Agency, Climate Change Division Retrieved from http://www.epa.gov/ghgreporting/documents/pdf/2010/Subpart-W_TSD.pdf.

EPA. (2011b). *Greenhouse Gas Emissions Reporting from the Petroleum and Natural Gas Industry Background Technical Support Document*. Washington, D.C.: U.S. Environmental Protection Agency, Climate Change Division Retrieved from http://www.epa.gov/climatechange/emissions/downloads10/Subpart-W_TSD.pdf.

EPA. (2011c). *Natural Gas STAR Recommended Technologies and Practices - Gathering and Processing Sector*. U.S. Environmental Protection Agency Retrieved from http://www.epa.gov/gasstar/documents/gathering_and_processing_fs.pdf.

EPA. (2011d). *SPECIATE Version 4.3*. Retrieved from: http://www.epa.gov/ttn/chief/software/speciate/index.html#documentation

EPA. (2012). *The Emissions and Generation Resource Integrated Database (eGRID)*. Washington, DC: U.S. Environmental Protection Agency Retrieved from http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html.

EPA. (2013a). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2011*. Washington, DC.: U.S. Environmental Protection Agency Retrieved from http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html.

EPA. (2013b). Oil and Gas Emission Estimation Tool. Retrieved August 8, 2014, from www.epa.gov/ttn/chief/net/2011inventory.html

EPA. (2014a). The emissions and generation resource integrated database, technical support document for the 9th edition of eGRID with year 2010 data: U.S. Environmental Protection Agency.

EPA. (2014b). *Envirofacts Greenhouse Gas (GHG) Customized Search*. Retrieved from http://www.epa.gov/enviro/facts/ghg/customized.html.

EPA. (2014c). Greenhouse Gas Reporting Rule: Revisions and Confidentiality Determinations for Petroleum and Natural Gas Systems; Proposed Rule.

EPA. (2014d). *Oil and Natural Gas Sector Leaks*. Retrieved from http://www.epa.gov/airquality/oilandgas/2014papers/20140415leaks.pdf.

EPA. (2014e). *Oil and Natural Gas Sector Liquids Unloading Processes*. Retrieved from http://www.epa.gov/airquality/oilandgas/2014papers/20140415liquids.pdf.

EPA. (2014f). *Partner Reported Opportunities for Reducing Methane Emissions: Wet Seal Degassing Recovery System for Centrifugal Compressors*. Retrieved from http://www.epa.gov/gasstar/documents/CaptureMethanefromCentrifugalCompressionSealOilDegassing.pdf.

EPA. (2015a). *Catalog of CHP Technologies. Section 3: Technology Characterization – Combustion Turbines*. EPA Retrieved from http://www.epa.gov/chp/documents/catalog_chptech_full.pdf.

EPA. (2015b). *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. Washington, DC: Retrieved from http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2015-Main-Text.pdf.

ERCOT. (2015). NERC Regions Map. Retrieved January 12, 2016, from http://www.ercot.com/content/news/mediakit/maps/nercRegionsMap.jpg

FERC. (2010). *Federal Energy Regulatory Commission: Form 2/2A - Major and Non-major Natural Gas Pipeline Annual Report: Data (Current and Historical)*. Federal Energy Regulatory Commission. Retrieved from http://www.ferc.gov/docs-filing/forms/form-2/data.asp.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D. W., . . . Dorland, R. V. (2007). Changes in Atmospheric Constituents and in Radiative Forcing. In S.

Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M.Tignor & H. L. Miller (Eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 212-213). Cambridge, United Kingdom and New York, NY, USA: Intergovernmental Panel on Climate Change.

Foss, M. M. (2004). Interstate Natural Gas -- Quality Specifications & Interchangeability. Sugar Land, Texas: Center for Energy Economics.

GGFRP. (2014). *Estimated Flared Volumes from Satellite Data, 2007-2011*. Retrieved from http://web.worldbank.org/WBSITE/EXTERNAL/TOPICS/EXTOGMC/EXTGGFR/0,,contentMDK:22137498~menuPK:3077311~pagePK:64168445~piPK:64168309~theSitePK:578069,00.html

Halliburton. (2009). API Casing Chart. Retrieved August 29, 2012, from http://www.halliburton.com/public/sdbs/sdbs_contents/Data_Sheets/H03038.pdf

Harris, N., Grimland, S., & Brown, S. (2009). Land Use Change and Emissions Factors: Updates Since the RFS Proposed Rule.

IPCC. (2013). *Climate Change 2013 The Physical Science Basis*. New York: Cambridge University Press: Intergovernmental Panel on Climate Change Retrieved from http://www.climatechange2013.org/images/uploads/WGIAR5_WGI-12Doc2b_FinalDraft_All.pdf.

Jiang, M., Griffin, W. M., Hendrickson, C., Jaramillo, P., VanBriesen, J., & Venkatesh, A. (2011). Life cycle greenhouse gas emissions of Marcellus shale gas. *Environmental Research Letters, 6*(3), 034014.

NaturalGas.org. (2010). Natural Gas Distribution. Retrieved November 12, 2013, from www.naturalgas.org/naturalgas/distribution.asp

NETL. (2010a). *Cost and Performance Baseline for Fossil Energy Plants: Volume 1*. Pittsburgh, PA: Retrieved from http://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Life%20Cycle%20Analysis/EXPC-LCA-Final-Report---Report---9-30-10---Final---Rev-1.pdf.

NETL. (2010b). *Life Cycle Analysis: Natural Gas Combined Cycle (NGCC) Power Plant*. (DOE/NETL-403-110509). Pittsburgh, PA: National Energy Technology Laboratory.

NETL. (2012). *Role of Alternative Energy Source: Natural Gas Technology Assessment* (NETL/DOE-2012/1539). Pittsburgh, PA: National Energy Technology Laboratory Retrieved from http://netl.doe.gov/research/energy-analysis/publications/details?pub=8ed467ca-598b-4d95-827c-eb4a20d1a102.

NETL. (2013). *Gate-to-Grave Life Cycle Analysis Model of Saline Aquifer Sequestration of Carbon Dioxide*. (DOE/NETL-2013/1600). Pittsburgh, PA: National Energy Technology Laboratory Retrieved from http://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Life%20Cycle%20Analysis/GtG-LCA-of-Saline-Aquifer-Sequestration.pdf.

NETL. (2014). *Life Cycle Analysis of Natural Gas Extraction and Power Generation*. (DOE/NETL-2014/1646). National Energy Technology Laboratory. Retrieved from http://www.netl.doe.gov/File Library/Research/Energy Analysis/Life Cycle Analysis/NETL-NG-Power-LCA-29May2014.pdf.

NOAA. (2011). *Global Gas Flaring Estimates: Global/Country Results 1994-2010*. Retrieved from http://ngdc.noaa.gov/eog/interest/gas_flares.html.

Pring, M. (2014, August 26, 2014).

Reum, D., Dahlem, J., & Pollock, J. (2008). Four-blade bit helps reduce drilling time by as much as half. Retrieved August 29, 2012, from http://www.worldoil.com/September-2008-Four-blade-bit-helps-reduce-drilling-time-by-as-much-as-half.html

Tubes, S. P. (2009). Steel Pipe Weight Calculator. Retrieved May 1, 2009, from http://www.steel-pipes-tubes.com/steel-pipe-weight-calculator.html

USDA. (2006). *Major Land Uses of the United States, 2002*. Retrieved from http://www.ers.usda.gov/Publications/EIB14/.

Vargas, K. J. (2010). Refrigeration provides economic process for recovering NGL from CO2-EOR recycle gas. *Oil & Gas Journal, 108*(2).

This page intentionally left blank.

# Appendix A:
# Unit Process Maps for Upstream Natural Gas

## Table of Contents

A.1 Model Overview ..... A-3
A.2 Model Connectivity and Unit Process Links ..... A-3

## Tables

Table A-1: Parent/Child Plan Connections for Natural Gas Extraction, Delivery and Electricity Production ..... A-4
Table A-2: Example Appendix table ..... A-5
Table A-3: Natural Gas with Destination Options ..... A-7
Table A-4: Natural Gas Extraction Processes ..... A-9
Table A-5: Land Use – No Reversion ..... A-11
Table A-6: Well Construction ..... A-12
Table A-7: Associated Gas Mixer ..... A-13
Table A-8: Extraction Water Use ..... A-15
Table A-9: Marcellus Shale Frack Water Delivery ..... A-16
Table A-10: Natural Gas Processing ..... A-18
Table A-11: Onshore Pipeline Deinstallation ..... A-21
Table A-12: Gas Pipeline Operation ..... A-22
Table A-13: Onshore Pipeline Construction and Installation ..... A-23
Table A-14: Land Use – Reversion ..... A-23
Table A-15: Generic U.S. and N.A. Power Grid Mix for 2007 and 2010[1] ..... A-24

# Figures

Figure A-1: Tiered Modeling Approach ..... A-3
Figure A-2: Natural Gas with Destination Options – Top-Level Plan ..... A-6
Figure A-3: Natural Gas Extraction Process – Second-Level Plan ..... A-8
Figure A-4: Land Use – No Reversion – Third-Level Plan ..... A-11
Figure A-5: Well Construction – Third-Level Plan ..... A-12
Figure A-6: Extraction Water Use – Second-Level Plan ..... A-14
Figure A-7: Marcellus Shale Frack Water Delivery – Third-Level Plan ..... A-16
Figure A-8: Natural Gas Processing – Second-Level Plan ..... A-17
Figure A-9: Domestic Pipeline Transport – Second-Level Plan ..... A-20
Figure A-10: Onshore Pipeline Deinstallation – Third-Level Plan ..... A-20
Figure A-11: Gas Pipeline Operation – Third-Level Plan ..... A-21
Figure A-12: Onshore Pipeline Construction and Installation – Third-Level Plan ..... A-22
Figure A-13: Land Use – Reversion – Fourth-Level Plan ..... A-23

## A.1 Model Overview

This model was created using unit processes developed by NETL and modeled in the GaBi 6.0 LCA modeling software package. All of the unit processes utilized to create this model are publicly available on the NETL website, with the exception of those noted explicitly below, which are available from PE International. The model can be re-created utilizing the GaBi 6.0 software or by utilizing a spreadsheet to perform the scaling calculations between the individual unit processes.

## A.2 Model Connectivity and Unit Process Links

The structure of LCA models in GaBi uses a tiered approach, which means that there are different groups of processes, known as plans, which are combined to create the model. To aid in the connectivity of various plans used in this model, the following naming convention will be utilized in the figure headings throughout the remainder of this section. The main plan will be referred to as the top-level plan, and all subsequent plans will be referred to as second-, third-, etc. level plans. An example of this tiered-nature of the model structure is shown in **Figure A-1**.

**Figure A-1: Tiered Modeling Approach**

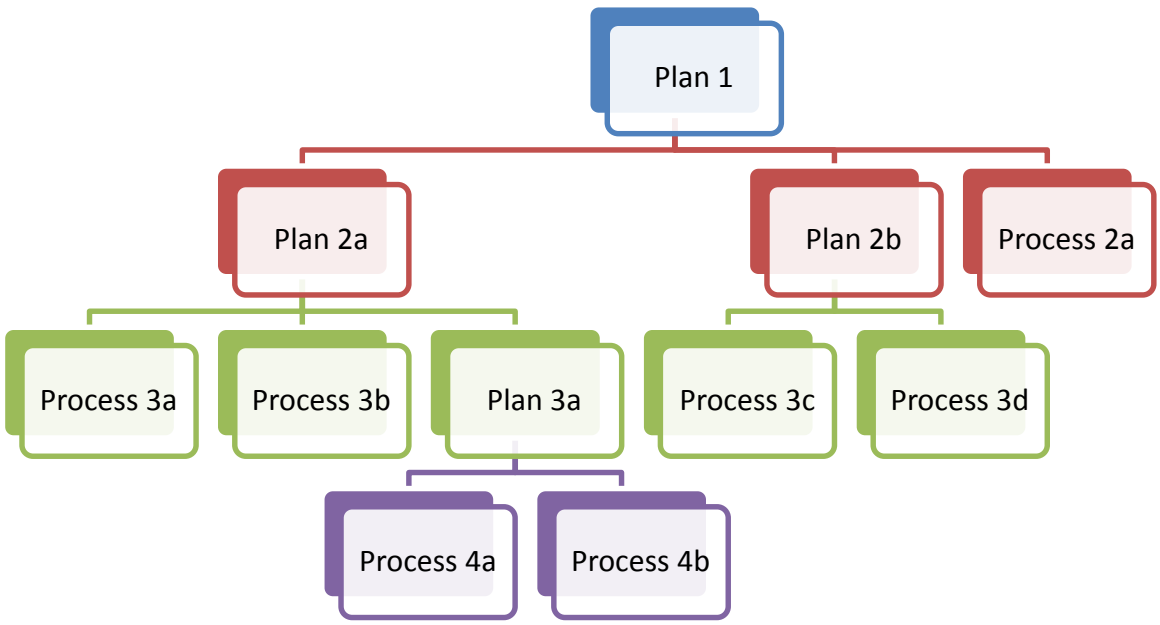



**Table A-1** demonstrates the relationships between the tiers of plans used in the construction of the model. The figures in this section illustrate the connectivity of the various processes and plans.

**Table A-1: Parent/Child Plan Connections for Natural Gas Extraction, Delivery and Electricity Production**

| Figure | Plan Name | Parent Plans | Child Plans |
|---|---|---|---|
| A-2 | Natural Gas with Destination Options | None | 1. Natural Gas Extraction Processes<br>2. Associated Gas Mixer<br>3. Extraction Water Use<br>4. Natural Gas Processing<br>5. Domestic Pipeline Transport |
| A-3 | Natural Gas Extraction Processes | Natural Gas with Destination Options | 1. Land Use - No Reversion<br>2. Well Construction |
| A-4 | Land Use - No Reversion | Natural Gas Extraction Processes | None |
| N/A | Well Construction | Natural Gas Extraction Processes | None |
| N/A | Associated Gas Mixer | Natural Gas with Destination Options | None |
| A-5 | Extraction Water Use | Natural Gas with Destination Options | Marcellus Shale Frack Water Delivery |
| A-6 | Marcellus Shale Frack Water Delivery | Extraction Water Use | None |
| A-7 | Natural Gas Processing | Natural Gas with Destination Options | None |
| A-8 | Domestic Pipeline Transport | Natural Gas with Destination Options | 1. Onshore Pipeline Deinstallation<br>2. Gas Pipeline Operation<br>3. Onshore Pipeline Construction and Installation |
| A-9 | Onshore Pipeline Deinstallation | Domestic Pipeline Transport | None |
| A-10 | Gas Pipeline Operation | Domestic Pipeline Transport | None |
| A-11 | Onshore Pipeline Construction and Installation | Domestic Pipeline Transport | Land Use - Reversion |
| A-12 | Land Use - Reversion | Onshore Pipeline Construction and Installation | None |

The following section includes screenshots of the GaBi plans followed by a table of the unit processes included in the corresponding plan. **Table A-2** gives an example of the tables. The "Unit Process" column provides the name of the unit process as it is called in the GaBi model, as well as the name of the unit process as it can be found on the NETL LCA website:

http://www.netl.doe.gov/research/energy-analysis/life-cycle-analysis/unit-process-library

To find the complete documentation of each unit process, either open the hyperlink provided OR go to the NETL LCA website and search for the files with the corresponding name.

NETL unit processes may have more than one version. Each version has its own unique Uniform Resource Locator (URL), version number, and version date. The unit process information reported in the Appendix A tables are for the specific version used by the model.

The majority of NETL unit processes are parameterized. The parameter values are utilized within calculations in the unit process to determine the input and output values for that corresponding process. In addition to allowing for the assessment of uncertainty and sensivity in the overall model results, parameters also make unit processes flexible. Unit processes posted on the NETL website are prepopulated with default parameter values. For this study, some parameter values were altered to accurately model the desired scenarios. These values can be found in **Appendix D**. To match the results presented in this study, it is important that the parameter values are tuned accordingly.

**Table A-2: Example Appendix table**

| Unit Process | Notes | Version | Version Date |
|---|---|---|---|
| NETL Unit Process Library Name | Brief Description of Unit Process or Plan | # | #/#### |

**Figure A-2: Natural Gas with Destination Options – Top-Level Plan**

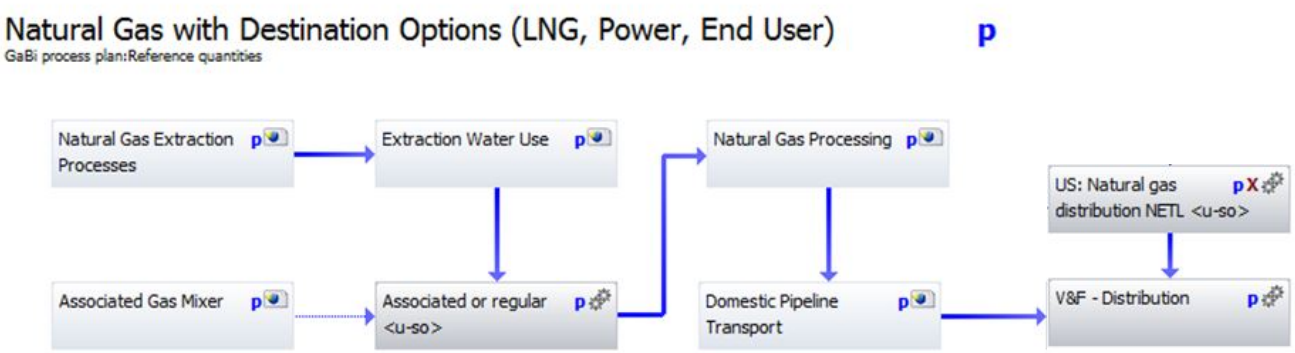


**Table A-3: Natural Gas with Destination Options**

| Unit Process | Notes | Version | Version Date |
|---|---|---|---|
| Natural Gas Distribution | This unit process provides a summary of relevant input and output flows associated with pipeline distribution of natural gas. Distribution begins at the city gate and ends when natural gas is delivered to the end user. The distribution system leaks natural gas, resulting in methane emissions and product losses. | 1 | 10/2013 |

**Figure A-3: Natural Gas Extraction Process – Second-Level Plan**

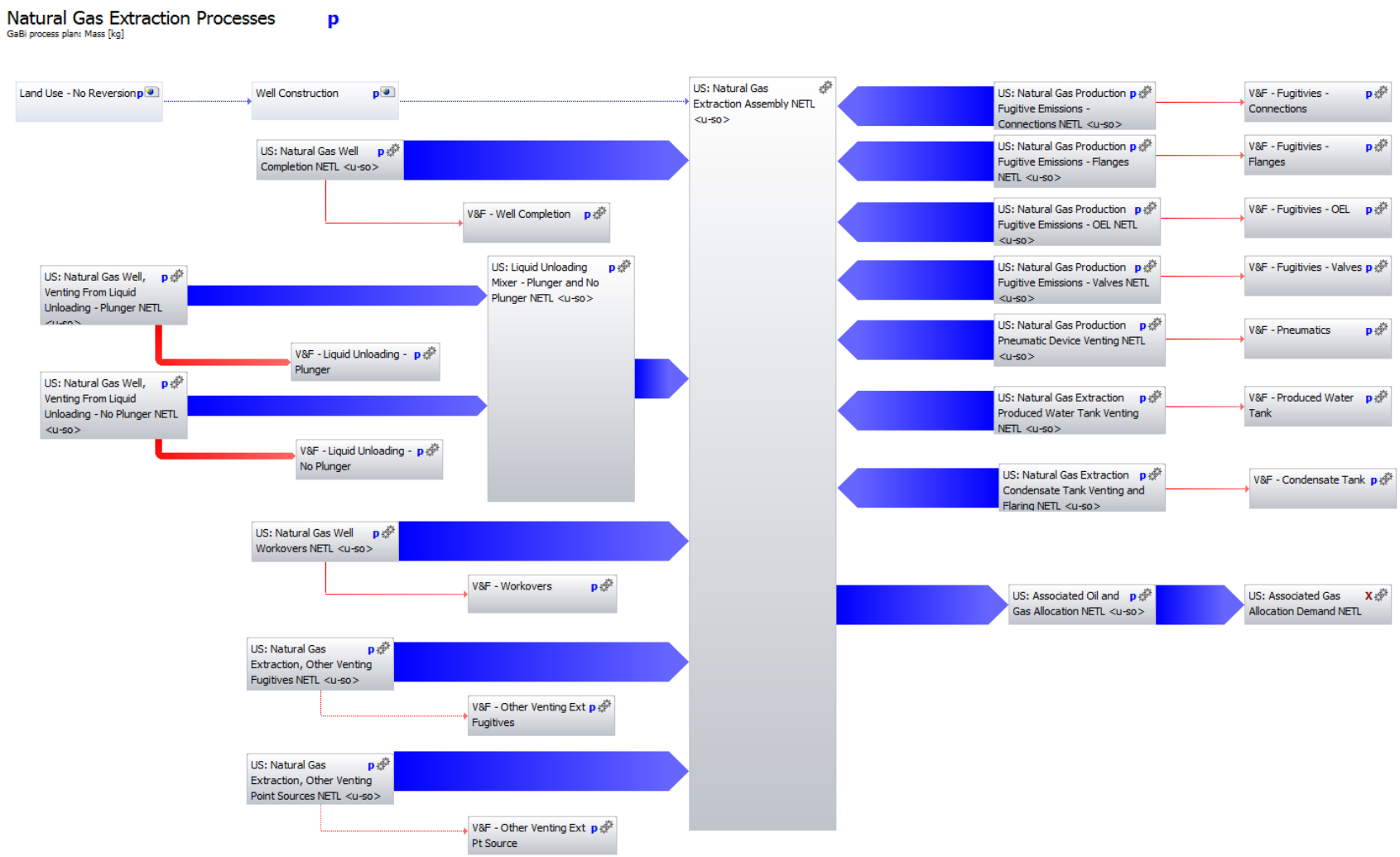


**Table A-4: Natural Gas Extraction Processes**

| Unit Process | Notes | Version | Version Date |
|---|---|---|---|
| Natural Gas Well Completion | This unit process accounts for natural gas venting during well completion. | 1 | 4/2011 |
| Liquid Unloading –Plunger and Liquid Unloading – No Plunger | This unit process accounts for natural gas that is vented during liquid unloading at a natural gas extraction site. This unit process includes multiple scenarios to account for parameterization differences. The scenarios discern between region (i.e. Northeast, Mid-Continent, Southwest, Gulf Coast, and Rocky Mountains), conventional vs. unconventional well type (unconventional considered to be shale gas, coal bed, and tight sand), the application of a plunger lift system, and the corresponding expected, minimum, and maximum parameter values. | 2 | 8/2014 |
| Natural Gas Well Workovers | This unit process accounts for the fraction of gas that is vented during the workover of a natural gas well. This unit process is considered to be applicable to workovers for all completed natural gas wells, both conventional and unconventional. | 1 | 4/2011 |
| Natural Gas Extraction, Other Venting Ext Fugitives | This unit process accounts for natural gas that is vented as fugitive emissions by unidentified processes at a natural gas extraction site. Unidentified processes include those that are not modeled in other unit processes in NETL's natural gas model. This unit process is applicable to all natural gas well types. | 1 | 5/2011 |
| Natural Gas Extraction, Other Venting Ext Pt Source | This unit process accounts for natural gas that is vented by unidentified processes at a natural gas well. Unidentified processes include those that are not modeled in other unit processes. This unit process is applicable to all natural gas well installation as relevant. | 1 | 5/2011 |
| Natural Gas Extraction Assembly | This process includes all inputs for the raw material acquisition for 1 kg of natural gas proportionally from all extraction methods. No calculations were made in this process. | N/A | N/A |
| Natural Gas Production Fugitive Emissions – Connections | This unit process provides a summary of relevant input and output flows associated with natural gas well fugitive losses from connections. Default parameter values presented are regional averages and values are available for conventional natural gas wells and coal bed methane production. | 1 | 1/2015 |

| Unit Process | Notes | Version | Version Date |
|---|---|---|---|
| Natural Gas Production Fugitive Emissions – Flanges | This unit process provides a summary of relevant input and output flows associated with natural gas well fugitive losses from flange operation. Default parameter values presented are regional averages and values are available for conventional natural gas wells and coal bed methane production. | 1 | 1/2015 |
| Natural Gas Production Fugitive Emissions – OEL | This unit process provides a summary of relevant input and output flows associated with natural gas well fugitive losses from open-ended lines. Default parameter values presented are regional averages and values are available for conventional natural gas wells and coal bed methane production. | 1 | 1/2015 |
| Natural Gas Production Fugitive Emissions – Valves | This unit process provides a summary of relevant input and output flows associated with natural gas well fugitive losses from valve operation. Default parameter values presented are regional averages and values are available for conventional natural gas wells and coal bed methane production. | 1 | 1/2015 |
| Natural Gas Production Pneumatic Device Venting | This unit process provides a summary of relevant input and output flows associated with natural gas well pneumatic device operation. Accounted for are the gaseous losses from no, low, high and intermittent pneumatic device operation. Default parameter values presented are regional averages and values are available for conventional natural gas wells and coal bed methane production. | 1 | 1/2015 |
| Natural Gas Extraction Produced Water Tank Venting | This unit process provides a summary of relevant input and output flows associated with natural gas well produced water tank filling and storage. Accounted for are the gaseous losses from flashing during the filling of tanks and breathing/working losses from water storage. Default parameter values presented are regional averages and values are available for conventional natural gas wells and Coal Bed Methane production. | 1 | 2/2015 |
| Natural Gas Extraction Condensate Tank Venting and Flaring | This unit process provides a summary of relevant input and output flows associated with natural gas well condensate tank filling and storage. Accounted for are the gaseous losses from flashing during the filling of tanks and breathing/working losses from condensate storage. Default parameter values presented are regional averages and values are available for conventional natural gas wells and Coal Bed Methane production. | 1 | 2/2015 |

| Unit Process | Notes | Version | Version Date |
|---|---|---|---|
| Associated Oil and Gas Allocation | This unit process provides a summary of relevant input and output flows associated with applied allocation of associated oil and gas from either an oil or gas well for multiple regions within the United States. Oil and Gas Supply Module (OGSM) Regions are utilized to aggregate state level associated gas and oil production data for oil and gas wells. | 1 | 8/2014 |

**Figure A-4: Land Use – No Reversion – Third-Level Plan**

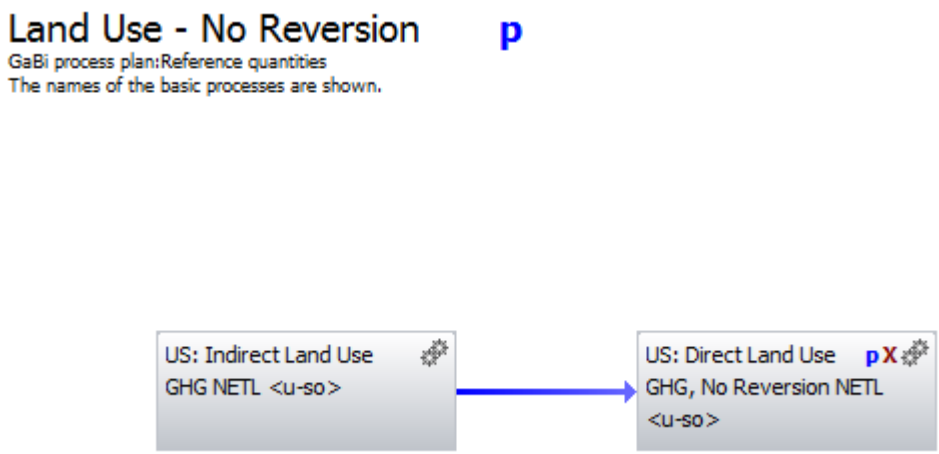



**Table A-5: Land Use – No Reversion**

| Unit Process | Notes | Version | Version Date |
|---|---|---|---|
| Indirect Land Use GHG | This unit process provides a summary of relevant input and output flows for the indirect greenhouse gas (GHG) emissions from land transformation. Indirect GHG emissions from land transformation are applied only to displacement of agricultural land. | 1 | 12/2012 |
| Direct Land Use GHG, No Reversion | This unit process provides a summary of relevant input and output flows for the direct greenhouse gas emissions from land transformation with no reversion to the original land type. | 2 | 12/2013 |

**Figure A-5: Well Construction – Third-Level Plan**

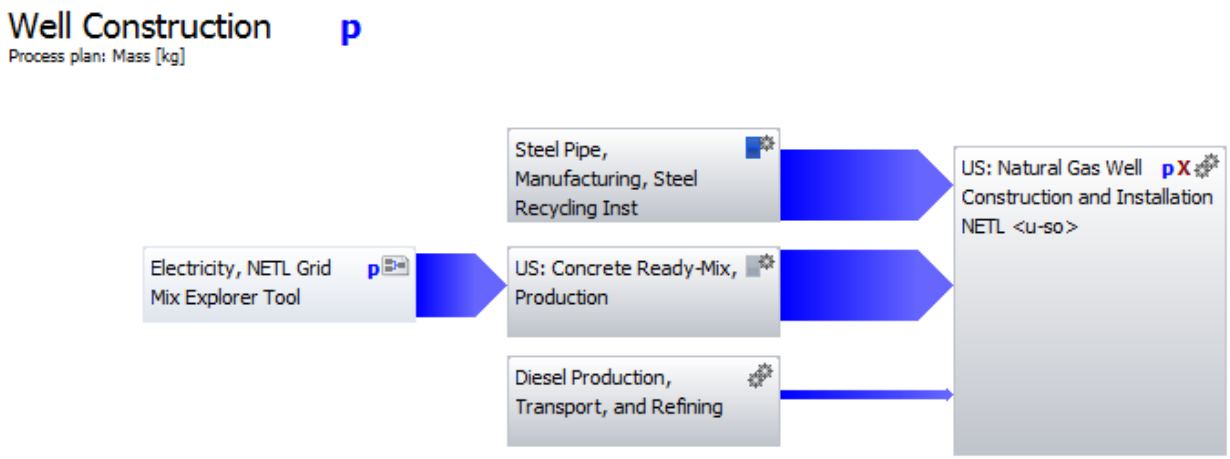



**Table A-6: Well Construction**

| Unit Process | Notes | Version | Version Date |
|---|---|---|---|
| Diesel, Production, Transport, and Refining | This unit process provides a summary of relevant input and output flows associated with production of diesel including the production of crude oil, crude oil transportation, and diesel fuel refining/energy conversion. All inputs and outputs are normalized per kg of diesel. | 2 | 5/2012 |
| Steel Pipe, Welded | This unit process provides a summary of relevant input and output flows associated with the manufacturing of steel blast furnace (BF) welded pipe. The data represents a world-wide, cradle-to-gate average of type BF steel welded pipe production with an 85 percent recovery rate. The key inputs are raw materials and water. Key outputs are air and water emissions from the manufacturing of steel BF welded pipe such as carbon dioxide, nickel, and ammonia. | 1 | 6/2013 |
| Electricity, NETL Grid Mix Explorer Tool | The goal of the Grid Mix Explorer is to allow the user to customize the makeup of their electricity grid specific to their life cycle case or desired scenario, and generate a life cycle inventories for that particular mix of technologies. For this project, the mix was tuned to the preloaded 2013 consumption mix. | 1 | 6/2012 |
| Concrete Ready-Mix, Production | Third-party data from Prusinski, Marceau and VanGeem, "Life Cycle Inventory of Slag Cement Concrete" | 1 | 6/2013 |

| Unit Process | Notes | Version | Version Date |
|---|---|---|---|
| Natural Gas Well Construction and Installation | This unit process provides a summary of relevant input and output flows associated with the construction and installation of a generic natural gas well, applicable to all natural gas well types. Steel and concrete are used for the construction of the well casing; these materials enter the boundaries of this unit process in the form of prefabricated steel pipe and ready-mix concrete. Diesel is used for firing of internal combustion engines used for powering the rotary drilling equipment. Air emissions from diesel combustion include greenhouse gases and criteria air pollutants. The energy and material flows of well construction and installation are apportioned per kg of natural gas production, based on the well production rate and life of the well, as relevant to the type of well in use. Venting of natural gas during well completion is included. | 1 | 2/2013 |

## Associated Gas Mixer – Second-Level Plan

### Table A-7: Associated Gas Mixer

| Unit Process | Notes | Version | Version Date |
|---|---|---|---|
| Natural Gas Associated Average | This unit process provides a summary of relevant input and output flows associated with the raw material acquisition of natural gas via average associated extraction. | 2 | 5/2012 |
| Natural Gas Associated Marginal | This unit process provides a summary of relevant input and output flows associated with the raw material acquisition of natural gas via marginal associated extraction. Marginal is defined as the next well which would be drilled | 2 | 5/2012 |

**Figure A-6: Extraction Water Use – Second-Level Plan**

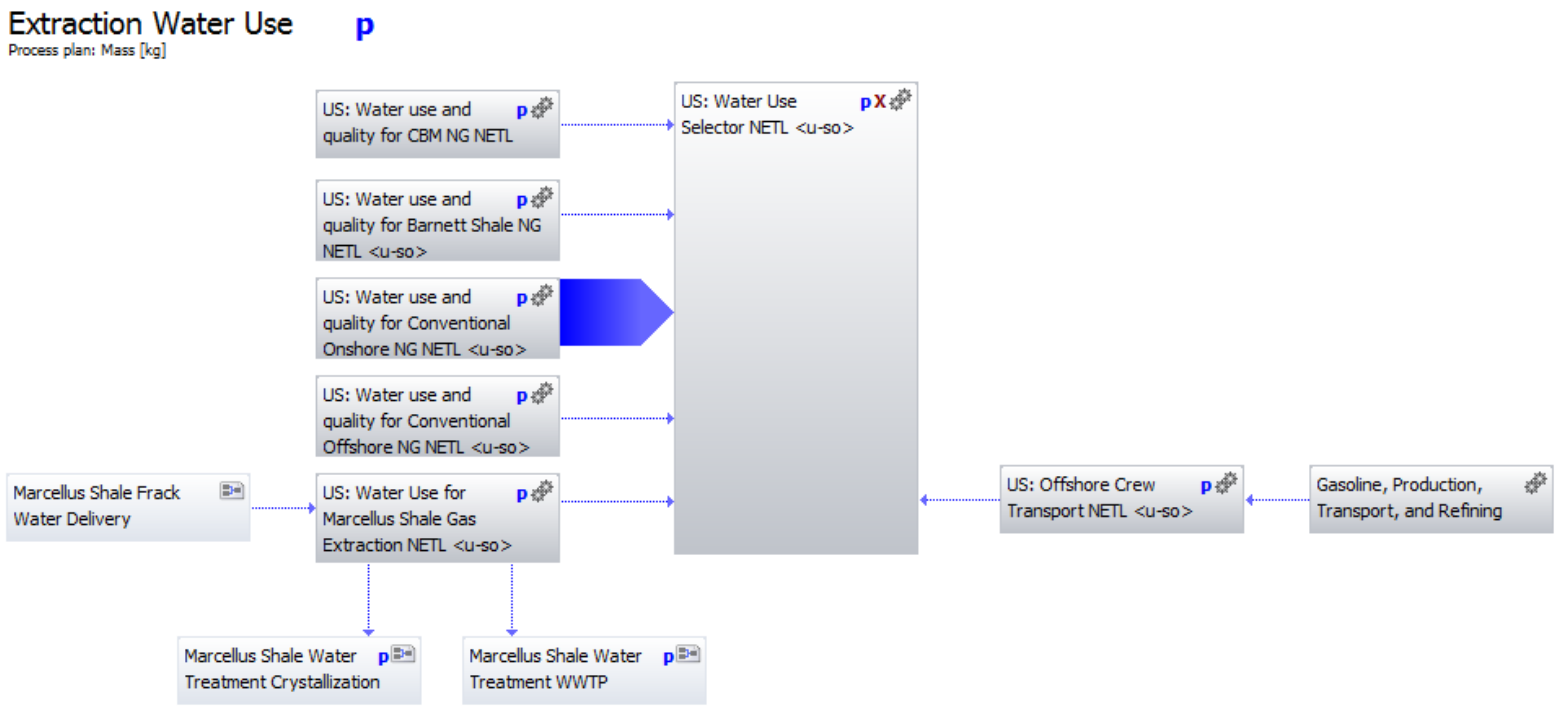


**Table A-8: Extraction Water Use**

| Unit Process | Notes | Version | Version Date |
|---|---|---|---|
| Water Use and Quality for CBM NG | This unit process covers produced water and water quality emissions associated with produced water in support of natural gas produced from coal bed methane (CBM) extraction. It considers only water and water quality related flows. | 2 | 4/2013 |
| Water Use and Quality for Barnett Shale NG | This unit process provides a summary of relevant water inputs and outputs, and water quality emissions, for natural gas production from Barnett Shale natural gas wells. Water consumption includes groundwater and surface water. Produced water (flowback water) is accounted for both in volume and quality, and is presumed to be treated (resulting in removal of 90% of water quality contaminant loads), and then discharged to the surface. | 2 | 4/2013 |
| Water Use and Quality for Conventional Onshore NG | This unit process covers water use, produced water, and water quality emissions associated with produced water in support of conventional onshore natural gas extraction activities. It considers only water and water quality related flows. | 1 | 4/2011 |
| Water Use and Quality for Conventional Offshore NG | This unit process covers produced water and water quality emissions associated with produced water in support of conventional offshore natural gas extraction activities. It considers only water and water quality related fields. | 1 | 4/2011 |
| Water Use for Marcellus Shale Gas | This unit process provides a summary of relevant inputs and outputs associated with the water withdrawal and discharge for the extraction of natural gas from a Marcellus Shale formation. It accounts for the amount of water from ground, surface, and recycled sources and the amount of water discharged to a water treatment plant. | 1 | 10/2011 |
| Marcellus Shale Water Treatment (WWTP) | This unit process provides a summary of relevant input and output flows associated with transport and treatment of flowback water from a natural gas well in the Marcellus Shale region. In this unit process, a wastewater treatment plant is used for treating water. The inputs to this unit process include flowback water and tanker truck transportation from the natural gas well site to through a wastewater treatment plant. Diesel combustion has been removed from this process and is now an input | 3 | 12/2014 |

| Unit Process | Notes | Version | Version Date |
|---|---|---|---|
| Marcellus Shale Water Treatment, Crystallization | This unit process provides a summary of relevant input and output flows associated with transport and treatment of flowback water from a natural gas well in the Marcellus Shale. The inputs to this unit process include flowback water and tanker truck transportation from the natural gas well site to a wastewater treatment process that uses crystallization. Diesel combustion has been removed from this process and is now an input. | 2 | 12/2014 |
| Gasoline, Production, Transport and Refining | This unit process provides a summary of relevant input and output flows associated with production of gasoline including the production of crude oil, crude oil transportation, and gasoline fuel refining/energy conversion. | 2 | 5/2012 |
| Offshore Crew Transport | This unit process accounts for the mass of aviation gas fuel and associated greenhouse gas emissions, including carbon dioxide, methane, and nitrous oxide, that result from the transport of employees and crew members to and from an offshore natural gas platform. | 1 | 3/2011 |

**Figure A-7: Marcellus Shale Frack Water Delivery – Third-Level Plan**

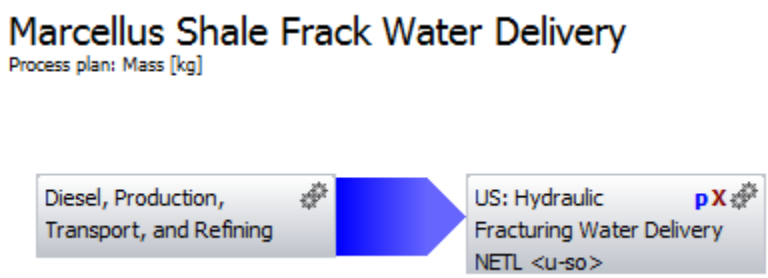



**Table A-9: Marcellus Shale Frack Water Delivery**

| Unit Process | Notes | Version | Version Date |
|---|---|---|---|
| Diesel, Production, Transport, and Refining | This unit process provides a summary of relevant input and output flows associated with production of diesel including the production of crude oil, crude oil transportation, and diesel fuel refining/energy conversion. | 2 | 5/2012 |
| Hydraulic Fracturing Water Delivery | This unit process accounts for the transport of water from a surface or ground source to a Marcellus Shale gas well to be used for hydraulic fracturing (hydrofracking). The only tracked input is diesel fuel, and the key outputs are diesel combustion emissions. | 1 | 10/2011 |

**Figure A-8: Natural Gas Processing – Second-Level Plan**

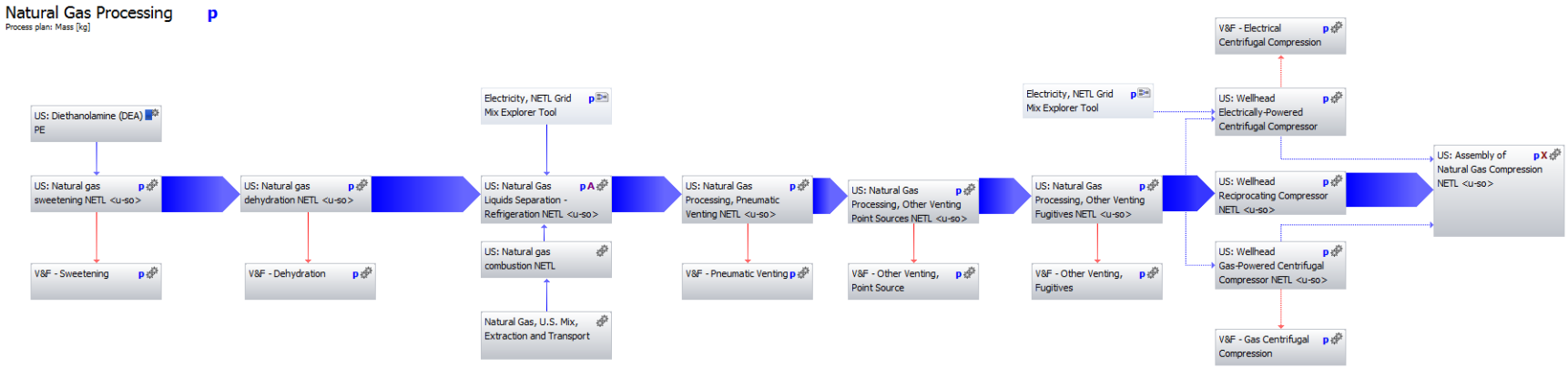


**Table A-10: Natural Gas Processing**

| Unit Process | Notes | Version | Version Date |
|---|---|---|---|
| Diethanolamine (DEA) | Third-party data available from thinkstep.<br>GUID: 894E2AB9-DA97-4357-8DFF-1306AD80D3E6<br>Last change: System, 11/1/2012 | N/A | N/A |
| Natural Gas Sweetening | This unit process provides a summary of relevant input and output flows associated with the acid gas removal (AGR) of natural gas, specifically the removal of $H_2S$. The scope of the unit process accounts for energy consumption, solvent use, greenhouse gas emissions, criteria air pollutants and other air emissions of concern. Water use is also quantified, however, water quality emissions are assumed to be insignificant for this unit process. The boundaries begin with the receipt of "sour" natural gas and end with "sweetened" natural gas ready for pipeline transmission. | 3 | 2/2015 |
| Natural Gas Dehydration | This unit process provides a summary of relevant input and output flows associated with the dehydration of natural gas from a generic formation. The scope of the unit process accounts for energy consumption and greenhouse gas emissions, as well as vented methane gas. | 1 | 4/2011 |
| Natural Gas Combustion | This unit process provides a summary of relevant input and output flows associated with the combustion of natural gas utilized for several downstream processes. | 1 | 1/2015 |
| Natural Gas Liquids Separation | This unit process provides a summary of relevant input and output flows associated with processing extracted natural gas to separate the pure natural gas (methane) from the other hydrocarbons and fluids (natural gas liquids (NGL)). Inputs include extracted natural gas (methane) and energy (natural gas and electricity). Outputs include pure natural gas (methane) and NGL. | 1 | 3/2015 |
| Natural Gas Processing, Pneumatic Venting | This unit process accounts for the gas that is vented by pneumatic devices and valves at a natural gas processing facility. This unit process is applicable to all natural gas types. | 1 | 3/2011 |
| Natural Gas Processing, Other Venting Point Sources | This unit process accounts for natural gas that is vented by unidentified activities at a natural gas processing plan. Unidentified activities are processes that are not identified elsewhere in NETL's natural gas model. | 1 | 5/2011 |

| Unit Process | Notes | Version | Version Date |
|---|---|---|---|
| Natural Gas Processing, Other Venting Fugitives | This unit process accounts for natural gas that is vented as fugitive emissions by unidentified processes at a natural gas extraction site. Unidentified processes include those that are not modeled explicitly in other unit processes in NETL's life cycle analysis model of natural gas. | 1 | 5/2011 |
| Electricity, NETL Grid Mix Explorer Tool | The goal of the Grid Mix Explorer is to allow the user to customize the makeup of their electricity grid specific to their life cycle case or desired scenario, and generate a life cycle inventories for that particular mix of technologies. For this project, the mix was tuned to the preloaded 2013 consumption mix. | 1 | 1/2015 |
| Wellhead Electrically-Powered Centrifugal Compressor | This unit process provides a summary of relevant input and output flows associated with the operation of 500 horsepower (HP), electrically-powered centrifugal compressors at a natural gas wellhead. This unit process is applicable to all natural gas well types considered. | 1 | 4/2011 |
| Wellhead Reciprocating Compressor | This unit process provides a summary of natural gas input and output flows associated with the operation of 200 horsepower (HP), gas-powered reciprocating compressors at a natural gas wellhead. This unit process is applicable to all natural gas well types considered. Emissions from natural gas combustion are accounted for in the externally linked natural gas combustion unit process. | 2 | 12/2014 |
| Wellhead Gas-Powered Centrifugal Compressor | This unit process provides a summary of relevant input and output flows associated with the operation of 187 horsepower (HP), gas-powered centrifugal compressors at a natural gas wellhead. This unit process is applicable to all natural gas well types considered. Emissions from natural gas combustion are accounted for in the externally linked natural gas combustion unit process. | 2 | 12/2014 |
| Assembly of Natural Gas Compression | This unit process assembles the 3 wellhead natural gas compressor types, including reciprocating, gas-powered centrifugal, and electrically-powered centrifugal. The proportions for each compressor type vary based on the natural gas extraction source. | 1 | 4/2011 |

**Figure A-9: Domestic Pipeline Transport – Second-Level Plan**

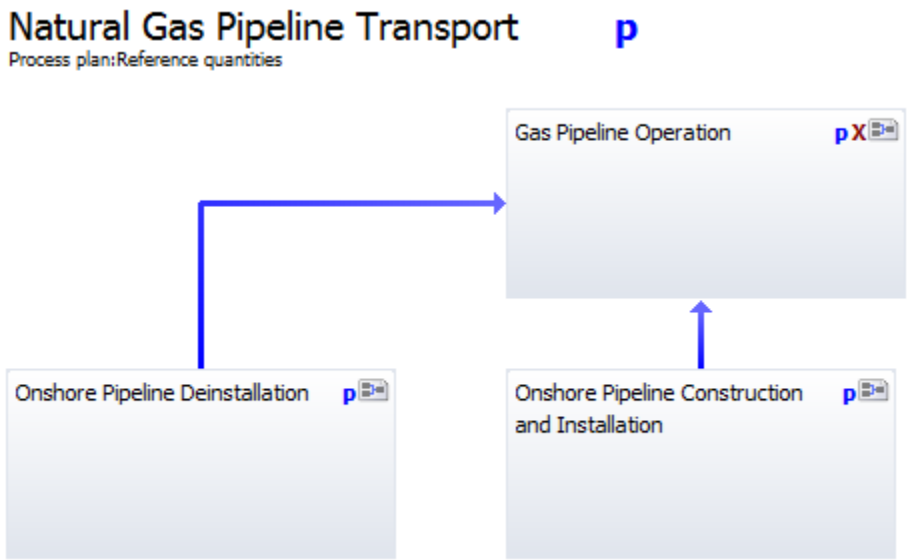



**Figure A-10: Onshore Pipeline Deinstallation – Third-Level Plan**

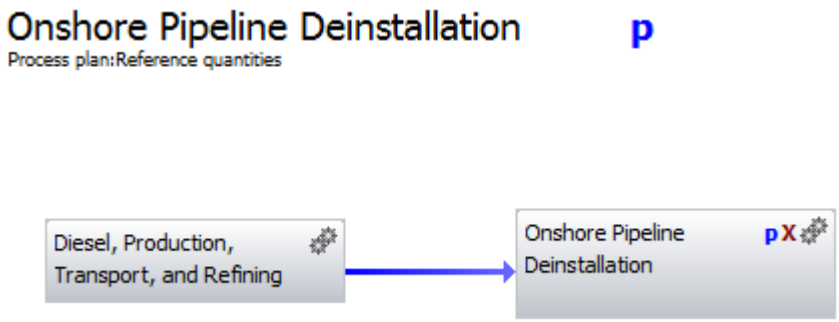


**Table A-11: Onshore Pipeline Deinstallation**

| Unit Process | Notes | Version | Version Date |
|---|---|---|---|
| Diesel, Production, Transport, and Refining | This unit process provides a summary of relevant input and output flows associated with production of diesel including the production of crude oil, crude oil transportation, and diesel fuel refining/energy conversion. All inputs and outputs are normalized per kg of diesel. | 2 | 5/2012 |
| Onshore Pipeline Deinstallation | Underground onshore pipeline deinstallation is covered in this unit process. Deinstallation includes heavy construction equipment exhaust emissions, emissions from transport of pipes and associated materials (200 miles round-trip), and fugitive dust from deinstallation activities. | 1 | 2/2010 |

**Figure A-11: Gas Pipeline Operation – Third-Level Plan**

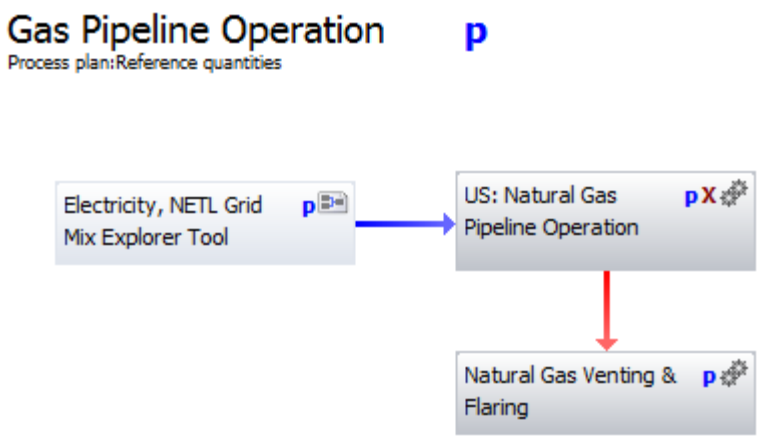


**Table A-12: Gas Pipeline Operation**

| Unit Process | Notes | Version | Version Date |
|---|---|---|---|
| Electricity, NETL Grid Mix Explorer Tool | The goal of the Grid Mix Explorer is to allow the user to customize the makeup of their electricity grid specific to their life cycle case or desired scenario, and generate a life cycle inventories for that particular mix of technologies. For this project, the mix was tuned to the preloaded 2013 consumption mix. | 1 | 6/2012 |
| Pipeline NG Operation | This unit process provides a summary of relevant input and output flows associated with the operation of a natural gas pipeline, including the use of electricity and combustion of natural gas used for powering compressor stations. The generation of electricity used by this unit process occurs upstream, and thus the emissions from electricity generation are not included in the boundaries of this unit process. Fugitive emissions of methane are also included. | 2 | 3/2014 |

**Figure A-12: Onshore Pipeline Construction and Installation – Third-Level Plan**

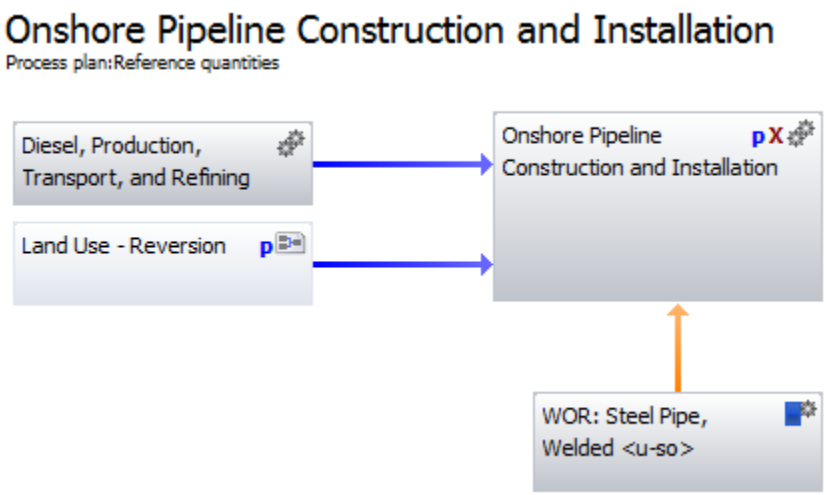


**Table A-13: Onshore Pipeline Construction and Installation**

| Unit Process | Notes | Version | Version Date |
|---|---|---|---|
| Diesel, Production, Transport, and Refining | This unit process provides a summary of relevant input and output flows associated with production of diesel including the production of crude oil, crude oil transportation, and diesel fuel refining/energy conversion. All inputs and outputs are normalized per kg of diesel. | 2 | 5/2012 |
| Onshore Pipeline, Construction and Installation | Underground onshore (rather than offshore) pipeline installation and deinstallation are covered in this unit process. Installation and deinstallation includes heavy construction equipment exhaust emissions, emissions from transport of pipes and associated materials (200 miles round-trip), and fugitive dust from installation and deinstallation activities. | 1 | 2/2010 |
| Steel Pipe, Welded | Third-party data available from the Steel Recycling Institute | 1 | 6/2013 |

**Figure A-13: Land Use – Reversion – Fourth-Level Plan**

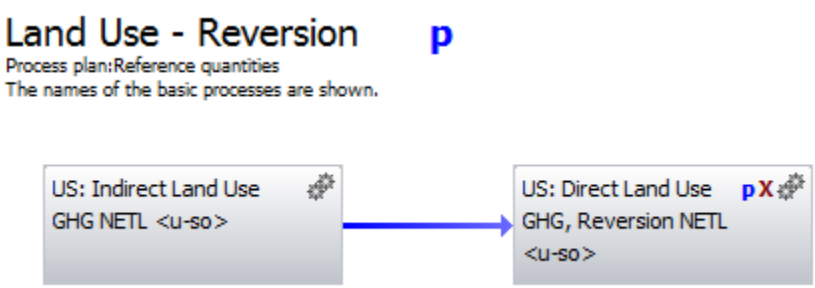



**Table A-14: Land Use – Reversion**

| Unit Process | Notes | Version | Version Date |
|---|---|---|---|
| Indirect Land Use | This unit process provides a summary of relevant input and output flows for the indirect greenhouse gas (GHG) emissions from land transformation. Indirect GHG emissions from land transformation are applied only to displacement of agricultural land. | 1 | 12/2012 |
| Direct Land Use, Reversion | This unit process provides a summary of relevant input and output flows for the direct greenhouse gas emissions from land transformation with reversion to the original land type. | 2 | 8/2013 |

**Table A-15: Generic U.S. and N.A. Power Grid Mix for 2007 and 2010[1]**

| Energy Source | 2007 | 2010 |
|---|---|---|
| Coal | 49.8% | 45.9% |
| Petroleum | 1.6% | 1.0% |
| Natural Gas | 20.3% | 22.7% |
| Nuclear | 20.2% | 20.4% |
| Hydro | 6.9% | 7.3% |
| Solar | 0.02% | 0.03% |
| Geothermal | 0.4% | 0.4% |
| Wind | 0.9% | 2.4% |

[1] Percentages in table do not add to exactly 100% due to rounding errors.

# Appendix B:
# Upstream Parameters by NETL Region and Extraction Technology

## Tables

Table B-1: Upstream Parameters for Eastern Regions (Appalachian, Illinois-Michigan, & Black Warrior) ..... B-2
Table B-2: Upstream Parameters for Midcontinent Regions (Central & North-Central)..... B-7
Table B-3: Upstream Parameters for Southern Regions (TX-LA-MS Salt, Gulf Coast, Fort Worth, West Texas-Permian)..... B-12
Table B-4: Upstream Parameters for Western Regions (Rocky Mountains, West Coast, & Alaska) ..... B-17
Table B-5: Upstream Parameters for Offshore Regions (Alaska Offshore, Gulf of Mexico Offshore, Pacific Offshore)..... B-22
Table B-6: Upstream Parameters for National Associated Gas, Gas Injection ..... B-24
Table B-7: Upstream Parameters for National Associated Gas, Steam Injection..... B-25
Table B-8: Upstream Parameters for National Associated Gas, Water Injection..... B-26

**Table B-1: Upstream Parameters for Eastern Regions (Appalachian, Illinois-Michigan, & Black Warrior)**

| Property (Units) | | Appalachian | | | | Illinois-Michigan | | | Black Warrior |
|---|---|---|---|---|---|---|---|---|---|
| | | Conventional | CBM | Tight Gas | Shale | Conventional | Tight Gas | Shale | CBM |
| **Natural Gas Source** | | | | | | | | | |
| Contribution to 2012 U.S. Domestic Supply | | 2.80% | 0.40% | 0.30% | 9.10% | 0.30% | 0.04% | 0.40% | 0.40% |
| EUR (Bcf) | Low | 1.81 | 0.548 | 0.060 | 2.38 | 1.81 | 0.060 | 2.58 | 0.913 |
| | Expected | 1.51 | 0.438 | 0.38 | 1.59 | 1.51 | 0.38 | 1.72 | 0.730 |
| | High | 1.21 | 0.329 | 0.69 | 0.795 | 1.21 | 0.69 | 0.861 | 0.548 |
| Weight Fraction : $CH_4$ | | 0.672 | | | | 0.688 | | | 0.672 |
| Weight Fraction : $CO_2$ | | 0.0327 | | | | 0.0329 | | | 0.0327 |
| Weight Fraction : NMVOC | | 0.00990 | | | | 0.00931 | | | 0.00990 |
| Weight Fraction : $H_2S$ [1] | | 1.18E-05 | | | | 1.11E-05 | | | 1.18E-05 |
| **Land Use** | | | | | | | | | |
| Land Use Area ($m^2$/well life) | | 10,100 | 1,000 | 0.00 | 6,000 | 10,100 | 0 | 20,200 | 1,000 |
| Fraction of Land Use | Agriculture | 0.157 | 0.154 | 0.157 | 0.224 | 0.505 | | 0.279 | 0.115 |
| | Forest | 0.754 | 0.729 | 0.754 | 0.723 | 0.409 | | 0.662 | 0.793 |
| | Grassland | 0.0888 | 0.117 | 0.0888 | 0.0532 | 0.0861 | | 0.0591 | 0.0923 |

[1] Mass fractions may not add up to 100% due to the omission of the weight fraction of $N_2$

**Table B-1: Upstream Parameters for Eastern Regions (Appalachian, Illinois-Michigan, & Black Warrior) continued**

| Property (Units) | Appalachian | | | | Illinois-Michigan | | | Black Warrior |
|---|---|---|---|---|---|---|---|---|
| | Conventional | CBM | Tight Gas | Shale | Conventional | Tight Gas | Shale | CBM |
| Flaring Activity (%) construction & completion | 59% (94%-39%) | 69% (95%-39%) | 65% (95%-39%) | 46% (51%-43%) | 59% (94%-39%) | 65% (95%-39%) | 46% (51%-43%) | 69% (95%-39%) |
| **Well Construction & Completion** | | | | | | | | |
| Drill Depth (m) | 1,040 (1,030-1,050) | 1,460 (762-2,130) | | | 1,040 (1,030-1,050) | 1,460 (762-2,130) | | 3,800 (2,590-4,880) |
| HF Completion Flowback Period (days) | NA | | 7.00 (3.00-10.0) | | NA | 7.00 (3.00-10.0) | | NA |
| HF Initial Production Rate (scf/day) | | | 41,300 (41,000-64,000) | 2,190,000 (2,170,000-3,390,000) | | 98,400 (97,700-153,000) | 2,370,000 (2,350,000-3,670,000) | |
| Non-HF Completion Emissions (scf/episode) | 37,000 (3,700-370,000) | 49,600 (4,960-496,000) | NA | | 37,000 (3,700-370,000) | NA | | 49,600 (4,960-496,000) |
| **Natural Gas Extraction Well Workover** | | | | | | | | |
| Lifetime Workovers (episodes/well) | 0.0750 (0.0600-0.0900) | 0.125 (0.100-0.1500) | | 0.0750 (0.0600-0.0900) | 0.0750 (0.0600-0.0900) | 0.125 (0.100-0.1500) | 0.0750 (0.0600-0.0900) | 0.125 (0.100-0.1500) |
| Non-HF Workover Emissions (scf/episode) | 2,450 (245-24,500) | 49,600 (4,960-496,000) | NA | | 2,450 (245-24,500) | NA | | 49,600 (4,960-496,000) |
| HF Flowback Period (days) | NA | | 7.00 (3.00-10.0) | | NA | 7.00 (3.00-10.0) | | NA |

**Table B-1: Upstream Parameters for Eastern Regions (Appalachian, Illinois-Michigan, & Black Warrior) continued**

| Property (Units) | Appalachian | | | | Illinois-Michigan | | | Black Warrior |
|---|---|---|---|---|---|---|---|---|
| | Conventional | CBM | Tight Gas | Shale | Conventional | Tight Gas | Shale | CBM |
| Wells Requiring Liquids Unloading | 10.0% | | | | 10.0% | | | 10.4% |
| **Liquids Unloading: Plunger** | | | | | | | | |
| Well Depth (m) | 1,040 (1,030-1,050) | 1,550 (762-2,130) | | | 1,040 (1,030-1,050) | 1,550 (762-2,130) | | 4,060 (2,590-4,880) |
| Tubing: Internal Diameter (in) | 2.24 (2.00-2.38) | 2.38 | | | 2.24 (2.00-2.38) | 2.38 | | 2.38 |
| Shut-in or Surface Pressure (psia) | 77.0 (64.7-99.7) | 148 (136-215) | | | 77.0 (64.7-99.7) | 148 (136-215) | | 484 (29.7-555) |
| Average Flow-line Rate (scf/hr) | 382 (300-535) | 7,230 (625-26,200) | | | 382 (300-535) | 7,230 (625-26,200) | | 258,000 (3,460-354,000) |
| Unloading Event Duration (hrs) | 0.545 (0.300-1.00) | 0.170 (0.0500-0.221) | | | 0.545 (0.300-1.00) | 0.170 (0.0500-0.221) | | 0.672 (0.300-2.00) |
| Total Unloading Events (events/well life) | 38.6 (38.6-38.7) | 229 (38.8-730) | | | 38.6 (38.6-38.7) | 229 (38.8-730) | | 2.36 (1.00-52.0) |
| Fraction of Production from Wells with Plunger Lifts | 11.4% | 55.2% | | | 11.4% | 55.2% | | 24.3% |
| **Liquids Unloading: No Plunger** | | | | | | | | |
| Well Depth (m) | 1,040 (1,030-1,050) | 1,480 | | | 1,040 (1,030-1,050) | 1,480 | | 4,080 (1,830-4,880) |
| Casing: Internal Diameter (in) | 4.63 (4.50-5.00) | 4.50 | | | 4.63 (4.50-5.00) | 4.50 | | 9.04 (4.50-10.8) |
| Shut-in or Surface Pressure (psia) | 74.1 (64.7-99.7) | 136 | | | 74.1 (64.7-99.7) | 136 | | 521 (29.7-555) |
| Average Flow-line Rate (scf/hr) | 364 (300-535) | 1,083 | | | 364 (300-535) | 1,083 | | 280,000 (1,040-354,000) |
| Unloading Event Duration (hrs) | 1.73 (1.00-2.00) | 1.36 | | | 1.73 (1.00-2.00) | 1.36 | | 1.36 (0.688-5.30) |
| Total Unloading Events (events/well life) | 37.8 (22.8-43.3) | 82.3 | | | 37.8 (22.8-43.3) | 82.3 | | 1.56 (0.600-52.0) |

**B-1: Upstream Parameters for Eastern Regions (Appalachian, Illinois-Michigan, & Black Warrior) continued**

| Property (Units) | | Appalachian | | | | Illinois-Michigan | | | Black Warrior |
|---|---|---|---|---|---|---|---|---|---|
| | | Conventional | CBM | Tight Gas | Shale | Conventional | Tight Gas | Shale | CBM |
| **Pneumatic Device Venting** | | | | | | | | | |
| Pneumatic Vent Rate (scf/hr) | High | 37.3 (32.1-37.3) | | | | 36.9 (32.1-37.3) | | | 37.3 (32.1-37.3) |
| | Intermittent | 13.5 (8.58-13.5) | | | | 13.5 (8.58-13.5) | | | 13.5 (8.58-13.5) |
| | Low | 1.39 (1.39-3.15) | | | | 1.52 (1.39-3.15) | | | 1.39 (1.39-3.15) |
| | Zero | 0 | | | | 0 | | | 0 |
| Pneumatic Device Count | High | 0.595 (0.222-3.00) | 0.244 (0.222-3.00) | 0.595 (0.222-3.00) | | 0.278 (0.222-3.00) | | | 0.318 (0.318-1.33) |
| | Intermittent | 0.104 (0-0.718) | 0.137 (0-0.718) | 0.104 (0 -0.718) | | 0.199 (0-1.20) | | | 0.171 (0.171-0.717) |
| | Low | 0.125 (0-0.865) | 0.159 (0-0.865) | 0.125 (0-0.865) | | 0.206 (0-1.00) | | | 0.206 (0.206-0.865) |
| | Zero | 0.330 | | | | 0.306 (0-0.330) | | | 0.330 |

**Table B-1: Upstream Parameters for Eastern Regions (Appalachian, Illinois-Michigan, & Black Warrior) continued**

| Property (Units) | | Appalachian | | | | Illinois-Michigan | | | Black Warrior |
|---|---|---|---|---|---|---|---|---|---|
| | | Conventional | CBM | Tight Gas | Shale | Conventional | Tight Gas | Shale | CBM |
| **Other Fugitive Emissions** | | | | | | | | | |
| Mass Leak Rate (kg/device hr) | Connections | 0.000207 | | | | 0.000207 | | | 0.000207 |
| | Flanges | 0.000403 | | | | 0.000403 | | | 0.000403 |
| | OEL | 0.00207 | | | | 0.00207 | | | 0.00207 |
| | Valves | 0.00465 | | | | 0.00465 | | | 0.00465 |
| Device Count | Connections | 38.5 (35.0-39.1) | 39.1 (35.0-39.1) | 38.5 (35.0-39.1) | | 38.8 (35.0-39.1) | | | 39.1 |
| | Flanges | 18.8 (0-21.7) | 21.7 (0-21.7) | 18.8 (0-21.7) | | 21.4 (0-21.7) | | | 21.7 |
| | OEL | 4.66 (1.00-5.23) | 5.23 (1.00-5.23) | 4.66 (1.00-5.23) | | 5.29 (1.00-6.00) | | | 5.23 |
| | Valves | 13.6 (12.0-13.8) | 13.8 (12.0-13.8) | 13.6 (12.0-13.8) | | 13.7 (12.0-13.8) | | | 13.8 |
| Hours of Operation (hr/yr) | | 7,620 (260-8,760) | 8,760 (260-8,760) | 7,619 (260-8,760) | | 8,760 (260-8,760) | | | 8,760 |
| Regional Production Rate (Bcf/yr): Used to scale fugitive emission factors[1] | | 0.447 (0.447-0.00511) | 39.5 (39.5-16.5) | 0.447 (0.447-0.00511) | | 0.0188 (0.0188-0.0120) | | | 67.1 |

[1]Values are used for Other Fugitive Emissions as well as Pneumatic Device Venting.

**Table B-2: Upstream Parameters for Midcontinent Regions (Central & North-Central)**

| Property (Units) | | Central | | | | North-Central | | |
|---|---|---|---|---|---|---|---|---|
| | | Conventional | CBM | Tight Gas | Shale | Conventional | Tight Gas | Shale |
| **Natural Gas Source** | | | | | | | | |
| Contribution to 2012 U.S. Domestic Supply | | 5.40% | 0.400% | 1.60% | 6.00% | 0.0900% | 0.0300% | 0.700% |
| EUR (Bcf) | Low | 1.81 | 4.56 | 0.90 | 2.17 | 1.81 | 0.21 | 0.660 |
| | Expected | 1.51 | 1.39 | 1.31 | 1.44 | 1.51 | 0.33 | 0.440 |
| | High | 1.21 | 0.329 | 1.72 | 0.722 | 1.21 | 0.61 | 0.220 |
| Weight Fraction : $CH_4$ | | 0.743 | 0.820 | 0.743 | 0.743 | 0.672 | | |
| Weight Fraction : $CO_2$ | | 0.0143 | 0.0308 | 0.0143 | 0.0143 | 0.0327 | | |
| Weight Fraction : NMVOC | | 0.00851 | 0.00433 | 0.00851 | 0.00851 | 0.0147 | | |
| Weight Fraction : $H_2S$ [1] | | 4.40E-05 | 6.55E-06 | 4.40E-05 | 4.40E-05 | 1.18E-05 | | |
| **Land Use** | | | | | | | | |
| Land Use Area ($m^2$/well life) | | 10,100 | 1,000 | 20,200 | | 10,100 | 0 | 20,200 |
| Fraction of Land Use | Agriculture | 0.366 | 0.413 | 0.366 | 0.291 | 0.591 | | 0.632 |
| | Forest | 0.201 | 0.149 | 0.201 | 0.478 | 0.0250 | | 0.0360 |
| | Grassland | 0.433 | 0.438 | 0.433 | 0.231 | 0.384 | | 0.332 |

[1] Mass fractions may not add up to 100% due to the omission of the weight fraction of $N_2$

**Table B-2: Upstream Parameters for Midcontinent Regions (Central & North-Central) continued**

| Property (Units) | Central | | | | North-Central | | |
|---|---|---|---|---|---|---|---|
| | Conventional | CBM | Tight Gas | Shale | Conventional | Tight Gas | Shale |
| Flaring Activity (%) | 59% (94%-39%) | 69% (95%-39%) | 65% (95%-39%) | 69% (95%-65%) | 59% (94%-39%) | 65% (95%-39%) | 46% (51%-43%) |
| **Well Construction & Completion** | | | | | | | |
| Drill Depth (m) | 2,110 (1,300-2,900) | 2,280 (1,190-3,140) | | | 2,110 (1,300-2,900) | 3,150 (2,260-3,400) | |
| HF Completion Flowback Period (days) | NA | | 7.00 (3.00-10.00) | | NA | 7.00 (3.00-10.00) | |
| HF Initial Production Rate (scf/day) | | | 652,000 (648,000-1,010,000) | 1,990,000 (1,970,000-3,080,000) | | 77,000 (76,500-119,000) | 605,000 (601,000-938,000) |
| Non-HF Completion Emissions (scf/episode) | 37,00 (3,700-370,000) | 49,600 (4,960-496,000) | NA | | 37,00 (3,700-370,000) | NA | |
| **Natural Gas Extraction Well Workover** | | | | | | | |
| Lifetime Workovers (episodes/well) | 0.0750 (0.0600-0.0900) | 0.125 (0.100-0.150) | | 0.0750 (0.0600-0.0900) | 0.0750 (0.0600-0.0900) | 0.125 (0.100-0.150) | 0.0750 (0.0600-0.0900) |
| Non-HF Workover Emissions (scf/episode) | 2,450 (245-24,500) | 49,600 (4,960-496,000) | NA | | 2,450 (245-24,500) | NA | |
| HF Flowback Period (days) | NA | | 7.00 (3.00-10.00) | | NA | 7.00 (3.00-10.00) | |

**Table B-2: Upstream Parameters for Midcontinent Regions (Central & North-Central) continued**

| Property (Units) | Central | | | | North-Central | | |
|---|---|---|---|---|---|---|---|
| | Conventional | CBM | Tight Gas | Shale | Conventional | Tight Gas | Shale |
| Wells Requiring Liquids Unloading | 5.17% | | | | 5.17% | 2.94% | |
| **Liquids Unloading: Plunger** | | | | | | | |
| Well Depth (m) | 1,340 (1,300-2,900) | 2,250 (1,190-3,140) | | | 1,340 (1,300-2,900) | 3,180 (2,260-3,400) | |
| Tubing: Internal Diameter (in) | 2.00 (1.99-2.38) | 3.62 (2.38-4.11) | | | 2.00 (1.99-2.38) | 2.30 (1.92-2.38) | |
| Shut-in or Surface Pressure (psia) | 84.5 (40.2-515) | 107 (89.4-113) | | | 84.5 (40.2-515) | 249 (165-305) | |
| Average Flow-line Rate (scf/hr) | 3,440 (1,250-3,500) | 29,600 (10,400-36,500) | | | 3,440 (1,250-3,500) | 13,200 (1,920-18,900) | |
| Unloading Event Duration (hrs) | 0.0728 (0.0670-0.750) | 1.97 (0.0833-2.99) | | | 0.0729 (0.0670-0.750) | 1.53 (0.407-2.10) | |
| Total Unloading Events (events/well life) | 2,920 (11.5-2,990) | 480 (2.40-3,250) | | | 2,920 (11.5-2,990) | 16.2 (2.24-1,150) | |
| Fraction of Production from Wells with Plunger Lifts | 81.9% | 21.5% | | | 81.9% | 90.3% | |
| **Liquids Unloading: No Plunger** | | | | | | | |
| Well Depth (m) | 1,320 (1,300-2,140) | 2,240 (1,190-3,350) | | | 1,320 (1,300-2,140) | 3,390 (3,300-3,540) | |
| Casing: Internal Diameter (in) | 4.01 (4.00-4.83) | 5.19 (4.92-5.50) | | | 4.01 (4.00-4.83) | 4.11 (2.38-4.70) | |
| Shut-in or Surface Pressure (psia) | 74.9 (40.2-75.5) | 121 (94.7-215) | | | 74.9 (40.2-75.5) | 261 (213-491) | |
| Average Flow-line Rate (scf/hr) | 3,480 (2,440-3,500) | 26,500 (4,170-36,500) | | | 3,480 (2,440-3,500) | 5,630 (1,730-18,000) | |
| Unloading Event Duration (hrs) | 4.87 (0.250-4.95) | 1.89 (0.500-2.50) | | | 4.87 (0.250-4.95) | 1.77 (0.750-3.18) | |
| Total Unloading Events (events/well life) | 63.2 (1.00-64.3) | 3.77 (2.26-12.0) | | | 63.2 (1.00-64.3) | 68.1 (2.00-378) | |

**Table B-2: Upstream Parameters for Midcontinent Regions (Central & North-Central) continued**

| Property (Units) | | Central | | | | North-Central | | |
|---|---|---|---|---|---|---|---|---|
| | | Conventional | CBM | Tight Gas | Shale | Conventional | Tight Gas | Shale |
| **Pneumatic Device Venting** | | | | | | | | |
| Pneumatic Vent Rate (scf/hr) | High | 32.1 | | | | 38.9 | | |
| | Intermittent | 7.36 (4.01-13.1) | 11.3 (4.01-13.1) | 7.36 (4.01-13.1) | | 23.7 | | |
| | Low | 3.02 (2.28-3.15) | 3.15 (2.28-3.15) | 3.02 (2.28-3.15) | | 4.62 | | |
| | Zero | 0 | | | | 0 | | |
| Pneumatic Device Count | High | 0.844 (0-1.33) | 1.13 (0-1.33) | 0.844 (0-1.33) | | 1.37 | | |
| | Intermittent | 0.868 (0.438-1.20) | 1.00 (0.438-1.20) | 0.868 (0.438-1.20) | | 1.19 | | |
| | Low | 0.871 (0-1.11) | 0.936 (0-1.11) | 0.871 (0-1.11) | | 0.336 | | |
| | Zero | 0.604 (0-0.990) | 0.137 (0-0.990) | 0.604 (0-0.990) | | 0 | | |

**Table B-2: Upstream Parameters for Midcontinent Regions (Central & North-Central) continued**

| Property (Units) | | Central | | | | North-Central | | |
|---|---|---|---|---|---|---|---|---|
| | | Conventional | CBM | Tight Gas | Shale | Conventional | Tight Gas | Shale |
| **Other Fugitive Emissions** | | | | | | | | |
| Mass Leak Rate (kg/device hr) | Connections | 0.000203 | 0.000206 | 0.000203 | | 0.000207 | | |
| | Flanges | 0.000396 | 0.000402 | 0.000396 | | 0.000403 | | |
| | OEL | 0.00203 | 0.00206 | 0.00203 | | 0.00207 | | |
| | Valves | 0.00457 | 0.00464 | 0.00457 | | 0.00465 | | |
| Device Count | Connections | 36.2 (35.0-47.9) | 36.7 (35.0-47.9) | 36.2 (35.0-47.9) | | 90.1 | | |
| | Flanges | 18.9 (18.0-25.4) | 19.5 (18.0-25.4) | 18.9 (18.0-25.4) | | 21.6 | | |
| | OEL | 5.86 (5.14-6.00) | 5.68 (5.14-6.00) | 5.86 (5.14-6.00) | | 2.27 | | |
| | Valves | 12.4 (12.0-14.6) | 12.8 (12.0-14.6) | 12.4 (12.0-14.6) | | 27.0 | | |
| Hours of Operation (hr/yr) | | 8,760 | | | | 8,760 | | |
| Regional Production Rate (bcf/yr): Used to scale fugitive emission factors[1] | | 0.130 (0.130-0.00521) | 5.68 (5.68-3.15) | 0.130 (0.130-0.00521) | | 0.0806 (0.129-0.0132) | | |

[1]Values are used for Other Fugitive Emissions as well as Pneumatic Device Venting.

**Table B-3: Upstream Parameters for Southern Regions (TX-LA-MS Salt, Gulf Coast, Fort Worth, West Texas-Permian)**

| Property (Units) | | TX-LA-MS Salt | | Gulf Coast | | Fort Worth | West Texas-Permian |
|---|---|---|---|---|---|---|---|
| | | Conventional | Tight Gas | Conventional | Tight Gas | Shale | Shale |
| **Natural Gas Source** | | | | | | | |
| Contribution to 2012 U.S. Domestic Supply | | 0.20% | 0.20% | 9.20% | 7.80% | 21.7% | 0.20% |
| EUR (Bcf) | Low | 1.81 | 1.39 | 1.81 | 0.44 | 4.40 | 2.27 |
| | Expected | 1.51 | 1.39 | 1.51 | 1.60 | 1.84 | 1.51 |
| | High | 1.21 | 1.39 | 1.21 | 2.36 | 0.551 | 0.757 |
| Weight Fraction : $CH_4$ | | 0.741 | | 0.731 | | 0.731 | 0.731 |
| Weight Fraction : $CO_2$ | | 0.0362 | | 0.0253 | | 0.0253 | 0.0253 |
| Weight Fraction : NMVOC | | 0.00719 | | 0.00787 | | 0.00787 | 0.00787 |
| Weight Fraction : $H_2S$ [1] | | 7.06E-06 | | 1.19E-05 | | 1.19E-05 | 1.19E-05 |
| **Land Use** | | | | | | | |
| Land Use Area ($m^2$/well life) | | 10,100 | 20,200 | 10,100 | 0 | 20,200 | 20,200 |
| Fraction of Land Use | Agriculture | 0.198 | | 0.222 | 0.221 | 0.223 | 0.0341 |
| | Forest | 0.725 | | 0.187 | 0.235 | 0.112 | 0.216 |
| | Grassland | 0.0770 | | 0.591 | 0.544 | 0.665 | 0.750 |

[1] Mass fractions may not add up to 100% due to the omission of the weight fraction of $N_2$

**Table B-3: Upstream Parameters for Southern Regions (TX-LA-MS Salt, Gulf Coast, Fort Worth, West Texas-Permian) continued**

| Property (Units) | TX-LA-MS Salt | | Gulf Coast | | Fort Worth | West Texas-Permian |
|---|---|---|---|---|---|---|
| | Conventional | Tight Gas | Conventional | Tight Gas | Shale | Shale |
| Flaring Activity (%) | 59% (94%-39%) | 65% (95%-39%) | 59% (94%-39%) | 65% (95%-39%) | 69% (95%-65%) | 69% (95%-65%) |
| **Well Construction & Completion** | | | | | | |
| Drill Depth (m) | 1,000 | 3,800 (2,590-4,880) | 1,000 | 3,800 (2,590-4,880) | 2,370 (2,070-2,660) | 2,370 (2,070-2,660) |
| HF Completion Flowback Period (days) | NA | 7.00 (3.00-10.0) | NA | 7.00 (3.00-10.0) | 7.00 (3.00-10.0) | 7.00 (3.00-10.0) |
| HF Initial production rate (scf/day) | | 1,010,000 (1,000,000-1,570,000) | | 33,000 (32,800-51,200) | 2,530,000 (1,410,000-4,200,000) | 2,080,000 (2,070,000-3,230,000) |
| Non-HF Completion Emissions (scf/episode) | 37,000 (3,700-370,000) | NA | 37,000 (3,700-370,000) | NA | NA | NA |
| **Natural Gas Extraction Well Workover** | | | | | | |
| Lifetime Workovers (Episodes/well) | 0.0750 (0.0600-0.0900) | 0.125 (0.100-0.150) | 0.0750 (0.0600-0.0900) | 0.125 (0.100-0.150) | 0.0750 (0.0600-0.0900) | 0.0750 (0.0600-0.0900) |
| Non-HF Workover Emissions (scf/episode) | 2,450 (245-24,500) | NA | 2,450 (245-24,500) | NA | NA | NA |
| HF Flowback Period (days) | NA | 7.00 (3.00-10.0) | NA | 7.00 (3.00-10.0) | 7.00 (3.00-10.0) | 7.00 (3.00-10.0) |

**Table B-3: Upstream Parameters for Southern Regions (TX-LA-MS Salt, Gulf Coast, Fort Worth, West Texas-Permian) continued**

| Property (Units) | TX-LA-MS Salt | | Gulf Coast | | Fort Worth | West Texas-Permian |
|---|---|---|---|---|---|---|
| | Conventional | Tight Gas | Conventional | Tight Gas | Shale | Shale |
| Wells Requiring Liquids Unloading | 10.4% | | 10.4% | | 14.2% | 14.2% |
| **Liquids Unloading: Plunger** | | | | | | |
| Well Depth (m) | 0 | 4,060 (2,590-4,880) | 0 | 4,060 (2,590-4,880) | 2,630 (2,070-2,660) | 2,630 (2,070-2,660) |
| Tubing: Internal Diameter (in) | 0 | 2.38 | 0 | 2.38 | 2.02 (2.00-2.38) | 2.02 (2.00-2.38) |
| Shut-in or Surface Pressure (psia) | 0 | 484 (29.7-555) | 0 | 484 (29.7-555) | 509 (125-531) | 509 (125-531) |
| Average Flow-line Rate (scf/hr) | 0 | 258,000 (3,460-354,000) | 0 | 258,000 (3,460-354,000) | 59,300 (1,040-62,500) | 59,300 (1,040-62,500) |
| Unloading Event duration (hrs) | 0 | 0.672 (0.300-2.00) | 0 | 0.672 (0.300-2.00) | 0.484 (0.200-0.500) | 0.484 (0.200-0.500) |
| Total Unloading Events (events/well life) | 0 | 2.36 (1.00-52.0) | 0 | 2.36 (1.00-52.0) | 1.37 (1.00-1.39) | 1.37 (1.00-1.39) |
| Production from Wells with Plunger Lifts | 0% | 24.3% | 0% | 24.3% | 24.8% | 24.8% |
| **Liquids Unloading: No Plunger** | | | | | | |
| Well Depth (m) | 4,540 (3,050-5,890) | 4,080 (1,830-4,880) | 4,540 (3,050-5,890) | 4,080 (1,830-4,880) | 2,660 (2,440-4,570) | 2,660 (2,440-4,570) |
| Casing: Internal Diameter (in) | 4.53 (3.65-5.50) | 9.04 (4.50-10.8) | 4.53 (3.65-5.50) | 9.04 (4.50-10.8) | 9.62 (5.00-9.63) | 9.62 (5.00-9.63) |
| Shut-in or Surface Pressure (psia) | 163 (79.9-239) | 521 (29.7-555) | 163 (79.9-239) | 521 (29.7-555) | 530 (64.7-531) | 530 (64.7-531) |
| Average Flow-line Rate (scf/hr) | 20,500 (12,500-27,700) | 280,000 (1,040-354,000) | 20,500 (12,500-27,700) | 280,000 (1,040-354,000) | 62,400 (500-62,500) | 62,400 (500-62,500) |
| Unloading Event Duration (hrs) | 1.79 (1.00-2.50) | 1.36 (0.688-5.30) | 1.79 (1.00-2.50) | 1.36 (0.688-5.30) | 1.01 (0.500-6.67) | 1.01 (0.500-6.67) |
| Total Unloading Events (events/well life) | 10.9 (10.0-12.0) | 1.56 (0.600-52.0) | 10.9 (10.0-12.0) | 1.56 (0.600-52.0) | 0.968 (0.333-1.00) | 0.968 (0.333-1.00) |

**Table B-3: Upstream Parameters for Southern Regions (TX-LA-MS Salt, Gulf Coast, Fort Worth, West Texas-Permian) continued**

| Property (Units) | | TX-LA-MS Salt | | Gulf Coast | | Fort Worth | West Texas-Permian |
|---|---|---|---|---|---|---|---|
| | | Conventional | Tight Gas | Conventional | Tight Gas | Shale | Shale |
| **Pneumatic Device Venting** | | | | | | | |
| Pneumatic Vent Rate (scf/hr) | High | 32.1 (32.1-37.3) | | 32.1 | | 32.1 | 32.1 |
| | Intermittent | 8.58 (8.58-13.5) | | 8.58 | | 8.58 | 8.58 |
| | Low | 3.15 (1.39-3.15) | | 3.15 | | 3.15 | 3.15 |
| | Zero | 0 | | 0 | | 0 | 0 |
| Pneumatic Device Count | High | 0.845 (0.318-1.33) | | 0.159 (0.110-1.33) | | 0.180 (0.180-1.33) | 0.0600 (0.0600-3.00) |
| | Intermittent | 0.421 (0-0.717) | | 2.26 (0.717-2.32) | | 1.09 (0.717-1.09) | 0.910 (0-0.91) |
| | Low | 0.585 (0.206-1.00) | | 0.975 (0.865-0.980) | | 2.40 (0.865-2.40) | 0.220 (0-0.865) |
| | Zero | 0.198 (0-0.330) | | 0.330 | | 0.330 | 0.0000128 (0–0.330) |

**Table B-3: Upstream Parameters for Southern Regions (TX-LA-MS Salt, Gulf Coast, Fort Worth, West Texas-Permian) continued**

| Property (Units) | | TX-LA-MS Salt | | Gulf Coast | | Fort Worth | West Texas-Permian |
|---|---|---|---|---|---|---|---|
| | | Conventional | Tight Gas | Conventional | Tight Gas | Shale | Shale |
| **Other Fugitive Emissions** | | | | | | | |
| Mass Leak Rate (kg/device hr) | Connections | 0.000208 | | 0.000205 | | 0.000205 | 0.000209 |
| | Flanges | 0.000405 | | 0.000400 | | 0.000400 | 0.000408 |
| | OEL | 0.00208 | | 0.00205 | | 0.00205 | 0.00209 |
| | Valves | 0.00467 | | 0.00462 | | 0.00462 | 0.00471 |
| Device Count | Connections | 37.4 (35.0-39.1) | | 39.1 | | 39.1 | 42.5 (39.1-42.5) |
| | Flanges | 20.2 (18.0-21.7) | | 21.7 | | 21.7 | 29.0 (21.7-29.0) |
| | OEL | 5.54 (5.23-6.00) | | 5.23 | | 5.23 | 3.00 (3.00-5.23) |
| | Valves | 13.1 (12.0-13.8) | | 13.8 | | 13.8 | 18.5 (13.8-18.5) |
| Hours of Operation (hr/yr) | | 8,760 | | 8,760 | | 8,760 | 8,760 |
| Regional Production Rate (Bcf/yr): Used to scale fugitive emission factors[1] | | 0.406 (0.406-0.0661) | | 0.190 (0.240-0.0646) | | 0.165 (0.165-0.0625) | 0.0667 (0.0741-0.0181) |

[1]Values are used for Other Fugitive Emissions as well as Pneumatic Device Venting.

**Table B-4: Upstream Parameters for Western Regions (Rocky Mountains, West Coast, & Alaska)**

| Property (Units) | | Rocky Mountains | | | | West Coast | | Alaska |
|---|---|---|---|---|---|---|---|---|
| | | Conventional | CBM | Tight Gas | Shale | Conventional | Shale | Conventional |
| **Natural Gas Source** | | | | | | | | |
| Contribution to 2012 U.S. Domestic Supply | | 4.6% | 4.7% | 10.3% | 0.90% | 0.40% | 0.20% | 0.30% |
| EUR (Bcf) | Low | 1.81 | 2.74 | 0.24 | 1.33 | 1.81 | 2.10 | 1.81 |
| | Expected | 1.51 | 2.19 | 0.82 | 0.888 | 1.51 | 1.40 | 1.51 |
| | High | 1.21 | 1.64 | 4.1 | 0.444 | 1.21 | 0.700 | 1.21 |
| Weight Fraction : $CH_4$ | | 0.691 | 0.820 | 0.691 | | 0.672 | | 0.672 |
| Weight Fraction : $CO_2$ | | 0.0473 | 0.124 | 0.0473 | | 0.0327 | | 0.0327 |
| Weight Fraction : NMVOC | | 0.00711 | 0.00178 | 0.00711 | | 0.00990 | | 0.00990 |
| Weight Fraction : $H_2S$ [1] | | 2.38E-03 | 1.71E-04 | 2.38E-03 | | 1.18E-05 | | 1.18E-05 |
| **Land Use** | | | | | | | | |
| Land Use Area ($m^2$/well life) | | 10,100 | 1,000 | 0.00 | 20,200 | 10,100 | 20,200 | 10,100 |
| Fraction of Land Use | Agriculture | 0.0819 | 0.0864 | 0.0819 | 0.194 | 0.149 | | 0.0045 |
| | Forest | 0.223 | 0.225 | 0.223 | 0.312 | 0.422 | 0.421 | 0.702 |
| | Grassland | 0.695 | 0.688 | 0.695 | 0.494 | 0.430 | | 0.294 |

[1] Mass fractions may not add up to 100% due to the omission of the weight fraction of $N_2$

**Table B-4: Upstream Parameters for Western Regions (Rocky Mountains, West Coast, & Alaska) continued**

| Property (Units) | Rocky Mountains | | | | West Coast | | Alaska |
|---|---|---|---|---|---|---|---|
| | Conventional | CBM | Tight Gas | Shale | Conventional | Shale | Conventional |
| Flaring Activity (%) | 59% (94%-39%) | 69% (95%-39%) | 65% (95%-39%) | 46% (51%-43%) | 59% (94%-39%) | 69% (95%-65%) | 47% (53%-41%) |
| **Well Construction & Completion** | | | | | | | |
| Drill Depth (m) | 1,000 | 3,150 (2,260-3,400) | | | 1,000 | 3,150 (2,260-3,400) | 2,000 |
| HF Completion Flowback Period (days) | NA | | 7.00 (3.00-10.0) | | NA | 7.00 3.00-10.0) | NA |
| HF Initial Production Rate (scf/day) | | | 125,000 (124,000-194,000) | 1,220,000 (1,210,000-1,890,000) | | 1,930,000 (1,910,000-2,990,000) | |
| Non-HF Completion Emissions (scf/episode) | 37,000 (3,700-370,000) | 49,600 (4,960-496,000) | NA | | 37,000 (3,700-370,000) | NA | 37,000 (3,700-370,000) |
| **Natural Gas Extraction Well Workover** | | | | | | | |
| Lifetime Workovers (Episodes/well) | 0.0750 (0.0600-0.0900) | 0.125 (0.100-0.150) | 0.750 (0.600-0.900) | | 0.750 (0.600-0.900) | | 0.750 (0.600-0.900) |
| Non-HF Workover Emissions (scf/episode) | 2,450 (245-24,500) | 49,600 (4,960-496,000) | NA | | 2,450 (245-24,500) | NA | 2,450 (245-24,500) |
| HF Flowback Period (days) | NA | | 7.00 (3.00-10.0) | | NA | 7.00 (3.00-10.0) | NA |

**Table B-4: Upstream Parameters for Western Regions (Rocky Mountains, West Coast, & Alaska) continued**

| Property (Units) | Rocky Mountains | | | | West Coast | | Alaska |
|---|---|---|---|---|---|---|---|
| | Conventional | CBM | Tight Gas | Shale | Conventional | Shale | Conventional |
| Wells Requiring Liquids Unloading | 10.4% | 29.4% | | | 10.4% | 29.4% | 10.4% |
| **Liquids Unloading: Plunger** | | | | | | | |
| Well Depth (m) | 0 | 3,180 (2,260-3,400) | | | 0 | 3,180 (2,260-3,400) | 0 |
| Tubing: Internal Diameter (in) | 0 | 2.30 (1.92-2.38) | | | 0 | 2.30 (1.92-2.38) | 0 |
| Shut-in or Surface Pressure (psia) | 0 | 249 (165-305) | | | 0 | 249 (165-305) | 0 |
| Average Flow-line Rate (scf/hr) | 0 | 13,200 (1,920-18,900) | | | 0 | 13,200 (1,920-18,900) | 0 |
| Unloading Event Duration (hrs) | 0 | 1.53 (0.407-2.10) | | | 0 | 1.53 (0.407-2.10) | 0 |
| Total Unloading Events (events/well life) | 0 | 16.2 (2.24-1,152) | | | 0 | 16.2 (2.24-1,150) | 0 |
| Production from Wells with Plunger Lifts | 0% | 90.3% | | | 0% | 90.3% | 0% |
| **Liquids Unloading: No Plunger** | | | | | | | |
| Well Depth (m) | 4,540 (3,050-5,890) | 3,390 (3,310-3,540) | | | 4,540 (3,050-5,890) | 3,390 (3,310-3,540) | 4,543 (3,048-5,893) |
| Casing: Internal Diameter (in) | 4.53 (3.65-5.50) | 4.11 (2.38-4.70) | | | 4.53 (3.65-5.50) | 4.11 (2.38-4.70) | 4.53 (3.65-5.50) |
| Shut-in or Surface Pressure (psia) | 163 (79.9-239) | 261 (213-491) | | | 163 (79.9-239) | 261 (213-491) | 163 (79.9-239) |
| Average Flow-line Rate (scf/hr) | 20,500 (12,500-27,700) | 5,630 (1,730-18,000) | | | 20,500 (12,500-27,700) | 5,630 (1,730-18,000) | 20,500 (12,500-27,700) |
| Unloading Event Duration (hrs) | 1.79 (1.00-2.50) | 1.77 (0.750-3.18) | | | 1.79 (1.00-2.50) | 1.77 (0.750-3.18) | 1.79 (1.00-2.50) |
| Total Unloading Events (events/well life) | 10.9 (10.0-12.0) | 68.1 (2.00-378) | | | 10.9 (10.0-12.0) | 68.1 (2.00-378) | 10.9 (10.0-12.0) |

**Table B-4: Upstream Parameters for Western Regions (Rocky Mountains, West Coast, & Alaska) continued**

| Property (Units) | | Rocky Mountain | | | | West Coast | | Alaska |
|---|---|---|---|---|---|---|---|---|
| | | Conventional | CBM | Tight Gas | Shale | Conventional | Shale | Conventional |
| **Pneumatic Device Venting** | | | | | | | | |
| Pneumatic Vent Rate (scf/hr) | High | 27.8 (0-38.9) | 37.2 (0-38.9) | 27.8 (0-38.9) | | 37.3 | | 37.3 |
| | Intermittent | 8.37 (0-23.7) | 13.9 (0-23.7) | 8.37 (0-23.7) | | 13.5 | | 13.5 |
| | Low | 1.99 (0.313-6.00) | 1.26 (0.313-6.00) | 1.99 (0.313-6.00) | | 1.39 | | 1.39 |
| | Zero | 0 | | | | 0 | | 0 |
| Pneumatic Device Count | High | 0.829 (0-4.75) | 0.575 (0-4.75) | 0.829 (0-4.75) | | 0.458 | | 0.458 |
| | Intermittent | 0.140 (0-1.19) | 0.296 (0-1.19) | 0.140 (0-1.19) | | 0.247 | | 0.247 |
| | Low | 2.68 (0.336-5.27) | 1.61 (0.336-5.27) | 2.68 (0.336-5.27) | | 0.297 | | 0.297 |
| | Zero | 0.111 (0-0.495) | 0.0649 (0-0.495) | 0.111 (0-0.495) | | 0.330 | | 0.330 |

**Table B-4: Upstream Parameters for Western Regions (Rocky Mountains, West Coast, & Alaska) continued**

| Property (Units) | | Rocky Mountain | | | | West Coast | | Alaska |
|---|---|---|---|---|---|---|---|---|
| | | Conventional | CBM | Tight Gas | Shale | Conventional | Shale | Conventional |
| **Other Fugitive Emissions** | | | | | | | | |
| Mass Leak Rate (kg/device hr) | Connections | 0.000210 | 0.000228 | 0.000210 | | 0.000207 | | 0.000200 |
| | Flanges | 0.000410 | 0.000445 | 0.000410 | | 0.000403 | | 0.000390 |
| | OEL | 0.00210 | 0.00228 | 0.00210 | | 0.00207 | | 0.00200 |
| | Valves | 0.00474 | 0.00514 | 0.00474 | | 0.00465 | | 0.00450 |
| Device Count | Connections | 47.5 (8.90-90.1) | 30.1 (13.1-90.1) | 47.5 (8.90-90.1) | | 39.1 | | 39.1 |
| | Flanges | 38.1 (0.592-143) | 20.6 (0.592-143) | 38.1 (0.592-143) | | 21.7 | | 21.7 |
| | OEL | 7.26 (0.237-31.0) | 2.35 (0.000267-31.0) | 7.26 (0.237-31.0) | | 5.23 | | 5.23 |
| | Valves | 29.6 (8.98-85.8) | 13.3 (8.98-85.8) | 29.6 (8.98-85.8) | | 13.8 | | 13.8 |
| Hours of Operation (hr/yr) | | 8,760 (7,250-8,760) | | | | 8,760 | | 8,760 |
| Regional Production Rate (scf/yr): Used to scale fugitive emission factors [1] | | 0.134 (0.134-0.0429) | 261 (314-121) | 0.134 (0.134-0.0429) | | 0.144 (0.144-0.0412) | | 0.144 (0.144-0.0412) |

[1] Values are used for Other Fugitive Emissions as well as Pneumatic Device Venting.

**Table B-5: Upstream Parameters for Offshore Regions (Alaska Offshore, Gulf of Mexico Offshore, Pacific Offshore)**

| Property (Units) | | Alaska Offshore | Gulf of Mexico Offshore | Pacific Offshore |
|---|---|---|---|---|
| | | Offshore | Offshore | Offshore |
| **Natural Gas Source** | | | | |
| Contribution to 2012 U.S. Domestic Supply | | 0.10% | 4.6% | 0.060% |
| EUR (Bcf) | Low | 23.1 | 23.1 | 23.1 |
| | Expected | 19.3 | 19.3 | 19.3 |
| | High | 15.4 | 15.4 | 15.4 |
| Weight Fraction : $CH_4$ | | 0.672 | 0.731 | 0.672 |
| Weight Fraction : $CO_2$ | | 0.0327 | 0.0253 | 0.0327 |
| Weight Fraction : NMVOC | | 0.00990 | 0.00787 | 0.00990 |
| Weight Fraction : $H_2S$ [1] | | 1.18E-05 | 1.19E-05 | 1.18E-05 |
| **Land Use** | | | | |
| Land Use Area ($m^2$/well life) | | 0 | 0 | 0 |
| Fraction of Land Use | Agriculture | 0 | 0 | 0 |
| | Forest | 0 | 0 | 0 |
| | Grassland | 0 | 0 | 0 |

[1] Mass fractions may not add up to 100% due to the omission of the weight fraction of $N_2$

**Table B-5: Upstream Parameters for Offshore Regions (Alaska Offshore, Gulf of Mexico Offshore, Pacific Offshore) continued**

| Property (Units) | Alaska Offshore | Gulf of Mexico Offshore | Pacific Offshore |
|---|---|---|---|
| | Offshore | Offshore | Offshore |
| Flaring Activity (%) | 47%<br>(53%-41%) | 44%<br>(53%-39%) | 44%<br>(53%-39%) |
| **Well Construction & Completion** | | | |
| Drill Depth (m) | 2,000 | 2,000 | 2,000 |
| Completion Emissions (scf/episode) | 37,000<br>(3,700-370,000) | 37,000<br>(3,700-370,000) | 37,000<br>(3,700-370,000) |
| **Natural Gas Extraction Well Workover** | | | |
| Lifetime Workovers (Episodes/well) | 0.0750<br>(0.0600-0.0900) | 0.0750<br>(0.0600-0.0900) | 0.0750<br>(0.0600-0.0900) |
| Workover Emissions (scf/episode) | 2,450<br>(245-24,500) | 2,450<br>(245-24,500) | 2,450<br>(245-24,500) |
| **Extraction: Venting Other Point Source** | | | |
| Point Source Emission Factor (fraction of *potential* NG emissions per unit of NG produced) | 0.0000708 | 0.0000651 | 0.0000708 |
| Flaring Activity (%) | 100% | 100% | 100% |
| **Extraction: Venting Other Fugitives** | | | |
| Fugitives Emission Factor (fraction of NG emissions per unit of NG produced) | 0.00354 | 0.00326 | 0.00354 |

**Table B-6: Upstream Parameters for National Associated Gas, Gas Injection**

| Gas Injection | | | | | |
|---|---|---|---|---|---|
| **Properties** | **Data Source** | **Heater Treater** | **Stabilizer** | **Both** | **None** |
| API Gravity (degree API) | Nehring Database | 13.4 (9.30 -17.9) | 32.6 (24.0-45.0) | 16.5 (10.0-18.0) | 29.8 (20.0-43.2) |
| EUR (bbl) | OPGEE Default | 130,000 | 130,000 | 130,000 | 130,000 |
| Field Age (yr) | | 35.0 | 35.0 | 35.0 | 35.0 |
| Flare Rate (scf/bbl) | | 16.2 | 16.2 | 16.2 | 16.2 |
| Productivity Index | | 3.00 | 3.00 | 3.00 | 3.00 |
| Production Volume (bbl/day) | Nehring Database | 86,900,000 (101,000,000-657,000) | 61,500,000 (20,700,000-351,000) | 16,600,000 (22,400,000-511,000) | 70,900,000 (16,600,000-398,000) |
| Well Depth (m) | | 235 (126-1,900) | 2,790 (859-4,240) | 1,940 (394-3,820) | 1,620 (600-3,480) |
| Reservoir Pressure (psi) | | 290 (1,440-150) | 3,280 (6530-910) | 1,420 (6,010-264) | 1,480 (3,330-639) |
| Gas Oil Ratio (scf/bbl) | | 67.0 (1.09-414) | 2,630 (598-14,400) | 1,490 (520-2,520) | 231 (12.9-461) |
| Steam Oil Ratio (bbl steam/bbl oil) | OPGEE Default | 3.00 | 3.00 | 3.00 | 3.00 |
| Water Oil Ratio (bbl water/bbl oil) | ARI Database | 9.95 | 9.95 | 9.95 | 9.95 |

**Table B-7: Upstream Parameters for National Associated Gas, Steam Injection**

| Steam Injection | | | | | |
|---|---|---|---|---|---|
| **Properties** | **Data Source** | **Heater Treater** | **Stabilizer** | **Both** | **None** |
| API Gravity (degree API) | Nehring Database | 13.4 (9.30-17.9) | 32.6 (24-45.0) | 16.5 (10.0-18.0) | 29.8 (20.0-43.2) |
| EUR (bbl) | OPGEE Default | 130,000 | 130,000 | 130,000 | 130,000 |
| Field Age (yr) | | 35.0 | 35.0 | 35.0 | 35.0 |
| Flare Rate (scf/bbl) | | 16.2 | 16.2 | 16.2 | 16.2 |
| Productivity Index | | 3.00 | 3.00 | 3.00 | 3.00 |
| Production Volume (bbl/day) | Nehring Database | 86,900,000 (101,000,000-657,000) | 61,500,000 (20,700,000-351,000) | 16,620,000 (22,400,000-511,000) | 70,900,000 (16,600,000-398,000) |
| Well Depth (m) | | 235 (126-1,900) | 2,790 (859-4,290) | 1,940 (394-3,820) | 1,620 (600-3,480) |
| Reservoir Pressure (psi) | | 290 (1,440-151) | 3,280 (6,530-910) | 1,420 (6,010-264) | 1,480 (3,330-639) |
| Gas Oil Ratio (scf/bbl) | | 67.0 (414-1.09) | 2,630 (14,400-598) | 1,486 (2,520-520) | 231 (461-12.9) |
| Steam Oil Ratio (bbl water/bbl oil) | OPGEE Default | 3.00 | 3.00 | 3.00 | 3.00 |
| Water Oil Ratio (bbl water/bbl oil) | ARI Database | 9.95 | 9.95 | 9.95 | 9.95 |

**Table B-8: Upstream Parameters for National Associated Gas, Water Injection**

| Water Injection | | | | | |
|---|---|---|---|---|---|
| **Properties** | **Data Source** | **Heater Treater** | **Stabilizer** | **Both** | **None** |
| API Gravity (degree API) | Nehring Database | 13.4 (9.30-17.9) | 32.6 (24.0-45.0) | 16.5 (10.0-18.0) | 29.8 (20.0-43.2) |
| EUR (bbl) | OPGEE Default | 130,000 | 130,000 | 130,000 | 130,000 |
| Field Age (yr) | | 35.0 | 35.0 | 35.0 | 35.0 |
| Flare Rate (scf/bbl) | | 16.2 | 16.2 | 16.2 | 16.2 |
| Productivity Index | | 3.00 | 3.00 | 3.00 | 3.00 |
| Production Volume (bbl/day) | Nehring Database | 86,900,000 (101,000,000-657,000) | 61,500,000 (20,700,000-351,000) | 16,600,000 (22,400,000-511,000) | 70,900,000 (16,600,000-398,000) |
| Well Depth (m) | | 235 (126-1,900) | 2,790 (859-4,290) | 1,940 (394-3,820) | 1,620 (600-3,480) |
| Reservoir Pressure (psi) | | 290 (1,440-151) | 3,280 (6,530-910) | 1,420 (6,010-264) | 1,480 (3,330-639) |
| Gas Oil Ratio (scf/bbl) | | 67.0 (414-1.09) | 2,630 (14,400-598) | 1,490 (2,520-520) | 231 (461-12.9) |
| Steam Oil Ratio (bbl steam/bbl oil) | OPGEE Default | 3.00 | 3.00 | 3.00 | 3.00 |
| Water Oil Ratio (bbl water/bbl oil) | ARI Database | 9.95 | 9.95 | 9.95 | 9.95 |

# Appendix C:
# GHG and Non-GHG Emissions Data for Natural Gas Systems

## Tables

Table C-1: Upstream Cradle-to-gate Natural Gas GHG Emissions Data by Source..... C-2
Table C-2: Expanded Greenhouse Gas Data for Appalachian Shale Gas ..... C-4
Table C-3: Expanded Greenhouse Gas Data for the Next Appalachian Shale Gas Well..... C-5
Table C-4: Life Cycle GHG Emissions for Electricity Production from Natural Gas ..... C-6
Table C-5: Upstream Cradle-to-gate Natural Gas Non-GHG Emissions to Air by Source..... C-7
Table C-6: Upstream Cradle-to-gate Natural Gas Non-GHG Emissions to Water by Source . C-12
Table C-7: Life Cycle Non-GHG Emissions to Air for Electricity Production from Natural Gas ..... C-17
Table C-8: Life Cycle Non-GHG Emissions to Water for Electricity Production from Natural Gas ..... C-20

**Table C-1: Upstream Cradle-to-gate Natural Gas GHG Emissions Data by Source**

| Region | kg $CO_2e$/MJ delivered | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | GWP | Mean | 25th Percentile | 75th Percentile | 5th Percentile | 50th Percentile | 95th Percentile | Minimum | Maximum |
| Alaska | 100 | 10.9 | 10.6 | 11.2 | 10.3 | 10.9 | 11.7 | 9.7 | 13.3 |
| | 20 | 22.1 | 21.4 | 22.7 | 20.7 | 22.0 | 23.9 | 19.8 | 26.6 |
| Alaska Offshore | 100 | 10.9 | 10.7 | 11.2 | 10.4 | 10.9 | 11.5 | 10.2 | 11.7 |
| | 20 | 22.4 | 21.9 | 22.9 | 21.2 | 22.4 | 23.5 | 20.7 | 24.0 |
| Appalachian | 100 | 14.3 | 13.6 | 14.9 | 13.0 | 14.2 | 16.1 | 12.3 | 18.9 |
| | 20 | 29.5 | 27.9 | 30.5 | 26.4 | 29.1 | 33.6 | 24.2 | 58.1 |
| Black Warrior | 100 | 12.1 | 11.7 | 12.4 | 11.2 | 12.0 | 13.3 | 10.4 | 16.6 |
| | 20 | 22.2 | 21.5 | 22.9 | 20.5 | 22.2 | 23.9 | 18.4 | 25.5 |
| Central | 100 | 15.6 | 14.4 | 16.5 | 13.4 | 15.4 | 18.6 | 12.2 | 23.9 |
| | 20 | 32.3 | 29.5 | 34.4 | 27.4 | 31.6 | 40.0 | 25.0 | 53.7 |
| Fort Worth | 100 | 13.1 | 12.2 | 13.6 | 11.5 | 12.8 | 15.5 | 10.7 | 23.9 |
| | 20 | 26.1 | 24.3 | 27.2 | 22.8 | 25.6 | 30.8 | 20.8 | 48.1 |
| Gulf of Mexico Offshore | 100 | 10.9 | 10.7 | 11.2 | 10.4 | 10.9 | 11.5 | 10.2 | 11.7 |
| | 20 | 22.4 | 21.9 | 22.9 | 21.2 | 22.4 | 23.5 | 20.7 | 24.0 |
| Gulf Coast | 100 | 11.1 | 10.8 | 11.4 | 10.5 | 11.1 | 11.8 | 10.0 | 12.6 |
| | 20 | 22.4 | 21.8 | 23.0 | 21.1 | 22.4 | 24.0 | 19.9 | 27.2 |
| Illinois-Michigan | 100 | 21.8 | 19.0 | 24.2 | 16.9 | 21.2 | 28.5 | 14.3 | 38.2 |
| | 20 | 47.5 | 41.3 | 52.2 | 34.9 | 46.2 | 63.5 | 30.6 | 82.7 |
| North-Central | 100 | 26.6 | 22.7 | 29.3 | 19.6 | 25.5 | 36.8 | 16.5 | 60.8 |
| | 20 | 57.7 | 48.4 | 64.1 | 41.0 | 55.0 | 82.6 | 33.6 | 134.8 |
| Pacific Offshore | 100 | 10.9 | 10.7 | 11.2 | 10.4 | 10.9 | 11.5 | 10.2 | 11.7 |
| | 20 | 22.4 | 21.9 | 22.9 | 21.2 | 22.4 | 23.5 | 20.7 | 24.1 |
| Rocky Mountains | 100 | 18.6 | 16.1 | 20.2 | 14.3 | 18.0 | 25.0 | 12.7 | 34.4 |
| | 20 | 40.2 | 34.4 | 44.3 | 29.8 | 38.6 | 56.4 | 26.0 | 80.2 |
| TX-LA-MS Salt | 100 | 11.8 | 11.5 | 12.0 | 11.1 | 11.8 | 12.4 | 10.7 | 13.0 |
| | 20 | 23.2 | 22.6 | 23.8 | 21.8 | 23.2 | 24.6 | 20.2 | 26.2 |
| West Coast | 100 | 14.3 | 13.0 | 15.2 | 12.1 | 13.9 | 18.0 | 10.7 | 25.5 |
| | 20 | 29.5 | 26.2 | 31.7 | 24.2 | 28.4 | 38.5 | 22.1 | 59.8 |
| West Texas-Permian | 100 | 16.1 | 14.3 | 17.4 | 12.9 | 15.7 | 20.7 | 11.0 | 28.0 |
| | 20 | 33.0 | 28.8 | 36.1 | 25.5 | 31.9 | 44.2 | 22.1 | 67.4 |

**Table C-1: Upstream Cradle-to-gate Natural Gas GHG Emissions Data by Source, continued**

| Region | kg $CO_2e$/MJ delivered | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | GWP | Mean | 25th Percentile | 75th Percentile | 5th Percentile | 50th Percentile | 95th Percentile | Minimum | Maximum |
| National Associated | 100 | 16.7 | 14.3 | 18.8 | 12.9 | 16.2 | 22.3 | 11.8 | 24.8 |
| | 20 | 31.5 | 26.8 | 35.4 | 24.2 | 30.5 | 41.9 | 23.6 | 46.8 |
| National Mix | 100 | 14.8 | 14.2 | 15.2 | 13.6 | 14.6 | 16.3 | 12.7 | 18.7 |
| | 20 | 30.4 | 29.0 | 31.5 | 27.7 | 30.1 | 33.9 | 26.1 | 39.3 |

**Table C-2: Expanded Greenhouse Gas Data for Appalachian Shale Gas**

| Stage & Process | | | kg $CO_2e$/MJ delivered | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Mean $CO_2$ | Mean $CH_4$ | Mean $N_2O$ | Mean GWP | 5th GWP | 95th GWP |
| Total (Cradle-to-gate) | | | 3.63 | 11.9 | 0.00699 | 15.5 | 13.7 | 18.1 |
| Distribution | | | 0.00151 | 2.60 | 0 | 2.60 | 2.60 | 2.60 |
| Transport | | Operation | 0.408 | 3.32 | 0.00309 | 3.73 | 3.22 | 4.23 |
| | | Construction/Installation | 0.111 | 0.00314 | 0.00165 | 0.116 | 0.116 | 0.116 |
| Processing | Fugitives | Compression | 1.839 | 0.0377 | 0 | 1.88 | 1.87 | 1.88 |
| | | Other | 0.000276 | 0.476 | 0 | 0.476 | 0.476 | 0.477 |
| | | Other Point Sources | 0.0380 | 0.00425 | 0.00000899 | 0.0423 | 0.0422 | 0.0424 |
| | | Pneumatics | 0.00000212 | 0.00366 | 0 | 0.00366 | 0.00365 | 0.00367 |
| | | Dehydration | 0.00878 | 0.0000832 | 0.0000127 | 0.00887 | 0.00886 | 0.00889 |
| | | Liquids Separation | 0.144 | 0.0110 | 0.000643 | 0.156 | 0.156 | 0.156 |
| | | Sweetening | 0.147 | 0.0125 | 0.0000368 | 0.159 | 0.159 | 0.160 |
| Extraction | Water use | Process | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Water Delivery | 0.0516 | 0.00239 | 0.000307 | 0.0543 | 0.0542 | 0.0544 |
| | | Crystallization | 0.0296 | 0.00206 | 0.000115 | 0.0318 | 0.0318 | 0.0319 |
| | | WWTP | 0.00722 | 0.000441 | 0.000323 | 0.00798 | 0.00797 | 0.00800 |
| | LU | Plunger | 0.000264 | 0.195 | 0 | 0.196 | 0.0407 | 0.534 |
| | | No Plunger | 0.00127 | 0.939 | 0 | 0.940 | 0.939 | 0.942 |
| | Fugitives | Other | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Other Point Sources | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Condensate Tank | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Produced Water Tank | 0.000728 | 0.744 | 0 | 0.745 | 0.744 | 0.747 |
| | | Pneumatics | 0.000715 | 0.529 | 0 | 0.529 | 0.107 | 1.40 |
| | | Valves | 0.0000306 | 0.0226 | 0 | 0.0227 | 0.00584 | 0.0564 |
| | | Open-Ended Lines | 0.00000377 | 0.00279 | 0 | 0.00279 | 0.000642 | 0.00744 |
| | | Flanges | 0.00000274 | 0.00202 | 0 | 0.00203 | 0.000315 | 0.00525 |
| | | Connections | 0.00000388 | 0.00287 | 0 | 0.00288 | 0.000732 | 0.00747 |
| | | Workovers | 0.0418 | 0.208 | 0.00000949 | 0.250 | 0.130 | 0.413 |
| | | Completion | 0.558 | 2.77 | 0.000127 | 3.33 | 1.82 | 5.47 |
| | | Land Use | 0.176 | 0 | 0 | 0.176 | 0.125 | 0.255 |
| | | Well Construction | 0.0669 | 0.00232 | 0.000665 | 0.0698 | 0.0399 | 0.110 |

**Table C-3: Expanded Greenhouse Gas Data for the Next Appalachian Shale Gas Well**

| Stage & Process | | | kg $CO_2e$/MJ delivered | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Mean $CO_2$ | Mean $CH_4$ | Mean $N_2O$ | Mean GWP | 5th GWP | 95th GWP |
| Total (Cradle-to-gate) | | | 3.76 | 8.20 | 0.00679 | 12.0 | 11.1 | 13.4 |
| Distribution | | | 0.00151 | 2.60 | 0 | 2.60 | 2.60 | 2.60 |
| Transport | | Operation | 0.408 | 3.32 | 0.00309 | 3.73 | 3.22 | 4.23 |
| | | Construction/Installation | 0.111 | 0.00314 | 0.00165 | 0.116 | 0.116 | 0.116 |
| Processing | Fugitives | Compression | 1.84 | 0.0377 | 0 | 1.88 | 1.87 | 1.88 |
| | | Other | 0.000276 | 0.476 | 0 | 0.476 | 0.476 | 0.477 |
| | | Other Point Sources | 0.0380 | 0.00425 | 0.00000899 | 0.0423 | 0.0422 | 0.0424 |
| | | Pneumatics | 0.00000212 | 0.00366 | 0 | 0.00366 | 0.00365 | 0.00367 |
| | | Dehydration | 0.00878 | 0.0000832 | 0.0000127 | 0.00887 | 0.00886 | 0.00889 |
| | | Liquids Separation | 0.144 | 0.0110 | 0.000643 | 0.156 | 0.156 | 0.156 |
| | | Sweetening | 0.147 | 0.0125 | 0.0000368 | 0.159 | 0.159 | 0.160 |
| Extraction | Water use | Process | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Water Delivery | 0.0516 | 0.00239 | 0.000307 | 0.0543 | 0.0542 | 0.0544 |
| | | Crystallization | 0.0296 | 0.00206 | 0.000115 | 0.0318 | 0.0318 | 0.0319 |
| | | WWTP | 0.00722 | 0.000441 | 0.000323 | 0.00798 | 0.00797 | 0.008 |
| | LU | Plunger | 0.000478 | 0.354 | 0 | 0.354 | 0.0736 | 0.966 |
| | | No Plunger | 0 | 0 | 0 | 0 | 0 | 0 |
| | Fugitives | Other | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Other Point Sources | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Condensate Tank | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Produced Water Tank | 0.000728 | 0.744 | 0 | 0.745 | 0.744 | 0.747 |
| | | Pneumatics | 0.000715 | 0.529 | 0 | 0.529 | 0.107 | 1.40 |
| | | Valves | 0.0000306 | 0.0226 | 0 | 0.0227 | 0.00584 | 0.0564 |
| | | Open-Ended Lines | 0.00000377 | 0.00279 | 0 | 0.00279 | 0.000642 | 0.00744 |
| | | Flanges | 0.00000274 | 0.00202 | 0 | 0.00203 | 0.000315 | 0.00525 |
| | | Connections | 0.00000388 | 0.00287 | 0 | 0.00288 | 0.000732 | 0.00747 |
| | | Workovers | 0.0568 | 0.00489 | 0.0000130 | 0.0617 | 0.0357 | 0.089 |
| | | Completion | 0.756 | 0.0651 | 0.000173 | 0.822 | 0.496 | 1.16 |
| | | Land Use | 0.112 | 0 | 0 | 0.112 | 0.112 | 0.112 |
| | | Well Construction | 0.0425 | 0.00147 | 0.000423 | 0.0444 | 0.0299 | 0.0586 |

**Table C-4: Life Cycle GHG Emissions for Electricity Production from Natural Gas**

| Stage | kg/MWh delivered | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | NGCC | | NGCC/CCS | | Fleet Baseload | | Fleet Load-Following | | Fleet Peaking | |
| | 100 GWP | 20 GWP | 100 GWP | 20 GWP | 100 GWP | 20 GWP | 100 GWP | 20 GWP | 100 GWP | 20 GWP |
| Upstream | 110 | | 129 | | 107 | | 116 | | 152 | |
| Power | 392 | | 46 | | 413 | | 450 | | 590 | |
| Transmission & Distribution | 3.37 | | 3.37 | | 3.37 | | 3.37 | | 3.37 | |
| Total (Cradle-to-grave) | 506 | 614 | 179 | 305 | 523 | 628 | 570 | 684 | 746 | 896 |
| Low (Cradle-to-grave) | 501 | 602 | 173 | 292 | 497 | 591 | 532 | 633 | 753 | 897 |
| High (Cradle-to-grave) | 510 | 624 | 183 | 317 | 570 | 690 | 615 | 742 | 1002 | 1214 |

**Table C-5: Upstream Cradle-to-gate Natural Gas Emissions to Air by Source**

| Emissions to Air | kg/MJ delivered | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Appalachian | | | | Illinois-Michigan | | | Black Warrior |
| | Conventional | CBM | Tight | Shale | Conventional | Tight | Shale | CBM |
| 2,2,4-Trimethylpentane | 2.32E-08 | 2.31E-08 | 2.32E-08 | 2.41E-08 | 2.41E-08 | 2.42E-08 | 2.49E-08 | 2.28E-08 |
| Benzene | 8.38E-08 | 8.03E-08 | 8.69E-08 | 1.73E-07 | 1.74E-07 | 1.84E-07 | 2.57E-07 | 4.16E-08 |
| Butane (n-butane) | 3.37E-06 | 3.16E-06 | 3.46E-06 | 7.24E-06 | 7.30E-06 | 7.66E-06 | 1.09E-05 | 1.51E-06 |
| Carbon dioxide | 3.17E-03 | 4.09E-03 | 3.74E-03 | 3.75E-03 | 3.08E-03 | 3.65E-03 | 3.79E-03 | 4.30E-03 |
| Carbon monoxide | 7.81E-06 | 1.22E-05 | 9.09E-06 | 8.67E-06 | 7.81E-06 | 9.20E-06 | 8.55E-06 | 1.45E-05 |
| Cyclohexane (hexahydro benzene) | 6.61E-09 | 5.99E-09 | 6.89E-09 | 1.81E-08 | 1.82E-08 | 1.93E-08 | 2.90E-08 | 1.12E-09 |
| Cyclopentane | 2.24E-08 | 2.03E-08 | 2.33E-08 | 6.11E-08 | 6.17E-08 | 6.54E-08 | 9.82E-08 | 3.81E-09 |
| Dust (PM10) | 2.47E-07 | 3.85E-07 | 2.84E-07 | 2.71E-07 | 2.48E-07 | 2.85E-07 | 2.50E-07 | 4.57E-07 |
| Ethane | 1.77E-05 | 1.74E-05 | 1.81E-05 | 2.68E-05 | 2.76E-05 | 2.86E-05 | 3.63E-05 | 1.34E-05 |
| Ethyl benzene | 5.05E-09 | 4.89E-09 | 5.25E-09 | 1.01E-08 | 1.02E-08 | 1.07E-08 | 1.49E-08 | 2.73E-09 |
| Heptane (isomers) | 5.23E-08 | 4.76E-08 | 5.46E-08 | 1.43E-07 | 1.44E-07 | 1.53E-07 | 2.29E-07 | 9.18E-09 |
| Hexane (isomers) | 9.25E-07 | 8.46E-07 | 9.61E-07 | 2.40E-06 | 2.42E-06 | 2.56E-06 | 3.81E-06 | 2.20E-07 |
| Hydrogen sulphide | 6.63E-09 | 2.22E-08 | 1.09E-08 | 9.23E-09 | 7.97E-09 | 1.23E-08 | 9.39E-09 | 2.98E-08 |
| iso-Butane | 1.21E-06 | 1.09E-06 | 1.26E-06 | 3.30E-06 | 3.33E-06 | 3.53E-06 | 5.30E-06 | 2.05E-07 |
| iso-Pentane | 4.10E-07 | 3.71E-07 | 4.27E-07 | 1.12E-06 | 1.13E-06 | 1.20E-06 | 1.80E-06 | 6.97E-08 |
| Methane | 2.22E-04 | 2.18E-04 | 2.23E-04 | 2.95E-04 | 3.04E-04 | 3.12E-04 | 3.79E-04 | 1.88E-04 |
| Methyl cyclohexane | 1.07E-08 | 9.69E-09 | 1.11E-08 | 2.92E-08 | 2.95E-08 | 3.12E-08 | 4.69E-08 | 1.82E-09 |
| Nitrogen oxides | 8.28E-05 | 8.79E-05 | 8.42E-05 | 8.32E-05 | 8.28E-05 | 8.42E-05 | 8.30E-05 | 9.06E-05 |
| Nitrous oxide (laughing gas) | 1.21E-08 | 3.87E-08 | 1.93E-08 | 2.00E-08 | 1.21E-08 | 1.94E-08 | 1.28E-08 | 5.26E-08 |
| NMVOC (unspecified) | 3.02E-06 | 3.20E-06 | 3.11E-06 | 4.18E-06 | 4.10E-06 | 4.26E-06 | 5.10E-06 | 2.87E-06 |
| Pentane (n-pentane) | 9.69E-07 | 9.23E-07 | 9.92E-07 | 1.86E-06 | 1.88E-06 | 1.96E-06 | 2.72E-06 | 5.44E-07 |
| Propane | 8.74E-06 | 8.24E-06 | 8.99E-06 | 1.85E-05 | 1.87E-05 | 1.96E-05 | 2.79E-05 | 4.10E-06 |
| Sulphur dioxide | 9.31E-05 | 1.10E-04 | 1.15E-04 | 2.47E-04 | 9.19E-05 | 1.40E-04 | 2.45E-04 | 1.06E-04 |
| Toluene (methyl benzene) | 5.47E-08 | 5.19E-08 | 5.77E-08 | 1.34E-07 | 1.36E-07 | 1.44E-07 | 2.09E-07 | 1.74E-08 |
| Xylene (para-Xylene; 1,4-Dimethylbenzene) | 1.60E-08 | 1.51E-08 | 1.68E-08 | 3.87E-08 | 3.89E-08 | 4.12E-08 | 6.00E-08 | 5.27E-09 |

**Table C-5: Upstream Cradle-to-gate Natural Gas Emissions to Air by Source, continued**

| Emissions to Air | kg/MJ delivered | | | | | | |
|---|---|---|---|---|---|---|---|
| | Central | | | | North-Central | | |
| | Conventional | CBM | Tight | Shale | Conventional | Tight | Shale |
| 2,2,4-Trimethylpentane | 2.35E-08 | 2.28E-08 | 2.35E-08 | 2.37E-08 | 2.55E-08 | 2.54E-08 | 2.66E-08 |
| Benzene | 4.68E-08 | 4.16E-08 | 4.65E-08 | 4.95E-08 | 2.33E-07 | 2.28E-07 | 3.08E-07 |
| Butane (n-butane) | 4.89E-06 | 1.78E-06 | 4.72E-06 | 5.79E-06 | 1.36E-05 | 1.32E-05 | 1.84E-05 |
| Carbon dioxide | 3.02E-03 | 3.90E-03 | 3.45E-03 | 4.03E-03 | 3.03E-03 | 3.84E-03 | 4.57E-03 |
| Carbon monoxide | 8.05E-06 | 1.27E-05 | 8.58E-06 | 9.23E-06 | 8.06E-06 | 1.12E-05 | 1.08E-05 |
| Cyclohexane (hexahydro benzene) | 1.11E-08 | 1.91E-09 | 1.06E-08 | 1.38E-08 | 3.69E-08 | 3.58E-08 | 5.11E-08 |
| Cyclopentane | 3.76E-08 | 6.45E-09 | 3.59E-08 | 4.66E-08 | 1.25E-07 | 1.21E-07 | 1.73E-07 |
| Dust (PM10) | 2.58E-07 | 4.07E-07 | 2.62E-07 | 2.60E-07 | 2.55E-07 | 3.48E-07 | 3.21E-07 |
| Ethane | 2.01E-05 | 1.45E-05 | 1.99E-05 | 2.23E-05 | 1.64E-05 | 1.63E-05 | 1.76E-05 |
| Ethyl benzene | 1.53E-08 | 3.41E-09 | 1.50E-08 | 1.93E-08 | 1.35E-08 | 1.32E-08 | 1.77E-08 |
| Heptane (isomers) | 8.78E-08 | 1.53E-08 | 8.40E-08 | 1.09E-07 | 2.92E-07 | 2.83E-07 | 4.04E-07 |
| Hexane (isomers) | 1.50E-06 | 3.20E-07 | 1.44E-06 | 1.85E-06 | 4.82E-06 | 4.68E-06 | 6.64E-06 |
| Hydrogen sulphide | 1.22E-08 | 2.39E-08 | 1.25E-08 | 1.38E-08 | 9.59E-09 | 2.01E-08 | 1.82E-08 |
| iso-Butane | 2.03E-06 | 3.48E-07 | 1.94E-06 | 2.51E-06 | 6.74E-06 | 6.54E-06 | 9.32E-06 |
| iso-Pentane | 6.88E-07 | 1.18E-07 | 6.58E-07 | 8.54E-07 | 2.29E-06 | 2.22E-06 | 3.16E-06 |
| Methane | 2.62E-04 | 2.04E-04 | 2.59E-04 | 2.85E-04 | 3.39E-04 | 3.35E-04 | 4.01E-04 |
| Methyl cyclohexane | 1.80E-08 | 3.08E-09 | 1.72E-08 | 2.23E-08 | 5.97E-08 | 5.79E-08 | 8.26E-08 |
| Nitrogen oxides | 8.31E-05 | 8.85E-05 | 8.33E-05 | 8.34E-05 | 8.31E-05 | 8.66E-05 | 8.57E-05 |
| Nitrous oxide (laughing gas) | 1.42E-08 | 4.20E-08 | 1.52E-08 | 1.52E-08 | 1.36E-08 | 3.17E-08 | 2.67E-08 |
| NMVOC (unspecified) | 3.45E-06 | 2.85E-06 | 3.41E-06 | 3.70E-06 | 5.85E-06 | 5.91E-06 | 7.27E-06 |
| Pentane (n-pentane) | 1.32E-06 | 6.04E-07 | 1.28E-06 | 1.53E-06 | 3.33E-06 | 3.25E-06 | 4.43E-06 |
| Propane | 1.26E-05 | 4.75E-06 | 1.22E-05 | 1.49E-05 | 3.46E-05 | 3.37E-05 | 4.67E-05 |
| Sulphur dioxide | 8.79E-05 | 9.84E-05 | 1.76E-04 | 3.33E-04 | 9.10E-05 | 1.35E-04 | 2.46E-04 |
| Toluene (methyl benzene) | 2.42E-08 | 1.55E-08 | 2.37E-08 | 2.58E-08 | 1.88E-07 | 1.83E-07 | 2.54E-07 |
| Xylene (para-Xylene; 1,4-Dimethylbenzene) | 1.88E-08 | 5.41E-09 | 1.82E-08 | 2.23E-08 | 5.37E-08 | 5.23E-08 | 7.28E-08 |

**Table C-5: Upstream Cradle-to-gate Natural Gas Emissions to Air by Source, continued**

| Emissions to Air | kg/MJ delivered | | | | | |
|---|---|---|---|---|---|---|
| | TX-LA-MS Salt | | Gulf Coast | | Fort Worth | West Texas-Permian |
| | Conventional | Tight | Conventional | Tight | Shale | Shale |
| 2,2,4-Trimethylpentane | 2.29E-08 | 2.31E-08 | 2.30E-08 | 2.30E-08 | 2.33E-08 | 2.34E-08 |
| Benzene | 5.34E-08 | 7.14E-08 | 4.76E-08 | 4.66E-08 | 5.95E-08 | 5.97E-08 |
| Butane (n-butane) | 1.99E-06 | 2.86E-06 | 2.48E-06 | 2.35E-06 | 3.99E-06 | 4.36E-06 |
| Carbon dioxide | 3.12E-03 | 3.94E-03 | 2.94E-03 | 3.04E-03 | 3.78E-03 | 3.77E-03 |
| Carbon monoxide | 7.78E-06 | 9.08E-06 | 7.78E-06 | 8.42E-06 | 9.12E-06 | 9.19E-06 |
| Cyclohexane (hexahydro benzene) | 2.54E-09 | 5.10E-09 | 3.98E-09 | 3.59E-09 | 8.44E-09 | 9.56E-09 |
| Cyclopentane | 8.60E-09 | 1.73E-08 | 1.35E-08 | 1.21E-08 | 2.86E-08 | 3.23E-08 |
| Dust (PM10) | 2.50E-07 | 2.73E-07 | 2.49E-07 | 2.68E-07 | 2.56E-07 | 2.59E-07 |
| Ethane | 1.46E-05 | 1.71E-05 | 1.58E-05 | 1.56E-05 | 2.02E-05 | 2.09E-05 |
| Ethyl benzene | 4.34E-09 | 7.52E-09 | 5.53E-09 | 5.27E-09 | 1.03E-08 | 1.12E-08 |
| Heptane (isomers) | 2.01E-08 | 4.04E-08 | 3.15E-08 | 2.84E-08 | 6.68E-08 | 7.56E-08 |
| Hexane (isomers) | 4.02E-07 | 7.31E-07 | 5.87E-07 | 5.37E-07 | 1.16E-06 | 1.30E-06 |
| Hydrogen sulphide | 6.22E-09 | 9.09E-09 | 6.48E-09 | 8.61E-09 | 7.98E-09 | 8.30E-09 |
| iso-Butane | 4.64E-07 | 9.32E-07 | 7.28E-07 | 6.56E-07 | 1.54E-06 | 1.75E-06 |
| iso-Pentane | 1.58E-07 | 3.16E-07 | 2.47E-07 | 2.23E-07 | 5.23E-07 | 5.92E-07 |
| Methane | 2.02E-04 | 2.26E-04 | 2.12E-04 | 2.09E-04 | 2.50E-04 | 2.57E-04 |
| Methyl cyclohexane | 4.11E-09 | 8.25E-09 | 6.44E-09 | 5.81E-09 | 1.37E-08 | 1.55E-08 |
| Nitrogen oxides | 8.28E-05 | 8.37E-05 | 8.28E-05 | 8.35E-05 | 8.32E-05 | 8.33E-05 |
| Nitrous oxide (laughing gas) | 1.21E-08 | 1.69E-08 | 1.21E-08 | 1.58E-08 | 1.41E-08 | 1.46E-08 |
| NMVOC (unspecified) | 2.64E-06 | 2.92E-06 | 2.77E-06 | 2.77E-06 | 3.20E-06 | 3.31E-06 |
| Pentane (n-pentane) | 6.52E-07 | 8.52E-07 | 7.64E-07 | 7.34E-07 | 1.11E-06 | 1.20E-06 |
| Propane | 5.27E-06 | 7.46E-06 | 6.50E-06 | 6.17E-06 | 1.03E-05 | 1.13E-05 |
| Sulphur dioxide | 8.82E-05 | 2.17E-04 | 8.89E-05 | 9.53E-05 | 3.35E-04 | 3.34E-04 |
| Toluene (methyl benzene) | 1.58E-08 | 1.58E-08 | 1.59E-08 | 1.57E-08 | 1.59E-08 | 1.51E-08 |
| Xylene (para-Xylene; 1,4-Dimethylbenzene) | 7.50E-09 | 1.12E-08 | 7.44E-09 | 7.10E-09 | 1.13E-08 | 1.14E-08 |

**Table C-5: Upstream Cradle-to-gate Natural Gas Emissions to Air by Source, continued**

| Emissions to Air | kg/MJ delivered | | | | | | |
|---|---|---|---|---|---|---|---|
| | Rocky Mountains | | | | West Coast | | Alaska |
| | Conventional | CBM | Tight | Shale | Conventional | Shale | Conventional |
| 2,2,4-Trimethylpentane | 2.31E-08 | 2.28E-08 | 2.34E-08 | 2.39E-08 | 2.30E-08 | 2.37E-08 | 2.31E-08 |
| Benzene | 6.26E-08 | 4.41E-08 | 7.56E-08 | 1.10E-07 | 6.73E-08 | 1.41E-07 | 6.79E-08 |
| Butane (n-butane) | 3.16E-06 | 1.63E-06 | 4.09E-06 | 6.67E-06 | 2.67E-06 | 5.75E-06 | 2.76E-06 |
| Carbon dioxide | 2.95E-03 | 3.87E-03 | 3.29E-03 | 3.88E-03 | 3.06E-03 | 4.13E-03 | 2.89E-03 |
| Carbon monoxide | 7.80E-06 | 1.28E-05 | 9.13E-06 | 9.51E-06 | 7.77E-06 | 9.35E-06 | 7.95E-06 |
| Cyclohexane (hexahydro benzene) | 5.99E-09 | 1.46E-09 | 8.73E-09 | 1.64E-08 | 4.54E-09 | 1.36E-08 | 4.82E-09 |
| Cyclopentane | 2.03E-08 | 4.93E-09 | 2.96E-08 | 5.54E-08 | 1.53E-08 | 4.62E-08 | 1.63E-08 |
| Dust (PM10) | 2.49E-07 | 4.13E-07 | 2.85E-07 | 2.81E-07 | 2.46E-07 | 2.61E-07 | 2.52E-07 |
| Ethane | 1.97E-05 | 1.38E-05 | 2.36E-05 | 3.31E-05 | 1.60E-05 | 2.37E-05 | 1.60E-05 |
| Ethyl benzene | 5.59E-09 | 4.93E-09 | 6.83E-09 | 9.94E-09 | 4.12E-09 | 8.32E-09 | 4.12E-09 |
| Heptane (isomers) | 4.73E-08 | 1.17E-08 | 6.91E-08 | 1.29E-07 | 3.59E-08 | 1.08E-07 | 3.81E-08 |
| Hexane (isomers) | 8.44E-07 | 2.62E-07 | 1.20E-06 | 2.18E-06 | 6.58E-07 | 1.83E-06 | 6.94E-07 |
| Hydrogen sulphide | 1.59E-07 | 2.97E-08 | 2.54E-07 | 4.79E-07 | 6.24E-09 | 9.05E-09 | 7.01E-09 |
| iso-Butane | 1.09E-06 | 2.66E-07 | 1.59E-06 | 2.99E-06 | 8.28E-07 | 2.49E-06 | 8.80E-07 |
| iso-Pentane | 3.71E-07 | 9.02E-08 | 5.41E-07 | 1.01E-06 | 2.81E-07 | 8.46E-07 | 2.99E-07 |
| Methane | 2.31E-04 | 2.12E-04 | 2.56E-04 | 3.25E-04 | 2.08E-04 | 2.66E-04 | 2.11E-04 |
| Methyl cyclohexane | 9.68E-09 | 2.35E-09 | 1.41E-08 | 2.65E-08 | 7.33E-09 | 2.21E-08 | 7.79E-09 |
| Nitrogen oxides | 8.28E-05 | 8.87E-05 | 8.42E-05 | 8.41E-05 | 8.27E-05 | 8.35E-05 | 8.30E-05 |
| Nitrous oxide (laughing gas) | 4.33E-08 | 4.50E-08 | 5.04E-08 | 5.00E-08 | 1.18E-08 | 1.54E-08 | 1.30E-08 |
| NMVOC (unspecified) | 2.96E-06 | 2.81E-06 | 3.28E-06 | 3.98E-06 | 2.82E-06 | 3.69E-06 | 2.86E-06 |
| Pentane (n-pentane) | 9.20E-07 | 5.69E-07 | 1.13E-06 | 1.73E-06 | 8.07E-07 | 1.52E-06 | 8.29E-07 |
| Propane | 8.21E-06 | 4.37E-06 | 1.06E-05 | 1.71E-05 | 6.97E-06 | 1.48E-05 | 7.21E-06 |
| Sulphur dioxide | 9.25E-05 | 9.60E-05 | 1.37E-04 | 2.46E-04 | 9.31E-05 | 3.39E-04 | 8.69E-05 |
| Toluene (methyl benzene) | 4.70E-08 | 2.02E-08 | 6.54E-08 | 1.12E-07 | 4.00E-08 | 1.06E-07 | 4.02E-08 |
| Xylene (para-Xylene; 1,4-Dimethylbenzene) | 1.70E-08 | 9.15E-09 | 2.31E-08 | 3.88E-08 | 1.18E-08 | 3.05E-08 | 1.20E-08 |

**Table C-5: Upstream Cradle-to-gate Natural Gas Emissions to Air by Source, continued**

| Emissions to Air | kg/MJ delivered | | | | |
|---|---|---|---|---|---|
| | Alaska | Gulf of Mexico | Pacific | National | Next Marcellus Well |
| | Offshore | Offshore | Offshore | Associated | Shale |
| 2,2,4-Trimethylpentane | 2.32E-08 | 2.31E-08 | 2.32E-08 | 1.56E-09 | 2.28E-08 |
| Benzene | 9.38E-08 | 5.09E-08 | 9.38E-08 | 7.66E-08 | 5.29E-08 |
| Butane (n-butane) | 3.54E-06 | 2.89E-06 | 3.54E-06 | 6.84E-06 | 1.82E-06 |
| Carbon dioxide | 2.75E-03 | 2.75E-03 | 2.75E-03 | 5.30E-03 | 3.98E-03 |
| Carbon monoxide | 7.47E-06 | 7.46E-06 | 7.47E-06 | 1.32E-05 | 8.99E-06 |
| Cyclohexane (hexahydro benzene) | 7.11E-09 | 5.20E-09 | 7.11E-09 | 2.02E-08 | 2.03E-09 |
| Cyclopentane | 2.41E-08 | 1.76E-08 | 2.41E-08 | 6.84E-08 | 6.87E-09 |
| Dust (PM10) | 2.40E-07 | 2.43E-07 | 2.40E-07 | 3.03E-07 | 2.68E-07 |
| Ethane | 1.90E-05 | 1.80E-05 | 1.90E-05 | 1.98E-05 | 1.48E-05 |
| Ethyl benzene | 5.69E-09 | 7.81E-09 | 5.69E-09 | 1.69E-08 | 3.41E-09 |
| Heptane (isomers) | 5.63E-08 | 4.11E-08 | 5.63E-08 | 1.61E-07 | 1.62E-08 |
| Hexane (isomers) | 9.90E-07 | 7.44E-07 | 9.90E-07 | 2.60E-06 | 3.36E-07 |
| Hydrogen sulphide | 5.87E-09 | 5.97E-09 | 5.87E-09 | 1.48E-07 | 7.04E-09 |
| iso-Butane | 1.30E-06 | 9.50E-07 | 1.30E-06 | 3.69E-06 | 3.71E-07 |
| iso-Pentane | 4.41E-07 | 3.22E-07 | 4.41E-07 | 1.25E-06 | 1.26E-07 |
| Methane | 2.23E-04 | 2.23E-04 | 2.23E-04 | 1.92E-04 | 1.91E-04 |
| Methyl cyclohexane | 1.15E-08 | 8.41E-09 | 1.15E-08 | 3.27E-08 | 3.28E-09 |
| Nitrogen oxides | 8.25E-05 | 8.25E-05 | 8.25E-05 | 7.52E-05 | 8.32E-05 |
| Nitrous oxide (laughing gas) | 1.11E-08 | 1.13E-08 | 1.11E-08 | 5.26E-08 | 1.95E-08 |
| NMVOC (unspecified) | 3.06E-06 | 2.88E-06 | 3.06E-06 | 6.30E-06 | 2.69E-06 |
| Pentane (n-pentane) | 1.01E-06 | 8.59E-07 | 1.01E-06 | 1.58E-06 | 6.13E-07 |
| Propane | 9.17E-06 | 7.54E-06 | 9.17E-06 | 1.80E-05 | 4.85E-06 |
| Sulphur dioxide | 6.43E-05 | 6.02E-05 | 6.43E-05 | 5.88E-05 | 3.47E-04 |
| Toluene (methyl benzene) | 6.49E-08 | 1.47E-08 | 6.49E-08 | 5.45E-08 | 2.85E-08 |
| Xylene (para-Xylene; 1,4-Dimethylbenzene) | 1.82E-08 | 8.43E-09 | 1.82E-08 | 2.79E-08 | 8.00E-09 |

**Table C-6: Upstream Cradle-to-gate Natural Gas Emissions to Water by Source**

| Emissions to Water | kg/MJ delivered | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Appalachian | | | | Illinois-Michigan | | | Black Warrior |
| | Conventional | CBM | Tight | Shale | Conventional | Tight | Shale | CBM |
| Ammonia | 1.08E-09 | 4.39E-09 | 1.98E-09 | 1.44E-07 | 1.09E-09 | 1.98E-09 | 1.13E-09 | 6.10E-09 |
| Barium | 1.38E-08 | 3.51E-04 | 1.56E-08 | 1.99E-08 | 1.41E-08 | 1.58E-08 | 1.41E-08 | 3.51E-04 |
| Biological oxygen demand (BOD) | 1.11E-09 | 1.89E-09 | 1.32E-09 | 1.77E-09 | 1.13E-09 | 1.34E-09 | 1.14E-09 | 2.30E-09 |
| Boron | 3.42E-08 | 2.65E-11 | 1.46E-11 | 2.23E-11 | 3.42E-08 | 1.48E-11 | 1.05E-11 | 3.51E-11 |
| Bromide | 8.78E-12 | 1.29E-11 | 9.91E-12 | 8.65E-07 | 8.96E-12 | 1.01E-11 | 9.01E-12 | 1.51E-11 |
| Calcium (+II) | 5.89E-09 | 6.08E-05 | 7.14E-09 | 9.69E-09 | 6.00E-09 | 7.25E-09 | 2.24E-06 | 6.08E-05 |
| Carbonate | 9.64E-08 | 2.48E-03 | 1.09E-07 | 1.41E-07 | 9.83E-08 | 1.11E-07 | 9.89E-08 | 2.48E-03 |
| Chloride | 4.90E-08 | 7.23E-08 | 5.53E-08 | 7.09E-08 | 5.00E-08 | 5.63E-08 | 5.03E-08 | 8.44E-08 |
| Hydrocarbons (unspecified) | 4.78E-07 | 1.08E-10 | 8.24E-11 | 8.68E-09 | 4.78E-07 | 8.38E-11 | 7.49E-11 | 1.26E-10 |
| Iron | 1.09E-08 | 3.86E-08 | 1.84E-08 | 1.39E-08 | 1.10E-08 | 1.85E-08 | 2.34E-08 | 5.30E-08 |
| Magnesium | 9.33E-10 | 2.01E-05 | 1.16E-09 | 1.61E-09 | 9.51E-10 | 1.18E-09 | 2.01E-07 | 2.01E-05 |
| Manganese (+II) | 8.35E-10 | 1.81E-05 | 9.45E-10 | 1.22E-09 | 8.51E-10 | 9.62E-10 | 8.57E-10 | 1.81E-05 |
| Nitrogen (as total N) | 3.99E-11 | 5.88E-11 | 4.50E-11 | 1.60E-07 | 4.07E-11 | 4.58E-11 | 4.10E-11 | 6.86E-11 |
| Phosphorus | 9.30E-11 | 1.97E-10 | 1.21E-10 | 2.27E-09 | 9.46E-11 | 1.23E-10 | 9.60E-11 | 2.52E-10 |
| Silicate particles | 1.57E-13 | 2.29E-13 | 1.76E-13 | 2.24E-13 | 1.60E-13 | 1.80E-13 | 8.13E-09 | 2.67E-13 |
| Sodium (+I) | 4.91E-08 | 1.17E-03 | 5.70E-08 | 7.46E-08 | 5.01E-08 | 5.79E-08 | 5.05E-08 | 1.17E-03 |
| Sodium chloride (rock salt) | 4.25E-08 | 6.26E-08 | 4.79E-08 | 6.14E-08 | 4.34E-08 | 4.88E-08 | 4.36E-08 | 7.30E-08 |
| Sulfates | 2.71E-05 | 4.94E-06 | 4.56E-09 | 5.85E-09 | 2.71E-05 | 4.65E-09 | 9.15E-08 | 4.94E-06 |
| Sulfite | 3.32E-13 | 4.89E-13 | 3.74E-13 | 3.27E-08 | 3.39E-13 | 3.81E-13 | 3.41E-13 | 5.71E-13 |
| Sulphur dioxide | 1.71E-14 | 2.51E-14 | 1.92E-14 | 1.68E-09 | 1.74E-14 | 1.96E-14 | 1.75E-14 | 2.93E-14 |
| Total biochemical oxygen demand | 2.14E-12 | 3.16E-12 | 2.42E-12 | 2.11E-07 | 2.19E-12 | 2.46E-12 | 2.20E-12 | 3.68E-12 |
| Total dissolved organic bounded carbon | 5.53E-10 | 8.15E-10 | 6.24E-10 | 1.72E-07 | 5.64E-10 | 6.35E-10 | 5.67E-10 | 9.51E-10 |
| Total dissolved solids | 7.10E-05 | 5.01E-03 | 1.12E-06 | 1.37E-04 | 7.10E-05 | 1.14E-06 | 4.19E-05 | 5.01E-03 |
| Total organic carbon, TOC (Ecoinvent) | 3.69E-12 | 5.44E-12 | 4.17E-12 | 9.98E-08 | 3.77E-12 | 4.24E-12 | 3.79E-12 | 6.35E-12 |
| Total suspended solids | 2.32E-08 | 3.42E-08 | 2.62E-08 | 2.45E-07 | 2.37E-08 | 2.67E-08 | 2.38E-08 | 3.99E-08 |

**Table C-6: Upstream Cradle-to-gate Natural Gas Emissions to Water by Source, continued**

| Emissions to Water | kg/MJ delivered | | | | | | |
|---|---|---|---|---|---|---|---|
| | Central | | | | North-Central | | |
| | Conventional | CBM | Tight | Shale | Conventional | Tight | Shale |
| Ammonia | 1.29E-09 | 4.81E-09 | 1.39E-09 | 1.34E-09 | 1.27E-09 | 3.51E-09 | 2.85E-09 |
| Barium | 1.52E-08 | 3.51E-04 | 1.53E-08 | 1.52E-08 | 1.40E-08 | 1.84E-08 | 1.71E-08 |
| Biological oxygen demand (BOD) | 1.23E-09 | 2.18E-09 | 1.25E-09 | 1.24E-09 | 1.14E-09 | 1.67E-09 | 1.51E-09 |
| Boron | 3.42E-08 | 3.01E-11 | 1.22E-11 | 1.20E-11 | 3.42E-08 | 2.21E-11 | 1.88E-11 |
| Bromide | 9.65E-12 | 1.50E-11 | 9.77E-12 | 9.72E-12 | 8.89E-12 | 1.17E-11 | 1.09E-11 |
| Calcium (+II) | 6.56E-09 | 6.08E-05 | 6.70E-09 | 2.24E-06 | 6.07E-09 | 9.19E-09 | 2.24E-06 |
| Carbonate | 1.06E-07 | 2.48E-03 | 1.07E-07 | 1.07E-07 | 9.77E-08 | 1.30E-07 | 1.21E-07 |
| Chloride | 5.39E-08 | 8.40E-08 | 5.46E-08 | 5.43E-08 | 4.97E-08 | 6.54E-08 | 6.08E-08 |
| Hydrocarbons (unspecified) | 4.78E-07 | 1.25E-10 | 8.12E-11 | 8.07E-11 | 4.78E-07 | 9.75E-11 | 9.06E-11 |
| Iron | 1.28E-08 | 4.25E-08 | 1.36E-08 | 2.53E-08 | 1.25E-08 | 3.12E-08 | 3.77E-08 |
| Magnesium | 1.05E-09 | 2.01E-05 | 1.07E-09 | 2.02E-07 | 9.69E-10 | 1.54E-09 | 2.02E-07 |
| Manganese (+II) | 9.18E-10 | 1.81E-05 | 9.30E-10 | 9.24E-10 | 8.46E-10 | 1.12E-09 | 1.04E-09 |
| Nitrogen (as total N) | 4.39E-11 | 6.83E-11 | 4.44E-11 | 4.42E-11 | 4.04E-11 | 5.32E-11 | 4.94E-11 |
| Phosphorus | 1.05E-10 | 2.24E-10 | 1.08E-10 | 1.06E-10 | 9.79E-11 | 1.69E-10 | 1.48E-10 |
| Silicate particles | 1.72E-13 | 2.67E-13 | 1.74E-13 | 8.13E-09 | 1.59E-13 | 2.08E-13 | 8.13E-09 |
| Sodium (+I) | 5.43E-08 | 1.17E-03 | 5.51E-08 | 5.47E-08 | 5.01E-08 | 6.97E-08 | 6.40E-08 |
| Sodium chloride (rock salt) | 4.67E-08 | 7.28E-08 | 4.73E-08 | 4.70E-08 | 4.30E-08 | 5.66E-08 | 5.27E-08 |
| Sulfates | 2.71E-05 | 4.94E-06 | 4.50E-09 | 9.19E-08 | 2.71E-05 | 5.39E-09 | 9.24E-08 |
| Sulfite | 3.65E-13 | 5.68E-13 | 3.69E-13 | 3.67E-13 | 3.36E-13 | 4.42E-13 | 4.11E-13 |
| Sulphur dioxide | 1.88E-14 | 2.92E-14 | 1.90E-14 | 1.89E-14 | 1.73E-14 | 2.27E-14 | 2.11E-14 |
| Total biochemical oxygen demand | 2.36E-12 | 3.67E-12 | 2.38E-12 | 2.37E-12 | 2.17E-12 | 2.86E-12 | 2.65E-12 |
| Total dissolved organic bounded carbon | 6.07E-10 | 9.47E-10 | 6.15E-10 | 6.11E-10 | 5.60E-10 | 7.37E-10 | 6.85E-10 |
| Total dissolved solids | 7.11E-05 | 5.01E-03 | 1.11E-06 | 4.20E-05 | 7.10E-05 | 1.33E-06 | 4.21E-05 |
| Total organic carbon, TOC (Ecoinvent) | 4.06E-12 | 6.32E-12 | 4.11E-12 | 4.09E-12 | 3.74E-12 | 4.92E-12 | 4.58E-12 |
| Total suspended solids | 2.55E-08 | 3.98E-08 | 2.58E-08 | 2.57E-08 | 2.35E-08 | 3.10E-08 | 2.88E-08 |

**Table C-6: Upstream Cradle-to-gate Natural Gas Emissions to Water by Source, continued**

| Emissions to Water | kg/MJ delivered | | | | | |
|---|---|---|---|---|---|---|
| | TX-LA-MS Salt | | Gulf Coast | | Fort Worth | West Texas-Permian |
| | Conventional | Tight | Conventional | Tight | Shale | Shale |
| Ammonia | 1.09E-09 | 1.65E-09 | 1.09E-09 | 1.55E-09 | 1.26E-09 | 1.33E-09 |
| Barium | 1.50E-08 | 1.61E-08 | 1.47E-08 | 1.56E-08 | 1.51E-08 | 1.52E-08 |
| Biological oxygen demand (BOD) | 1.20E-09 | 1.33E-09 | 1.18E-09 | 1.29E-09 | 1.22E-09 | 1.23E-09 |
| Boron | 3.42E-08 | 1.37E-11 | 3.42E-08 | 1.30E-11 | 1.16E-11 | 1.19E-11 |
| Bromide | 9.57E-12 | 1.03E-11 | 9.37E-12 | 9.95E-12 | 9.59E-12 | 9.67E-12 |
| Calcium (+II) | 6.39E-09 | 7.17E-09 | 6.26E-09 | 6.90E-09 | 2.24E-06 | 2.24E-06 |
| Carbonate | 1.05E-07 | 1.13E-07 | 1.03E-07 | 1.09E-07 | 1.05E-07 | 1.06E-07 |
| Chloride | 5.34E-08 | 5.74E-08 | 5.23E-08 | 5.56E-08 | 5.36E-08 | 5.40E-08 |
| Hydrocarbons (unspecified) | 4.78E-07 | 8.54E-11 | 4.78E-07 | 8.27E-11 | 7.97E-11 | 8.04E-11 |
| Iron | 1.12E-08 | 1.58E-08 | 1.11E-08 | 1.49E-08 | 2.46E-08 | 2.51E-08 |
| Magnesium | 1.01E-09 | 1.15E-09 | 9.91E-10 | 1.11E-09 | 2.02E-07 | 2.02E-07 |
| Manganese (+II) | 9.10E-10 | 9.78E-10 | 8.90E-10 | 9.47E-10 | 9.12E-10 | 9.20E-10 |
| Nitrogen (as total N) | 4.35E-11 | 4.67E-11 | 4.26E-11 | 4.52E-11 | 4.36E-11 | 4.40E-11 |
| Phosphorus | 1.00E-10 | 1.18E-10 | 9.81E-11 | 1.13E-10 | 1.04E-10 | 1.06E-10 |
| Silicate particles | 1.71E-13 | 1.83E-13 | 1.67E-13 | 1.77E-13 | 8.13E-09 | 8.13E-09 |
| Sodium (+I) | 5.34E-08 | 5.83E-08 | 5.23E-08 | 5.63E-08 | 5.39E-08 | 5.44E-08 |
| Sodium chloride (rock salt) | 4.63E-08 | 4.97E-08 | 4.53E-08 | 4.81E-08 | 4.64E-08 | 4.68E-08 |
| Sulfates | 2.71E-05 | 4.73E-09 | 2.71E-05 | 4.58E-09 | 9.18E-08 | 9.18E-08 |
| Sulfite | 3.62E-13 | 3.88E-13 | 3.54E-13 | 3.76E-13 | 3.63E-13 | 3.66E-13 |
| Sulphur dioxide | 1.86E-14 | 2.00E-14 | 1.82E-14 | 1.93E-14 | 1.86E-14 | 1.88E-14 |
| Total biochemical oxygen demand | 2.34E-12 | 2.51E-12 | 2.29E-12 | 2.43E-12 | 2.34E-12 | 2.36E-12 |
| Total dissolved organic bounded carbon | 6.02E-10 | 6.46E-10 | 5.90E-10 | 6.26E-10 | 6.04E-10 | 6.09E-10 |
| Total dissolved solids | 7.11E-05 | 1.16E-06 | 7.11E-05 | 1.13E-06 | 4.20E-05 | 4.20E-05 |
| Total organic carbon, TOC (Ecoinvent) | 4.02E-12 | 4.32E-12 | 3.94E-12 | 4.18E-12 | 4.03E-12 | 4.07E-12 |
| Total suspended solids | 2.53E-08 | 2.72E-08 | 2.48E-08 | 2.63E-08 | 2.54E-08 | 2.56E-08 |

**Table C-6: Upstream Cradle-to-gate Natural Gas Emissions to Water by Source, continued**

| Emissions to Water | kg/MJ delivered | | | | | | |
|---|---|---|---|---|---|---|---|
| | Rocky Mountains | | | | West Coast | | Alaska |
| | Conventional | CBM | Tight | Shale | Conventional | Shale | Conventional |
| Ammonia | 1.08E-09 | 4.90E-09 | 1.95E-09 | 1.87E-09 | 1.05E-09 | 1.42E-09 | 1.20E-09 |
| Barium | 1.44E-08 | 3.51E-04 | 1.61E-08 | 1.59E-08 | 1.37E-08 | 1.45E-08 | 1.40E-08 |
| Biological oxygen demand (BOD) | 1.15E-09 | 2.31E-09 | 1.36E-09 | 1.34E-09 | 1.10E-09 | 1.19E-09 | 1.13E-09 |
| Boron | 3.42E-08 | 3.13E-11 | 1.48E-11 | 1.44E-11 | 3.42E-08 | 1.18E-11 | 3.42E-08 |
| Bromide | 9.16E-12 | 1.60E-11 | 1.03E-11 | 1.02E-11 | 8.74E-12 | 9.21E-12 | 8.94E-12 |
| Calcium (+II) | 6.13E-09 | 6.08E-05 | 7.34E-09 | 2.24E-06 | 5.84E-09 | 2.24E-06 | 6.06E-09 |
| Carbonate | 1.01E-07 | 2.48E-03 | 1.13E-07 | 1.12E-07 | 9.58E-08 | 1.01E-07 | 9.81E-08 |
| Chloride | 5.12E-08 | 8.96E-08 | 5.73E-08 | 5.67E-08 | 4.88E-08 | 5.14E-08 | 4.99E-08 |
| Hydrocarbons (unspecified) | 4.78E-07 | 1.34E-10 | 8.52E-11 | 8.44E-11 | 4.78E-07 | 7.65E-11 | 4.78E-07 |
| Iron | 1.10E-08 | 4.34E-08 | 1.83E-08 | 2.96E-08 | 1.06E-08 | 2.58E-08 | 1.19E-08 |
| Magnesium | 9.70E-10 | 2.01E-05 | 1.19E-09 | 2.02E-07 | 9.24E-10 | 2.02E-07 | 9.64E-10 |
| Manganese (+II) | 8.71E-10 | 1.81E-05 | 9.78E-10 | 9.68E-10 | 8.30E-10 | 8.77E-10 | 8.50E-10 |
| Nitrogen (as total N) | 4.16E-11 | 7.29E-11 | 4.66E-11 | 4.61E-11 | 3.97E-11 | 4.18E-11 | 4.06E-11 |
| Phosphorus | 9.63E-11 | 2.35E-10 | 1.24E-10 | 1.21E-10 | 9.18E-11 | 1.04E-10 | 9.68E-11 |
| Silicate particles | 1.64E-13 | 2.85E-13 | 1.83E-13 | 8.13E-09 | 1.56E-13 | 8.13E-09 | 1.60E-13 |
| Sodium (+I) | 5.12E-08 | 1.17E-03 | 5.88E-08 | 5.81E-08 | 4.88E-08 | 5.21E-08 | 5.02E-08 |
| Sodium chloride (rock salt) | 4.44E-08 | 7.76E-08 | 4.96E-08 | 4.91E-08 | 4.23E-08 | 4.46E-08 | 4.32E-08 |
| Sulfates | 2.71E-05 | 4.94E-06 | 4.72E-09 | 9.21E-08 | 2.71E-05 | 9.16E-08 | 2.71E-05 |
| Sulfite | 3.46E-13 | 6.06E-13 | 3.88E-13 | 3.84E-13 | 3.30E-13 | 3.48E-13 | 3.38E-13 |
| Sulphur dioxide | 1.78E-14 | 3.12E-14 | 1.99E-14 | 1.97E-14 | 1.70E-14 | 1.79E-14 | 1.74E-14 |
| Total biochemical oxygen demand | 2.24E-12 | 3.91E-12 | 2.50E-12 | 2.48E-12 | 2.13E-12 | 2.25E-12 | 2.18E-12 |
| Total dissolved organic bounded carbon | 5.77E-10 | 1.01E-09 | 6.45E-10 | 6.39E-10 | 5.50E-10 | 5.80E-10 | 5.62E-10 |
| Total dissolved solids | 7.11E-05 | 5.01E-03 | 1.16E-06 | 4.20E-05 | 7.10E-05 | 4.19E-05 | 7.10E-05 |
| Total organic carbon, TOC (Ecoinvent) | 3.85E-12 | 6.75E-12 | 4.31E-12 | 4.27E-12 | 3.67E-12 | 3.87E-12 | 3.76E-12 |
| Total suspended solids | 2.42E-08 | 4.24E-08 | 2.71E-08 | 2.68E-08 | 2.31E-08 | 2.43E-08 | 2.36E-08 |

**Table C-6: Upstream Cradle-to-gate Natural Gas Emissions to Water by Source, continued**

| Emissions to Water | kg/MJ delivered | | | | |
|---|---|---|---|---|---|
| | Alaska | Gulf of Mexico | Pacific | National | Next Marcellus Well |
| | Offshore | Offshore | Offshore | Associated | Shale |
| Ammonia | 9.20E-10 | 9.45E-10 | 9.20E-10 | 1.33E-05 | 1.44E-07 |
| Barium | 1.34E-08 | 1.44E-08 | 1.34E-08 | 2.37E-06 | 1.98E-08 |
| Biological oxygen demand (BOD) | 1.77E-05 | 1.77E-05 | 1.77E-05 | 1.56E-07 | 1.75E-09 |
| Boron | 9.60E-12 | 1.03E-11 | 9.60E-12 | 7.53E-10 | 2.18E-11 |
| Bromide | 8.57E-12 | 9.18E-12 | 8.57E-12 | 8.05E-05 | 8.65E-07 |
| Calcium (+II) | 5.70E-09 | 6.10E-09 | 5.70E-09 | 4.88E-07 | 9.57E-09 |
| Carbonate | 9.39E-08 | 1.01E-07 | 9.39E-08 | 1.68E-05 | 1.40E-07 |
| Chloride | 4.78E-08 | 5.13E-08 | 4.78E-08 | 9.99E-08 | 7.03E-08 |
| Hydrocarbons (unspecified) | 7.11E-11 | 7.62E-11 | 7.11E-11 | 8.09E-07 | 8.68E-09 |
| Iron | 9.52E-09 | 9.85E-09 | 9.52E-09 | 2.02E-08 | 1.32E-08 |
| Magnesium | 9.00E-10 | 9.64E-10 | 9.00E-10 | 1.38E-07 | 1.59E-09 |
| Manganese (+II) | 8.14E-10 | 8.72E-10 | 8.14E-10 | 1.23E-07 | 1.20E-09 |
| Nitrogen (as total N) | 7.97E-07 | 7.97E-07 | 7.97E-07 | 1.49E-05 | 1.60E-07 |
| Phosphorus | 1.06E-08 | 1.06E-08 | 1.06E-08 | 1.97E-07 | 2.26E-09 |
| Silicate particles | 1.53E-13 | 1.64E-13 | 1.53E-13 | 1.63E-11 | 2.23E-13 |
| Sodium (+I) | 4.78E-08 | 5.11E-08 | 4.78E-08 | 8.00E-06 | 7.39E-08 |
| Sodium chloride (rock salt) | 8.40E-04 | 8.40E-04 | 8.40E-04 | 7.34E-06 | 6.09E-08 |
| Sulfates | 3.95E-09 | 4.23E-09 | 3.95E-09 | 5.86E-07 | 5.80E-09 |
| Sulfite | 3.24E-13 | 3.47E-13 | 3.24E-13 | 3.04E-06 | 3.27E-08 |
| Sulphur dioxide | 1.66E-14 | 1.78E-14 | 1.66E-14 | 2.98E-12 | 1.68E-09 |
| Total biochemical oxygen demand | 2.09E-12 | 2.24E-12 | 2.09E-12 | 1.97E-05 | 2.11E-07 |
| Total dissolved organic bounded carbon | 1.09E-05 | 1.09E-05 | 1.09E-05 | 1.60E-05 | 1.72E-07 |
| Total dissolved solids | 9.71E-07 | 1.04E-06 | 9.71E-07 | 1.27E-02 | 1.37E-04 |
| Total organic carbon, TOC (Ecoinvent) | 3.60E-12 | 3.86E-12 | 3.60E-12 | 9.29E-06 | 9.98E-08 |
| Total suspended solids | 2.26E-08 | 2.43E-08 | 2.26E-08 | 1.97E-05 | 2.44E-07 |

**Table C-7: Life Cycle Emissions to Air for Electricity Production from Natural Gas**

| Emissions to Air | kg/MJ delivered | | | | |
|---|---|---|---|---|---|
| | NGCC | NGCC/CCS | Fleet Baseload | Fleet Load Following | Fleet Peaking |
| 1,1,2,2-Tetrachloroethane | 0.00E+00 | 0.00E+00 | 1.34E-11 | 0.00E+00 | 6.70E-10 |
| 1,1,2-Trichloroethane | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 4.04E-10 |
| 1,3-Butadiene | 0.00E+00 | 0.00E+00 | 1.57E-06 | 1.54E-06 | 1.97E-06 |
| 1,3-dichloropropene | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 3.37E-10 |
| 1,4-Dichlorobenzene | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.16E-08 | 1.65E-07 |
| 2,2,4-Trimethylpentane | 1.11E-04 | 1.30E-04 | 1.01E-04 | 1.10E-04 | 1.45E-04 |
| 2,4-Dinitrophenol | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.77E-09 |
| 2,4-Dinitrotoluene | 2.95E-18 | 1.20E-16 | 2.61E-18 | 5.86E-10 | 1.43E-09 |
| 2-Chloroacetophenone | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.24E-08 | 3.57E-08 |
| 2-Chloronaphthalene | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 9.16E-13 |
| 2-Methylnaphthalene | 0.00E+00 | 0.00E+00 | 3.98E-09 | 1.45E-08 | 5.35E-08 |
| 3-Methylcholanthrene | 0.00E+00 | 0.00E+00 | 2.47E-10 | 5.30E-10 | 2.46E-09 |
| 4-Nitrophenol | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.09E-09 |
| 5-Methylchrysene | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.12E-10 |
| 7,12-Dimethylbenz[a]Anthracene | 0.00E+00 | 0.00E+00 | 2.18E-09 | 4.71E-09 | 2.14E-08 |
| Acenaphthene | 1.96E-16 | 2.48E-15 | 1.73E-16 | 1.89E-16 | 2.47E-16 |
| Acenaphthylene | 9.59E-17 | 1.21E-15 | 9.18E-11 | 1.52E-09 | 1.16E-08 |
| Acetaldehyde (Ethanal) | 4.73E-08 | 1.47E-07 | 1.27E-04 | 1.38E-04 | 2.43E-04 |
| Acetophenone | 1.58E-16 | 6.45E-15 | 1.40E-16 | 2.62E-08 | 7.65E-08 |
| Acrolein | 3.07E-10 | 3.83E-10 | 2.31E-05 | 2.01E-05 | 2.87E-05 |
| Acrylonitrile | 2.89E-17 | 3.89E-17 | 6.29E-18 | 6.85E-18 | 8.97E-18 |
| Ammonia | 1.92E-02 | 2.29E-02 | 1.29E-02 | 1.42E-02 | 1.86E-02 |
| Anthracene | 4.35E-11 | 5.42E-11 | 6.84E-10 | 2.85E-09 | 8.94E-09 |
| Antimony | 6.82E-10 | 1.05E-09 | 3.98E-08 | 1.24E-07 | 4.82E-07 |
| Arsenic | 0.00E+00 | 0.00E+00 | 8.99E-08 | 2.41E-07 | 1.10E-06 |
| Asbestos | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.58E-10 | 1.46E-09 |
| Benz[a]Anthracene | 0.00E+00 | 0.00E+00 | 1.14E-07 | 4.10E-07 | 7.77E-07 |
| Benzene | 4.70E-04 | 5.51E-04 | 4.69E-04 | 5.09E-04 | 6.85E-04 |
| Benzo[a]Pyrene | 0.00E+00 | 0.00E+00 | 1.28E-10 | 1.77E-07 | 7.62E-07 |
| Benzo[b]Fluoranthene | 0.00E+00 | 0.00E+00 | 2.49E-10 | 8.65E-10 | 4.32E-09 |
| Benzo[e]Pyrene | 0.00E+00 | 0.00E+00 | 0.00E+00 | 8.44E-11 | 3.39E-11 |
| Benzo[g,h,i,]Perylene | 0.00E+00 | 0.00E+00 | 1.83E-10 | 4.75E-07 | 2.29E-07 |
| Benzo[j]fluoranthene | 0.00E+00 | 0.00E+00 | 0.00E+00 | 5.17E-11 | 0.00E+00 |
| Benzo[k]Fluoranthene | 0.00E+00 | 0.00E+00 | 6.19E-11 | 6.99E-10 | 3.42E-09 |
| Benzofluoranthenes | 0.00E+00 | 0.00E+00 | 0.00E+00 | 8.84E-12 | 0.00E+00 |
| Benzyl Chloride | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.22E-06 | 3.57E-06 |
| Beryllium | 5.77E-10 | 1.98E-09 | 4.46E-09 | 1.33E-08 | 8.94E-08 |
| Biphenyl | 6.52E-16 | 8.25E-15 | 5.77E-16 | 2.94E-09 | 1.30E-07 |
| Bis(2-Ethylhexyl)Phthalate | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.27E-07 | 3.72E-07 |
| Bromoform | 4.11E-16 | 1.68E-14 | 3.64E-16 | 6.79E-08 | 1.98E-07 |
| Butane (n-butane) | 3.07E-02 | 3.60E-02 | 2.81E-02 | 3.07E-02 | 4.01E-02 |
| Cadmium | 0.00E+00 | 0.00E+00 | 5.89E-07 | 1.49E-06 | 4.58E-06 |
| Carbon dioxide | 4.25E+02 | 9.41E+01 | 4.45E+02 | 4.85E+02 | 6.46E+02 |

**Table C-7: Life Cycle Emissions to Air for Electricity Production from Natural Gas, continued**

| Emissions to Air | kg/MJ delivered | | | | |
|---|---|---|---|---|---|
| | NGCC | NGCC/ CCS | Fleet Baseload | Fleet Load Following | Fleet Peaking |
| Carbon disulphide | 6.74E-12 | 1.04E-11 | 6.11E-12 | 2.26E-07 | 6.63E-07 |
| Carbon monoxide | 7.77E-02 | 9.16E-02 | 1.22E-01 | 1.47E-01 | 3.35E-01 |
| Carbon tetrachloride (tetrachloromethane) | -1.95E-13 | 7.04E-13 | -1.72E-13 | -1.87E-13 | 4.24E-07 |
| Carbonyl sulfide | 6.42E-10 | 4.35E-09 | 5.68E-10 | 6.19E-10 | 8.10E-10 |
| Chlorine | 5.40E-09 | 7.95E-09 | 1.54E-06 | 2.02E-05 | 2.66E-06 |
| Chlorobenzene | 2.32E-16 | 9.46E-15 | 2.05E-16 | 3.83E-08 | 3.94E-07 |
| Chloromethane (methyl chloride) | 5.59E-15 | 2.28E-13 | 4.94E-15 | 9.20E-07 | 2.84E-06 |
| Chromic acid (V) | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.33E-09 |
| Chromium (+III) | 3.72E-11 | 6.76E-11 | 9.61E-07 | 2.77E-06 | 7.40E-06 |
| Chromium (+VI) | 2.28E-11 | 2.15E-10 | 4.75E-08 | 2.46E-07 | 4.49E-07 |
| Chrysene | 5.37E-11 | 6.70E-11 | 2.58E-10 | 3.20E-07 | 5.63E-09 |
| Cobalt | 3.81E-09 | 1.26E-08 | 1.35E-07 | 1.91E-07 | 9.09E-07 |
| Cumene (isopropylbenzene) | 1.35E-14 | 2.97E-14 | 1.22E-14 | 9.19E-09 | 2.70E-08 |
| Cyanide (unspecified) | 3.29E-09 | 1.10E-08 | 2.81E-09 | 4.49E-07 | 1.15E-05 |
| Cyclohexane (hexahydro benzene) | 7.54E-05 | 8.84E-05 | 6.90E-05 | 7.52E-05 | 9.85E-05 |
| Cyclopentane | 2.55E-04 | 2.99E-04 | 2.34E-04 | 2.55E-04 | 3.33E-04 |
| Dibenzo[a,h]Anthracene | 0.00E+00 | 0.00E+00 | 4.31E-11 | 8.25E-10 | 3.03E-09 |
| Dibenzo[a,h]Pyrene | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.06E-10 | 0.00E+00 |
| Dimethyl sulfate | 0.00E+00 | 0.00E+00 | 0.00E+00 | 8.35E-08 | 2.45E-07 |
| Dust (PM10) | 2.29E-03 | 3.32E-03 | 2.07E-03 | 2.26E-03 | 2.95E-03 |
| Ethane | 1.21E-01 | 1.42E-01 | 1.11E-01 | 1.21E-01 | 1.58E-01 |
| Ethyl benzene | 6.83E-05 | 8.02E-05 | 1.64E-04 | 1.62E-04 | 2.12E-04 |
| Ethyl chloride | 4.43E-16 | 1.81E-14 | 3.92E-16 | 7.31E-08 | 2.15E-07 |
| Ethylene Dibromide | 0.00E+00 | 0.00E+00 | 0.00E+00 | 2.15E-09 | 6.68E-09 |
| Ethylene Dichloride | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.95E-08 | 4.86E-07 |
| Ethylene glycol | 0.00E+00 | 2.75E-10 | 0.00E+00 | 0.00E+00 | 5.15E-08 |
| Ethylidene Dichloride | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 2.80E-15 |
| Fluoranthene | 1.42E-10 | 1.77E-10 | 6.54E-08 | 1.83E-06 | 3.27E-07 |
| Fluorene | 4.49E-10 | 5.60E-10 | 1.03E-09 | 6.92E-09 | 3.36E-08 |
| Formaldehyde (methanal) | 1.97E-07 | 5.39E-07 | 1.78E-03 | 1.42E-03 | 2.71E-03 |
| Glycol Ethers | 0.00E+00 | 0.00E+00 | 0.00E+00 | 2.66E-10 | 0.00E+00 |
| Heptane (isomers) | 5.97E-04 | 7.00E-04 | 5.47E-04 | 5.96E-04 | 7.80E-04 |
| Hexane (isomers) | 1.00E-02 | 1.18E-02 | 9.42E-03 | 1.08E-02 | 1.65E-02 |
| Hydrazine | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.27E-08 |
| Hydrogen chloride | 1.00E-04 | 1.18E-04 | 8.22E-05 | 1.24E-04 | 9.57E-04 |
| Hydrogen cyanide (prussic acid) | 3.25E-10 | 5.14E-10 | 2.96E-10 | 3.23E-10 | 4.23E-10 |
| Hydrogen fluoride | 8.44E-07 | 1.10E-06 | 2.94E-07 | 3.60E-06 | 4.78E-05 |
| Hydrogen sulphide | 4.41E-04 | 5.18E-04 | 3.98E-04 | 4.34E-04 | 5.68E-04 |
| Indeno[1,2,3-c,d]Pyrene | 0.00E+00 | 0.00E+00 | 2.64E-10 | 1.03E-09 | 4.63E-09 |
| iso-Butane | 1.38E-02 | 1.61E-02 | 1.26E-02 | 1.37E-02 | 1.80E-02 |
| iso-Pentane | 4.67E-03 | 5.48E-03 | 4.28E-03 | 4.66E-03 | 6.11E-03 |
| Isophorone | 6.11E-15 | 2.49E-13 | 5.41E-15 | 1.01E-06 | 2.96E-06 |

**Table C-7: Life Cycle Emissions to Air for Electricity Production from Natural Gas, continued**

| Emissions to Air | kg/MJ delivered | | | | |
|---|---|---|---|---|---|
| | NGCC | NGCC/ CCS | Fleet Baseload | Fleet Load Following | Fleet Peaking |
| Lead (+II) | 5.17E-06 | 6.16E-06 | 4.70E-06 | 5.75E-06 | 1.12E-05 |
| Manganese (+II) | 4.36E-08 | 1.07E-07 | 7.62E-06 | 1.80E-05 | 4.53E-05 |
| Mercury (+II) | 1.76E-07 | 2.55E-07 | 5.27E-07 | 1.44E-06 | 2.34E-06 |
| meta-Cresol | 7.18E-16 | 1.11E-15 | 4.13E-16 | 4.51E-16 | 5.90E-16 |
| Methane | 1.99E+00 | 2.21E+00 | 1.93E+00 | 2.10+00 | 2.83E+00 |
| Methanol | 8.67E-08 | 2.85E-07 | 7.33E-08 | 7.87E-08 | 6.19E-05 |
| Methyl bromide | 1.69E-15 | 6.88E-14 | 1.49E-15 | 2.77E-07 | 9.57E-07 |
| Methyl chloroform | 0.00E+00 | 0.00E+00 | 1.76E-09 | 1.96E-10 | 2.89E-07 |
| Methyl cyclohexane | 1.22E-04 | 1.43E-04 | 1.12E-04 | 1.22E-04 | 1.59E-04 |
| Methyl isobutyl ketone | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.06E-07 |
| Methyl methacrylate (MMA) | 1.12E-14 | 2.10E-14 | 4.98E-15 | 3.48E-08 | 1.02E-07 |
| Methyl Tert-Butyl Ether | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.09E-08 | 1.85E-07 |
| Methylene Chloride | 0.00E+00 | 0.00E+00 | 2.19E-11 | 1.11E-06 | 4.31E-06 |
| Methylhydrazine | 0.00E+00 | 0.00E+00 | 0.00E+00 | 2.96E-07 | 8.66E-07 |
| Naphthalene | 5.54E-09 | 7.24E-09 | 4.31E-06 | 4.38E-06 | 8.86E-06 |
| Nickel (Ni) | 0.00E+00 | 0.00E+00 | 7.15E-06 | 2.55E-05 | 5.40E-05 |
| Nitrogen oxides | 6.94E-01 | 8.17E-01 | 6.62E-01 | 8.21E-01 | 1.37E+00 |
| Nitrous oxide (laughing gas) | 2.15E-04 | 2.93E-04 | 9.93E-04 | 1.10E-03 | 1.42E-03 |
| NMVOC (unspecified) | 2.85E-02 | 3.40E-02 | 2.59E-02 | 2.82E-02 | 3.69E-02 |
| ortho-Cresol | 2.31E-13 | 1.86E-12 | 2.04E-13 | 2.23E-13 | 2.91E-13 |
| PAH, total | 0.00E+00 | 0.00E+00 | 3.99E-07 | 6.39E-07 | 1.44E-06 |
| PAH/POM (Unspecified) | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.66E-07 | 1.54E-07 |
| para-Cresol | 2.50E-13 | 2.01E-12 | 2.21E-13 | 2.41E-13 | 3.15E-13 |
| Particulate Matter, unspecified | 1.53E-04 | 2.29E-04 | 1.40E-04 | 1.53E-04 | 2.00E-04 |
| Pentachlorophenol | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 5.03E-10 |
| Pentane (n-pentane) | 7.98E-03 | 9.36E-03 | 7.31E-03 | 7.96E-03 | 1.04E-02 |
| Perylene | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 3.28E-11 |
| Phenanthrene | 1.43E-09 | 1.79E-09 | 3.27E-09 | 2.07E-08 | 8.81E-08 |
| Phenol (hydroxy benzene) | 5.97E-11 | 8.10E-10 | 9.91E-07 | 1.76E-06 | 6.56E-06 |
| Phosphorus | 0.00E+00 | 0.00E+00 | 7.26E-08 | 1.85E-07 | 7.63E-07 |
| PM Condensible | 0.00E+00 | 0.00E+00 | 1.16E-02 | 1.37E-02 | 2.52E-02 |
| PM10 Filterable | 0.00E+00 | 0.00E+00 | 1.42E-02 | 1.52E-02 | 2.92E-02 |
| PM10 Primary (Filt + Cond) | 0.00E+00 | 0.00E+00 | 2.59E-02 | 2.92E-02 | 5.52E-02 |
| PM2.5 Filterable | 0.00E+00 | 0.00E+00 | 1.34E-02 | 1.40E-02 | 2.62E-02 |
| PM2.5 Primary (Filt + Cond) | 0.00E+00 | 0.00E+00 | 2.50E-02 | 2.82E-02 | 5.20E-02 |
| Propane | 7.91E-02 | 9.28E-02 | 7.25E-02 | 7.90E-02 | 1.03E-01 |
| Propionaldehyde | 4.01E-15 | 1.63E-13 | 3.54E-15 | 6.60E-07 | 2.49E-06 |
| Propylene Dichloride | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 2.82E-07 |
| Propylene oxide | 0.00E+00 | 0.00E+00 | 9.72E-05 | 7.06E-05 | 6.24E-05 |
| Pyrene | 0.00E+00 | 0.00E+00 | 8.85E-10 | 4.91E-09 | 2.15E-08 |
| Selenium | 1.12E-08 | 1.94E-08 | 1.20E-07 | 5.07E-07 | 1.68E-06 |
| Styrene | 2.01E-13 | 2.68E-13 | 1.75E-13 | 4.34E-08 | 1.89E-05 |
| Sulphur dioxide | 1.50E+00 | 1.76E+00 | 1.37E+00 | 1.50E+00 | 1.96E+00 |

**Table C-7: Life Cycle Emissions to Air for Electricity Production from Natural Gas, continued**

| Emissions to Air | kg/MJ delivered | | | | |
|---|---|---|---|---|---|
| | NGCC | NGCC/ CCS | Fleet Baseload | Fleet Load Following | Fleet Peaking |
| Sulphur hexafluoride | 1.44E-04 | 1.45E-04 | 1.44E-04 | 1.44E-04 | 1.44E-04 |
| Tetrachloroethylene | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.49E-08 | 5.02E-07 |
| Toluene (methyl benzene) | 2.98E-04 | 3.49E-04 | 6.79E-04 | 6.53E-04 | 9.18E-04 |
| Trichloroethylene | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.23E-07 |
| Trichloromethane (chloroform) | 6.22E-16 | 2.54E-14 | 5.50E-16 | 7.69E-06 | 2.10E-05 |
| Vinyl Chloride | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.49E-07 |
| VOC (unspecified) | 3.11E-04 | 3.73E-04 | 5.87E-03 | 8.41E-03 | 2.36E-02 |
| Xylene (meta-Xylene; 1,3-Dimethylbenzene) | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 4.05E-08 |
| Xylene (ortho-Xylene; 1,2-Dimethylbenzene) | 0.00E+00 | 0.00E+00 | 8.12E-10 | 6.51E-10 | 3.88E-09 |
| Xylene (para-Xylene; 1,4-Dimethylbenzene) | 1.30E-04 | 1.52E-04 | 1.19E-04 | 1.29E-04 | 1.69E-04 |
| Xylenes (Mixed Isomers) | 0.00E+00 | 0.00E+00 | 2.00E-04 | 1.82E-04 | 2.45E-04 |

**Table C-8: Life Cycle Emissions to Water for Electricity Production from Natural Gas**

| Emissions to Water | kg/MJ delivered | | | | |
|---|---|---|---|---|---|
| | NGCC | NGCC/CCS | Fleet Baseload | Fleet Load Following | Fleet Peaking |
| Ammonia | 6.88E-03 | 8.07E-03 | 6.29E-03 | 6.85E-03 | 8.97E-03 |
| Barium | 1.74E-01 | 2.04E-01 | 1.59E-01 | 1.73E-01 | 2.27E-01 |
| Biological oxygen demand (BOD) | 7.12E-03 | 8.40E-03 | 6.50E-03 | 7.09E-03 | 9.28E-03 |
| Boron | 6.68E-05 | 7.86E-05 | 6.11E-05 | 6.66E-05 | 8.72E-05 |
| Bromide | 4.15E-02 | 4.87E-02 | 3.81E-02 | 4.15E-02 | 5.43E-02 |
| Calcium (+II) | 3.58E-02 | 4.21E-02 | 3.27E-02 | 3.57E-02 | 4.67E-02 |
| Carbonate | 1.23E+00 | 1.45E+00 | 1.12E+00 | 1.22E+00 | 1.60E+00 |
| Chloride | 5.13E-04 | 1.50E-03 | 4.57E-04 | 4.98E-04 | 6.51E-04 |
| Hydrocarbons (unspecified) | 1.35E-03 | 1.58E-03 | 1.23E-03 | 1.34E-03 | 1.76E-03 |
| Iron | 1.70E-04 | 2.62E-04 | 1.46E-04 | 1.59E-04 | 2.08E-04 |
| Magnesium | 1.04E-02 | 1.23E-02 | 9.55E-03 | 1.04E-02 | 1.36E-02 |
| Manganese (+II) | 8.97E-03 | 1.06E-02 | 8.20E-03 | 8.94E-03 | 1.17E-02 |
| Nitrogen (as total N) | 8.01E-03 | 9.39E-03 | 7.33E-03 | 7.99E-03 | 1.05E-02 |
| Phosphorus | 1.08E-04 | 1.28E-04 | 9.79E-05 | 1.07E-04 | 1.40E-04 |
| Silicate particles | 2.04E-05 | 2.39E-05 | 1.87E-05 | 2.03E-05 | 2.66E-05 |
| Sodium (+I) | 5.81E-01 | 6.84E-01 | 5.31E-01 | 5.79E-01 | 7.58E-01 |
| Sodium chloride (rock salt) | 3.38E-01 | 3.98E-01 | 3.09E-01 | 3.36E-01 | 4.40E-01 |
| Sulfates | 5.55E-02 | 6.53E-02 | 5.08E-02 | 5.53E-02 | 7.25E-02 |
| Sulfite | 1.57E-03 | 1.84E-03 | 1.44E-03 | 1.57E-03 | 2.05E-03 |
| Sulphur dioxide | 1.27E-06 | 1.50E-06 | 1.17E-06 | 1.27E-06 | 1.66E-06 |
| Total biochemical oxygen demand | 1.01E-02 | 1.19E-02 | 9.28E-03 | 1.01E-02 | 1.32E-02 |
| Total dissolved organic bounded carbon | 1.26E-02 | 1.48E-02 | 1.15E-02 | 1.26E-02 | 1.64E-02 |
| Total dissolved solids | 9.25E+00 | 1.09E+01 | 8.47E+00 | 9.23E+00 | 1.21E+01 |
| Total organic carbon, TOC (Ecoinvent) | 4.79E-03 | 5.62E-03 | 4.39E-03 | 4.78E-03 | 6.26E-03 |
| Total suspended solids | 1.04E-02 | 1.26E-02 | 9.50E-03 | 1.04E-02 | 1.36E-02 |

# Appendix D:
# Parameter Inputs for Unit Processes Used in Natural Gas Model

## Tables

Table D-1: Natural Gas Well, Venting From Liquid Unloading ..... D-3
Table D-2: Natural Gas Extraction, Other Venting Fugitives ..... D-7
Table D-3: Natural Gas Extraction, Other Venting Point Sources ..... D-7
Table D-4: Natural Gas Production Fugitive Emissions - Connections ..... D-8
Table D-5: Natural Gas Production Fugitive Emissions - Flanges ..... D-11
Table D-6: Natural Gas Production Fugitive Emissions - OEL ..... D-15
Table D-7: Natural Gas Production Fugitive Emissions - Valves ..... D-19
Table D-8: Natural Gas Production Pneumatic Device Venting ..... D-23
Table D-9: Natural Gas Extraction Produced Water Tank Venting ..... D-27
Table D-10: Natural Gas Extraction Condensate Tank Venting and Flaring ..... D-31
Table D-11: Direct Land Use GHG, No Reversion ..... D-35
Table D-12: Combustion of Natural Gas (only one scenario used in model) ..... D-37
Table D-13: Natural gas distribution ..... D-39
Table D-14: Natural Gas Well Completion ..... D-39
Table D-15: Natural Gas Well Workovers ..... D-39
Table D-16: Indirect Land Use GHG ..... D-40
Table D-17: Diesel, Production, Transport, and Refining ..... D-40
Table D-18: U.S. National Average Electricity Grid Mix 2007 ..... D-40
Table D-19: Natural Gas Well Construction and Installation ..... D-40
Table D-20: Natural Gas, Average Associated, Extraction ..... D-41
Table D-21: Natural Gas, Marginal Associated, Extraction ..... D-41
Table D-22: Coal Bed Methane Natural Gas, Water Use and Water Quality ..... D-41
Table D-23: Barnett Shale Natural Gas, Water Use and Water Quality ..... D-41
Table D-24: Conventional Onshore Natural Gas, Water Use and Water Quality ..... D-42
Table D-25: Conventional Offshore Natural Gas, Water Use and Water Quality ..... D-42
Table D-26: Water Use for Marcellus Shale Gas Extraction ..... D-42
Table D-27: Marcellus Shale Water Treatment at a WWTP ..... D-43
Table D-28: Marcellus Shale Water Treatment with Crystallization ..... D-43
Table D-29: Gasoline, Production, Transport, and Refining ..... D-43
Table D-30: Offshore Natural Gas Rig, Crew Transport ..... D-44
Table D-31: Hydraulic Fracturing Water Delivery ..... D-44
Table D-32: Natural Gas Sweetening, Amine Process Acid Gas Removal ..... D-44
Table D-33: Natural Gas Dehydration ..... D-44
Table D-34: U.S. National Average Electricity Grid Mix 2007 ..... D-45
Table D-35: Wellhead Compressor, Electrically-Powered Centrifugal, 500 HP ..... D-45
Table D-36: Wellhead Compressor, Gas-Powered Reciprocating, 200 HP ..... D-45
Table D-37: Wellhead Compressor, Gas-Powered Centrifugal, 200 HP X ..... D-45
Table D-38: Natural Gas Compressors, Assembly ..... D-45
Table D-39: Onshore Pipeline, Installation/Deinstallation ..... D-46
Table D-40: Pipeline NG Operation ..... D-47

## Overview

The following tables describe the values used in the Natural Gas model for this study. Each table is taken from the Unit Process available online, as described in **Appendix A**. Tables D-1 to 12 provide information from unit processes that have more than one scenario. They therefore provide several inputs to the same parameters. For example, the Tables D-13 to 40 were taken from unit processes which do not have built-in scenarios, so the information comes from the Data Summary tab in the excel file.

**Table D-1: Natural Gas Well, Venting from Liquid Unloading**

| Parameter Name | Scenario ID | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| | *Conventional, Northeast, Plunger, Expected* | *Conventional, Northeast, Plunger, Min* | *Conventional, Northeast, Plunger, Max* | *Conventional, Northeast, NO Plunger, Expected* | *Conventional, Northeast, NO Plunger, Min* | *Conventional, Northeast, NO Plunger, Max* | *Conventional, Mid-Continent, Plunger, Expected* |
| Vent_episode [Vents/well] | 38.6381 | 38.5455 | 38.6881 | 37.7817 | 22.8158 | 43.3057 | 2915.0539 |
| Internal_diam [in] | 2.2437 | 2.0000 | 2.3750 | 4.6348 | 4.5000 | 5.0000 | 2.0031 |
| Well_Depth [ft] | 3422.4414 | 3375.0000 | 3448.0000 | 3428.3195 | 3375.0000 | 3448.0000 | 4402.3277 |
| Pressure [psia] | 76.9541 | 64.7000 | 99.7000 | 74.1358 | 64.7000 | 99.7000 | 84.4929 |
| Flow_Rate_NG [ft3/hr] | 382.4025 | 300.4167 | 534.5833 | 363.5470 | 300.4167 | 534.5833 | 3443.6685 |
| Hour_Vent [hr] | 0.5451 | 0.3000 | 1.0000 | 1.7304 | 1.0000 | 2.0000 | 0.0729 |
| Plunger_Switch [binary] | 1.0000 | 1.0000 | 1.0000 | 0.0000 | 0.0000 | 0.0000 | 1.0000 |

**Table D-1: Natural Gas Well, Venting from Liquid Unloading, continued**

| Parameter Name | Scenario ID | | | | | | |
|---|---|---|---|---|---|---|---|
| | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| | *Conventional, Mid-Continent, Plunger, Min* | *Conventional, Mid-Continent, Plunger, Max* | *Conventional, Mid-Continent, NO Plunger, Expected* | *Conventional, Mid-Continent, NO Plunger, Min* | *Conventional, Mid-Continent, NO Plunger, Max* | *Conventional, Southwest, NO Plunger, Expected* | *Conventional, Southwest, NO Plunger, Min* |
| Vent_episode [Vents/well] | 11.5000 | 2987.2683 | 63.1776 | 1.0000 | 64.3158 | 4.0000 | 4.0000 |
| Internal_diam [in] | 1.9950 | 2.3750 | 4.0149 | 4.0000 | 4.8300 | 5.5000 | 5.5000 |
| Well_Depth [ft] | 4269.0000 | 9500.0000 | 4318.6859 | 4269.0000 | 7033.0000 | 8000.0000 | 8000.0000 |
| Pressure [psia] | 40.2000 | 514.7000 | 74.8654 | 40.2000 | 75.5000 | 114.7000 | 114.7000 |
| Flow_Rate_NG [ft3/hr] | 1250.0000 | 3500.0000 | 3480.8480 | 2434.5833 | 3500.0000 | 4166.6667 | 4166.6667 |
| Hour_Vent [hr] | 0.0670 | 0.7500 | 4.8655 | 0.2500 | 4.9500 | 1.0000 | 1.0000 |
| Plunger_Switch [binary] | 1.0000 | 1.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Parameter Name | Scenario ID | | | | | | |
| | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
| | *Conventional, Southwest, NO Plunger, Max* | *Conventional, Gulf Coast, NO Plunger, Expected* | *Conventional, Gulf Coast, NO Plunger, Min* | *Conventional, Gulf Coast, NO Plunger, Max* | *Unconventional, Northeast, Plunger, Expected* | *Unconventional, Northeast, Plunger, Min* | *Unconventional, Northeast, Plunger, Max* |
| Vent_episode [Vents/well] | 4.0000 | 10.9494 | 10.0000 | 12.0000 | 229.2226 | 38.8000 | 730.0000 |
| Internal_diam [in] | 5.5000 | 4.5282 | 3.6500 | 5.5000 | 2.3750 | 2.3750 | 2.3750 |
| Well_Depth [ft] | 8000.0000 | 14903.3038 | 10000.0000 | 19334.0000 | 5092.6700 | 2500.0000 | 7000.0000 |
| Pressure [psia] | 114.7000 | 163.3203 | 79.9000 | 238.7000 | 147.9209 | 136.3000 | 214.7000 |
| Flow_Rate_NG [ft3/hr] | 4166.6667 | 20467.2996 | 12500.0000 | 27666.6667 | 7232.6709 | 625.0000 | 26166.6667 |
| Hour_Vent [hr] | 1.0000 | 1.7880 | 1.0000 | 2.5000 | 0.1703 | 0.0500 | 0.2210 |
| Plunger_Switch [binary] | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 |

**Table D-1: Natural Gas Well, Venting from Liquid Unloading, continued**

| Parameter Name | Scenario ID | | | | | | |
|---|---|---|---|---|---|---|---|
| | 22 | 23 | 24 | 25 | 26 | 27 | 28 |
| | *Unconventional, Northeast, NO Plunger, Expected* | *Unconventional, Northeast, NO Plunger, Min* | *Unconventional, Northeast, NO Plunger, Max* | *Unconventional, Mid-Continent, Plunger, Expected* | *Unconventional, Mid-Continent, Plunger, Min* | *Unconventional, Mid-Continent, Plunger, Max* | *Unconventional, Mid-Continent, NO Plunger, Expected* |
| Vent_episode [Vents/well] | 82.2552 | 82.2552 | 82.2552 | 480.2514 | 2.4000 | 3244.6250 | 3.7743 |
| Internal_diam [in] | 4.5000 | 4.5000 | 4.5000 | 3.6216 | 2.3750 | 4.1100 | 5.1877 |
| Well_Depth [ft] | 4845.0000 | 4845.0000 | 4845.0000 | 7389.2642 | 3911.0000 | 10293.0000 | 7332.5601 |
| Pressure [psia] | 136.3000 | 136.3000 | 136.3000 | 107.2150 | 89.3900 | 113.4500 | 120.5552 |
| Flow_Rate_NG [ft3/hr] | 1083.3333 | 1083.3333 | 1083.3333 | 29645.6469 | 10416.6667 | 36458.3333 | 26507.7950 |
| Hour_Vent [hr] | 1.3600 | 1.3600 | 1.3600 | 1.9730 | 0.0833 | 2.9900 | 1.8932 |
| Plunger_Switch [binary] | 0.0000 | 0.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 0.0000 |
| Parameter Name | Scenario ID | | | | | | |
| | 29 | 30 | 31 | 32 | 33 | 34 | 35 |
| | *Unconventional, Mid-Continent, NO Plunger, Min* | *Unconventional, Mid-Continent, NO Plunger, Max* | *Unconventional, Southwest, Plunger, Expected* | *Unconventional, Southwest, Plunger, Min* | *Unconventional, Southwest, Plunger, Max* | *Unconventional, Southwest, NO Plunger, Expected* | *Unconventional, Southwest, NO Plunger, Min* |
| Vent_episode [Vents/well] | 2.2599 | 12.0000 | 1.3684 | 1.0000 | 1.3889 | 0.9685 | 0.3333 |
| Internal_diam [in] | 4.9200 | 5.5000 | 2.0150 | 1.9950 | 2.3750 | 9.6181 | 5.0000 |
| Well_Depth [ft] | 3911.0000 | 11000.0000 | 8623.6842 | 6800.0000 | 8725.0000 | 8733.0916 | 8000.0000 |
| Pressure [psia] | 94.7000 | 214.7000 | 509.3316 | 124.7000 | 530.7000 | 530.1869 | 64.7000 |
| Flow_Rate_NG [ft3/hr] | 4166.6667 | 36458.3333 | 59265.3509 | 1041.6667 | 62500.0000 | 62413.0669 | 500.0000 |
| Hour_Vent [hr] | 0.5000 | 2.5000 | 0.4842 | 0.2000 | 0.5000 | 1.0073 | 0.5000 |
| Plunger_Switch [binary] | 0.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 0.0000 | 0.0000 |

**Table D-1: Natural Gas Well, Venting from Liquid Unloading, continued**

| Parameter Name | Scenario ID | | | | | | |
|---|---|---|---|---|---|---|---|
| | 36 | 37 | 38 | 39 | 40 | 41 | 42 |
| | *Unconventional, Southwest, NO Plunger, Max* | *Unconventional, Rocky Mountains, Plunger, Expected* | *Unconventional, Rocky Mountains, Plunger, Min* | *Unconventional, Rocky Mountains, Plunger, Max* | *Unconventional, Rocky Mountains, NO Plunger, Expected* | *Unconventional, Rocky Mountains, NO Plunger, Min* | *Unconventional, Rocky Mountains, NO Plunger, Max* |
| Vent_episode [Vents/well] | 1.0000 | 16.1795 | 2.2361 | 1152.0000 | 68.1449 | 2.0000 | 378.0000 |
| Internal_diam [in] | 9.6250 | 2.2952 | 1.9200 | 2.3750 | 4.1113 | 2.3750 | 4.7000 |
| Well_Depth [ft] | 15000.0000 | 10432.7709 | 7400.0000 | 11164.0000 | 11109.7685 | 10844.0000 | 11597.0000 |
| Pressure [psia] | 530.7000 | 248.7789 | 164.7000 | 304.7000 | 260.5359 | 212.7000 | 490.7000 |
| Flow_Rate_NG [ft3/hr] | 62500.0000 | 13225.0325 | 1916.6667 | 18916.6667 | 5632.0436 | 1730.8333 | 18041.6667 |
| Hour_Vent [hr] | 6.6700 | 1.5323 | 0.4070 | 2.1000 | 1.7686 | 0.7500 | 3.1800 |
| Plunger_Switch [binary] | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 0.0000 | 0.0000 | 0.0000 |

| Parameter Name | Scenario ID | | | | | |
|---|---|---|---|---|---|---|
| | 43 | 44 | 45 | 46 | 47 | 48 |
| | *Unconventional, Gulf Coast, Plunger, Expected* | *Unconventional, Gulf Coast, Plunger, Min* | *Unconventional, Gulf Coast, Plunger, Max* | *Unconventional, Gulf Coast, NO Plunger, Expected* | *Unconventional, Gulf Coast, NO Plunger, Min* | *Unconventional, Gulf Coast, NO Plunger, Max* |
| Vent_episode [Vents/well] | 2.3619 | 1.0000 | 52.0000 | 1.5644 | 0.6000 | 52.0000 |
| Internal_diam [in] | 2.3750 | 2.3750 | 2.3750 | 9.0418 | 4.5000 | 10.7500 |
| Well_Depth [ft] | 13331.7439 | 8500.0000 | 16000.0000 | 13395.4521 | 6000.0000 | 16000.0000 |
| Pressure [psia] | 483.8093 | 29.7000 | 554.7000 | 521.4117 | 29.7000 | 554.7000 |
| Flow_Rate_NG [ft3/hr] | 257910.4782 | 3458.3333 | 354166.6667 | 279991.7262 | 1041.6667 | 354166.6667 |
| Hour_Vent [hr] | 0.6722 | 0.3000 | 2.0000 | 1.3579 | 0.6875 | 5.3000 |
| Plunger_Switch [binary] | 1.0000 | 1.0000 | 1.0000 | 0.0000 | 0.0000 | 0.0000 |

**Table D-2: Natural Gas Extraction, Other Venting Fugitives**

| Parameter Name | Scenario ID | |
|---|---|---|
| | 1 | 2 |
| | *Natural Gas Extraction, Pneumatic Venting* | |
| | *Onshore* | *Offshore* |
| vent_rate [kg/kg] | 1.02E-03 | 2.41E-04 |
| share_CO2 [dimensionless] | 0.0152 | 0.0152 |
| share_CH4 [dimensionless] | 0.788 | 0.788 |
| share_NMVOC [dimensionless] | 0.179 | 0.179 |
| share_N2 [dimensionless] | 0.018 | 0.018 |

**Table D-3: Natural Gas Extraction, Other Venting Point Sources**

| Parameter Name | Scenario ID | |
|---|---|---|
| | 1 | 2 |
| | *Natural Gas Extraction, Pneumatic Venting* | |
| | *Onshore* | *Offshore* |
| Vent_rate [dimensionless] | 7.49E-05 | 3.90E-05 |

## Table D-4: Natural Gas Production Fugitive Emissions - Connections

| *Natural Gas Production Fugitive Emissions – Connections Gas Well* | | | | | | |
|---|---|---|---|---|---|---|
| **Parameter Name** | **Scenario ID** | | | | | |
| | **1** | **2** | **3** | **4** | **5** | **6** |
| | **Appalachian Basin** | **Black Warrior Basin** | **Central** | **Ft Worth Basin (Barnett)** | **Gulf Coast (onshore)** | **Illinois/Michigan Basins** |
| ***Avg_NG_Prod*** | 13816.5340 | 23522.6827 | 42612.1886 | 88451.8006 | 88927.7682 | 12008.4996 |
| ***C_Valve*** | 13.5831 | 13.8286 | 12.3757 | 13.8286 | 13.8286 | 13.8113 |
| ***C_Conn*** | 38.5248 | 39.0714 | 36.2220 | 39.0714 | 39.0714 | 39.0330 |
| ***C_Flange*** | 18.7743 | 21.6857 | 18.8735 | 21.6857 | 21.6857 | 21.6510 |
| ***C_OEL*** | 4.6609 | 5.2286 | 5.8558 | 5.2286 | 5.2286 | 5.2358 |
| ***WF_VOC*** | 0.1867 | 0.1867 | 0.1604 | 0.1484 | 0.1484 | 0.1852 |
| ***WF_H2S*** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_CO2*** | 0.0327 | 0.0327 | 0.0143 | 0.0253 | 0.0253 | 0.0327 |
| ***WF_CH4*** | 0.6722 | 0.6722 | 0.7434 | 0.7311 | 0.7311 | 0.6742 |
| ***WF_Benz*** | 0.0008 | 0.0008 | 0.0001 | 0.0002 | 0.0002 | 0.0008 |
| ***WF_Ebenz*** | 0.0000 | 0.0000 | 0.0001 | 0.0001 | 0.0001 | 0.0000 |
| ***WF_Tol*** | 0.0008 | 0.0008 | 0.0001 | 0.0000 | 0.0000 | 0.0007 |
| ***WF_Xyl*** | 0.0002 | 0.0002 | 0.0001 | 0.0001 | 0.0001 | 0.0002 |
| ***WF_N2*** | 0.0190 | 0.0190 | 0.0145 | 0.0169 | 0.0169 | 0.0189 |
| ***WF_C2H6*** | 0.0875 | 0.0875 | 0.0670 | 0.0778 | 0.0778 | 0.0870 |
| ***WF_trimetpen2*** | 8.24E-06 | 8.24E-06 | 7.08E-06 | 6.55E-06 | 6.55E-06 | 8.18E-06 |
| ***WF_cyclohexane*** | 1.07E-04 | 1.07E-04 | 9.16E-05 | 8.48E-05 | 8.48E-05 | 1.06E-04 |
| ***WF_cyclopentane*** | 3.61E-04 | 3.61E-04 | 3.10E-04 | 2.87E-04 | 2.87E-04 | 3.58E-04 |
| ***WF_isobut*** | 1.95E-02 | 1.95E-02 | 1.67E-02 | 1.55E-02 | 1.55E-02 | 1.93E-02 |
| ***WF_isopentane*** | 6.61E-03 | 6.61E-03 | 5.68E-03 | 5.26E-03 | 5.26E-03 | 6.56E-03 |
| ***WF_methcychex*** | 1.72E-04 | 1.72E-04 | 1.48E-04 | 1.37E-04 | 1.37E-04 | 1.71E-04 |
| ***WF_N_but*** | 3.60E-02 | 3.60E-02 | 3.10E-02 | 2.87E-02 | 2.87E-02 | 3.58E-02 |
| ***WF_N_hex*** | 1.29E-02 | 1.29E-02 | 1.11E-02 | 1.02E-02 | 1.02E-02 | 1.28E-02 |
| ***WF_N_pentane*** | 8.31E-03 | 8.31E-03 | 7.14E-03 | 6.61E-03 | 6.61E-03 | 8.25E-03 |
| ***WF_C3H8ass*** | 9.11E-02 | 9.11E-02 | 7.83E-02 | 7.24E-02 | 7.24E-02 | 9.04E-02 |
| ***WF_i_heptanes*** | 8.43E-04 | 8.43E-04 | 7.24E-04 | 6.70E-04 | 6.70E-04 | 8.37E-04 |
| ***WF_i_hexanes*** | 8.44E-04 | 8.44E-04 | 7.25E-04 | 6.71E-04 | 6.71E-04 | 8.38E-04 |
| ***WF_undef_VOC*** | 9.90E-03 | 9.90E-03 | 8.51E-03 | 7.87E-03 | 7.87E-03 | 9.83E-03 |
| ***MW_VOC*** | 55.3283 | 55.3283 | 55.5986 | 55.3283 | 55.3283 | 55.2978 |
| ***MW_Gas*** | 19.8748 | 19.8748 | 18.9307 | 18.9974 | 18.9974 | 19.8442 |
| ***OP_HR*** | 7618.8377 | 8760.0000 | 8760.0000 | 8760.0000 | 8760.0000 | 8760.0000 |
| ***NG_Conn*** | 0.00020677 | 0.00020677 | 0.00020292 | 0.00020520 | 0.00020520 | 0.00020677 |

**Table D-4: Natural Gas Production Fugitive Emissions – Connections, continued**

| Parameter Name | Scenario ID | | | | |
|---|---|---|---|---|---|
| | 7 | 8 | 9 | 10 | 11 |
| | North-Central | Rocky Mountains | TX-LA-MS Salt Basin | West coast (onshore) | West Texas/Permian Basin |
| ***Avg_NG_Prod*** | 18489.6325 | 63670.1644 | 112913.3906 | 60539.0682 | 28294.9264 |
| ***C_Valve*** | 27.0221 | 29.6167 | 13.0969 | 13.8286 | 18.4998 |
| ***C_Conn*** | 90.0660 | 47.4532 | 37.4424 | 39.0714 | 42.4999 |
| ***C_Flange*** | 21.5539 | 38.1386 | 20.2110 | 21.6857 | 28.9997 |
| ***C_OEL*** | 2.2714 | 7.2609 | 5.5372 | 5.2286 | 3.0001 |
| ***WF_VOC*** | 0.2761 | 0.1340 | 0.1355 | 0.1867 | 0.1956 |
| ***WF_H2S*** | 0.0000 | 0.0024 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_CO2*** | 0.0327 | 0.0473 | 0.0362 | 0.0327 | 0.0450 |
| ***WF_CH4*** | 0.6722 | 0.6910 | 0.7413 | 0.6722 | 0.5628 |
| ***WF_Benz*** | 0.0008 | 0.0004 | 0.0005 | 0.0008 | 0.0000 |
| ***WF_Ebenz*** | 0.0000 | 0.0000 | 0.0001 | 0.0000 | 0.0000 |
| ***WF_Tol*** | 0.0008 | 0.0005 | 0.0000 | 0.0008 | 0.0000 |
| ***WF_Xyl*** | 0.0002 | 0.0002 | 0.0001 | 0.0002 | 0.0000 |
| ***WF_N2*** | 0.0030 | 0.0222 | 0.0154 | 0.0190 | 0.0350 |
| ***WF_C2H6*** | 0.0140 | 0.1021 | 0.0709 | 0.0875 | 0.1615 |
| ***WF_trimetpen2*** | 1.22E-05 | 5.92E-06 | 5.98E-06 | 8.24E-06 | 8.64E-06 |
| ***WF_cyclohexane*** | 1.58E-04 | 7.66E-05 | 7.74E-05 | 1.07E-04 | 1.12E-04 |
| ***WF_cyclopentane*** | 5.34E-04 | 2.59E-04 | 2.62E-04 | 3.61E-04 | 3.78E-04 |
| ***WF_isobut*** | 2.88E-02 | 1.40E-02 | 1.41E-02 | 1.95E-02 | 2.04E-02 |
| ***WF_isopentane*** | 9.78E-03 | 4.75E-03 | 4.80E-03 | 6.61E-03 | 6.93E-03 |
| ***WF_methcychex*** | 2.55E-04 | 1.24E-04 | 1.25E-04 | 1.72E-04 | 1.81E-04 |
| ***WF_N_but*** | 5.33E-02 | 2.59E-02 | 2.62E-02 | 3.60E-02 | 3.78E-02 |
| ***WF_N_hex*** | 1.90E-02 | 9.24E-03 | 9.34E-03 | 1.29E-02 | 1.35E-02 |
| ***WF_N_pentane*** | 1.23E-02 | 5.97E-03 | 6.03E-03 | 8.31E-03 | 8.71E-03 |
| ***WF_C3H8ass*** | 1.35E-01 | 6.54E-02 | 6.61E-02 | 9.11E-02 | 9.55E-02 |
| ***WF_i_heptanes*** | 1.25E-03 | 6.05E-04 | 6.12E-04 | 8.43E-04 | 8.83E-04 |
| ***WF_i_hexanes*** | 1.25E-03 | 6.06E-04 | 6.13E-04 | 8.44E-04 | 8.85E-04 |
| ***WF_undef_VOC*** | 1.47E-02 | 7.11E-03 | 7.19E-03 | 9.90E-03 | 1.04E-02 |
| ***MW_VOC*** | 53.9072 | 54.8723 | 56.9991 | 55.3283 | 50.6362 |
| ***MW_Gas*** | 20.6269 | 19.3559 | 18.9110 | 19.8748 | 20.8997 |
| ***OP_HR*** | 8760.0000 | 8760.0000 | 8760.0000 | 8760.0000 | 8760.0000 |
| ***NG_Conn*** | 0.00020677 | 0.00021046 | 0.00020752 | 0.00020677 | 0.00020943 |

**Table D-4: Natural Gas Production Fugitive Emissions – Connections, continued**

| *Natural Gas Production Fugitive Emissions – Connections CBM* | | | | | | |
|---|---|---|---|---|---|---|
| **Parameter Name** | **Scenario ID** | | | | | |
| | **1** | **2** | **3** | **4** | **5** | **6** |
| | **Appalachian Basin** | **Black Warrior Basin** | **Central** | **Ft Worth Basin (Barnett)** | **Gulf Coast (onshore)** | **Illinois/Michigan Basins** |
| ***Avg_NG_Prod*** | 22183.3258 | 16255.6969 | 9108.2858 | 0.0000 | 0.0000 | 0.0000 |
| ***C_Valve*** | 13.8286 | 13.8286 | 12.7566 | 0.0000 | 0.0000 | 0.0000 |
| ***C_Conn*** | 39.0714 | 39.0714 | 36.6868 | 0.0000 | 0.0000 | 0.0000 |
| ***C_Flange*** | 21.6857 | 21.6857 | 19.5257 | 0.0000 | 0.0000 | 0.0000 |
| ***C_OEL*** | 5.2286 | 5.2286 | 5.6809 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_VOC*** | 0.1867 | 0.1867 | 0.0815 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_H2S*** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_CO2*** | 0.0327 | 0.0327 | 0.0308 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_CH4*** | 0.6722 | 0.6722 | 0.8195 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_Benz*** | 0.0008 | 0.0008 | 0.0001 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_Ebenz*** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_Tol*** | 0.0008 | 0.0008 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_Xyl*** | 0.0002 | 0.0002 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_N2*** | 0.0190 | 0.0190 | 0.0121 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_C2H6*** | 0.0875 | 0.0875 | 0.0559 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_trimetpen2*** | 8.24E-06 | 8.24E-06 | 3.60E-06 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_cyclohexane*** | 1.07E-04 | 1.07E-04 | 4.66E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_cyclopentane*** | 3.61E-04 | 3.61E-04 | 1.58E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_isobut*** | 1.95E-02 | 1.95E-02 | 8.50E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_isopentane*** | 6.61E-03 | 6.61E-03 | 2.89E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_methcychex*** | 1.72E-04 | 1.72E-04 | 7.53E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_N_but*** | 3.60E-02 | 3.60E-02 | 1.57E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_N_hex*** | 1.29E-02 | 1.29E-02 | 5.62E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_N_pentane*** | 8.31E-03 | 8.31E-03 | 3.63E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_C3H8ass*** | 9.11E-02 | 9.11E-02 | 3.98E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_i_heptanes*** | 8.43E-04 | 8.43E-04 | 3.68E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_i_hexanes*** | 8.44E-04 | 8.44E-04 | 3.69E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_undef_VOC*** | 9.90E-03 | 9.90E-03 | 4.33E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***MW_VOC*** | 55.3283 | 55.3283 | 53.4344 | 0.0000 | 0.0000 | 0.0000 |
| ***MW_Gas*** | 19.8748 | 19.8748 | 17.8431 | 0.0000 | 0.0000 | 0.0000 |
| ***OP_HR*** | 8760.0000 | 8760.0000 | 8760.0000 | 0.0000 | 0.0000 | 0.0000 |
| ***NG_Conn*** | 0.00020677 | 0.00020677 | 0.00020635 | 0.00000000 | 0.00000000 | 0.00000000 |

## Table D-5: Natural Gas Production Fugitive Emissions - Flanges

| *Natural Gas Production Fugitive Emissions – Flanges Gas Well* | | | | | | |
|---|---|---|---|---|---|---|
| **Parameter Name** | **Scenario ID** | | | | | |
| | **1** | **2** | **3** | **4** | **5** | **6** |
| | **Appalachian Basin** | **Black Warrior Basin** | **Central** | **Ft Worth Basin (Barnett)** | **Gulf Coast (onshore)** | **Illinois/Michigan Basins** |
| ***Avg_NG_Prod*** | 13816.5340 | 23522.6827 | 42612.1886 | 88451.8006 | 88927.7682 | 12008.4996 |
| ***C_Valve*** | 13.5831 | 13.8286 | 12.3757 | 13.8286 | 13.8286 | 13.8113 |
| ***C_Conn*** | 38.5248 | 39.0714 | 36.2220 | 39.0714 | 39.0714 | 39.0330 |
| ***C_Flange*** | 18.7743 | 21.6857 | 18.8735 | 21.6857 | 21.6857 | 21.6510 |
| ***C_OEL*** | 4.6609 | 5.2286 | 5.8558 | 5.2286 | 5.2286 | 5.2358 |
| ***WF_VOC*** | 0.1867 | 0.1867 | 0.1604 | 0.1484 | 0.1484 | 0.1852 |
| ***WF_H2S*** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_CO2*** | 0.0327 | 0.0327 | 0.0143 | 0.0253 | 0.0253 | 0.0327 |
| ***WF_CH4*** | 0.6722 | 0.6722 | 0.7434 | 0.7311 | 0.7311 | 0.6742 |
| ***WF_Benz*** | 0.0008 | 0.0008 | 0.0001 | 0.0002 | 0.0002 | 0.0008 |
| ***WF_Ebenz*** | 0.0000 | 0.0000 | 0.0001 | 0.0001 | 0.0001 | 0.0000 |
| ***WF_Tol*** | 0.0008 | 0.0008 | 0.0001 | 0.0000 | 0.0000 | 0.0007 |
| ***WF_Xyl*** | 0.0002 | 0.0002 | 0.0001 | 0.0001 | 0.0001 | 0.0002 |
| ***WF_N2*** | 0.0190 | 0.0190 | 0.0145 | 0.0169 | 0.0169 | 0.0189 |
| ***WF_C2H6*** | 0.0875 | 0.0875 | 0.0670 | 0.0778 | 0.0778 | 0.0870 |
| ***WF_trimetpen2*** | 8.24E-06 | 8.24E-06 | 7.08E-06 | 6.55E-06 | 6.55E-06 | 8.18E-06 |
| ***WF_cyclohexane*** | 1.07E-04 | 1.07E-04 | 9.16E-05 | 8.48E-05 | 8.48E-05 | 1.06E-04 |
| ***WF_cyclopentane*** | 3.61E-04 | 3.61E-04 | 3.10E-04 | 2.87E-04 | 2.87E-04 | 3.58E-04 |
| ***WF_isobut*** | 1.95E-02 | 1.95E-02 | 1.67E-02 | 1.55E-02 | 1.55E-02 | 1.93E-02 |
| ***WF_isopentane*** | 6.61E-03 | 6.61E-03 | 5.68E-03 | 5.26E-03 | 5.26E-03 | 6.56E-03 |
| ***WF_methcychex*** | 1.72E-04 | 1.72E-04 | 1.48E-04 | 1.37E-04 | 1.37E-04 | 1.71E-04 |
| ***WF_N_but*** | 3.60E-02 | 3.60E-02 | 3.10E-02 | 2.87E-02 | 2.87E-02 | 3.58E-02 |
| ***WF_N_hex*** | 1.29E-02 | 1.29E-02 | 1.11E-02 | 1.02E-02 | 1.02E-02 | 1.28E-02 |
| ***WF_N_pentane*** | 8.31E-03 | 8.31E-03 | 7.14E-03 | 6.61E-03 | 6.61E-03 | 8.25E-03 |
| ***WF_C3H8ass*** | 9.11E-02 | 9.11E-02 | 7.83E-02 | 7.24E-02 | 7.24E-02 | 9.04E-02 |
| ***WF_i_heptanes*** | 8.43E-04 | 8.43E-04 | 7.24E-04 | 6.70E-04 | 6.70E-04 | 8.37E-04 |
| ***WF_i_hexanes*** | 8.44E-04 | 8.44E-04 | 7.25E-04 | 6.71E-04 | 6.71E-04 | 8.38E-04 |
| ***WF_undef_VOC*** | 9.90E-03 | 9.90E-03 | 8.51E-03 | 7.87E-03 | 7.87E-03 | 9.83E-03 |
| ***MW_VOC*** | 55.3283 | 55.3283 | 55.5986 | 55.3283 | 55.3283 | 55.2978 |
| ***MW_Gas*** | 19.8748 | 19.8748 | 18.9307 | 18.9974 | 18.9974 | 19.8442 |
| ***OP_HR*** | 7618.8377 | 8760.0000 | 8760.0000 | 8760.0000 | 8760.0000 | 8760.0000 |
| ***NG_Flange*** | 0.00040320 | 0.00040320 | 0.00039569 | 0.00040014 | 0.00040014 | 0.00040321 |

**Table D-5: Natural Gas Production Fugitive Emissions – Flanges, continued**

| Parameter Name | Scenario ID | | | | |
|---|---|---|---|---|---|
| | 7 | 8 | 9 | 10 | 11 |
| | North-Central | Rocky Mountains | TX-LA-MS Salt Basin | West coast (onshore) | West Texas/Permian Basin |
| ***Avg_NG_Prod*** | 18489.6325 | 63670.1644 | 112913.3906 | 60539.0682 | 28294.9264 |
| ***C_Valve*** | 27.0221 | 29.6167 | 13.0969 | 13.8286 | 18.4998 |
| ***C_Conn*** | 90.0660 | 47.4532 | 37.4424 | 39.0714 | 42.4999 |
| ***C_Flange*** | 21.5539 | 38.1386 | 20.2110 | 21.6857 | 28.9997 |
| ***C_OEL*** | 2.2714 | 7.2609 | 5.5372 | 5.2286 | 3.0001 |
| ***WF_VOC*** | 0.2761 | 0.1340 | 0.1355 | 0.1867 | 0.1956 |
| ***WF_H2S*** | 0.0000 | 0.0024 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_CO2*** | 0.0327 | 0.0473 | 0.0362 | 0.0327 | 0.0450 |
| ***WF_CH4*** | 0.6722 | 0.6910 | 0.7413 | 0.6722 | 0.5628 |
| ***WF_Benz*** | 0.0008 | 0.0004 | 0.0005 | 0.0008 | 0.0000 |
| ***WF_Ebenz*** | 0.0000 | 0.0000 | 0.0001 | 0.0000 | 0.0000 |
| ***WF_Tol*** | 0.0008 | 0.0005 | 0.0000 | 0.0008 | 0.0000 |
| ***WF_Xyl*** | 0.0002 | 0.0002 | 0.0001 | 0.0002 | 0.0000 |
| ***WF_N2*** | 0.0030 | 0.0222 | 0.0154 | 0.0190 | 0.0350 |
| ***WF_C2H6*** | 0.0140 | 0.1021 | 0.0709 | 0.0875 | 0.1615 |
| ***WF_trimetpen2*** | 1.22E-05 | 5.92E-06 | 5.98E-06 | 8.24E-06 | 8.64E-06 |
| ***WF_cyclohexane*** | 1.58E-04 | 7.66E-05 | 7.74E-05 | 1.07E-04 | 1.12E-04 |
| ***WF_cyclopentane*** | 5.34E-04 | 2.59E-04 | 2.62E-04 | 3.61E-04 | 3.78E-04 |
| ***WF_isobut*** | 2.88E-02 | 1.40E-02 | 1.41E-02 | 1.95E-02 | 2.04E-02 |
| ***WF_isopentane*** | 9.78E-03 | 4.75E-03 | 4.80E-03 | 6.61E-03 | 6.93E-03 |
| ***WF_methcychex*** | 2.55E-04 | 1.24E-04 | 1.25E-04 | 1.72E-04 | 1.81E-04 |
| ***WF_N_but*** | 5.33E-02 | 2.59E-02 | 2.62E-02 | 3.60E-02 | 3.78E-02 |
| ***WF_N_hex*** | 1.90E-02 | 9.24E-03 | 9.34E-03 | 1.29E-02 | 1.35E-02 |
| ***WF_N_pentane*** | 1.23E-02 | 5.97E-03 | 6.03E-03 | 8.31E-03 | 8.71E-03 |
| ***WF_C3H8ass*** | 1.35E-01 | 6.54E-02 | 6.61E-02 | 9.11E-02 | 9.55E-02 |
| ***WF_i_heptanes*** | 1.25E-03 | 6.05E-04 | 6.12E-04 | 8.43E-04 | 8.83E-04 |
| ***WF_i_hexanes*** | 1.25E-03 | 6.06E-04 | 6.13E-04 | 8.44E-04 | 8.85E-04 |
| ***WF_undef_VOC*** | 1.47E-02 | 7.11E-03 | 7.19E-03 | 9.90E-03 | 1.04E-02 |
| ***MW_VOC*** | 53.9072 | 54.8723 | 56.9991 | 55.3283 | 50.6362 |
| ***MW_Gas*** | 20.6269 | 19.3559 | 18.9110 | 19.8748 | 20.8997 |
| ***OP_HR*** | 8760.0000 | 8760.0000 | 8760.0000 | 8760.0000 | 8760.0000 |
| ***NG_Flange*** | 0.00040320 | 0.00041039 | 0.00040466 | 0.00040320 | 0.00040838 |

**Table D-5: Natural Gas Production Fugitive Emissions – Flanges, continued**

| *Natural Gas Production Fugitive Emissions – Flanges CBM* | | | | | | |
|---|---|---|---|---|---|---|
| Parameter Name | Scenario ID | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 |
| | Appalachian Basin | Black Warrior Basin | Central | Ft Worth Basin (Barnett) | Gulf Coast (onshore) | Illinois/Michigan Basins |
| *Avg_NG_Prod* | 22183.3258 | 16255.6969 | 9108.2858 | 0.0000 | 0.0000 | 0.0000 |
| *C_Valve* | 13.8286 | 13.8286 | 12.7566 | 0.0000 | 0.0000 | 0.0000 |
| *C_Conn* | 39.0714 | 39.0714 | 36.6868 | 0.0000 | 0.0000 | 0.0000 |
| *C_Flange* | 21.6857 | 21.6857 | 19.5257 | 0.0000 | 0.0000 | 0.0000 |
| *C_OEL* | 5.2286 | 5.2286 | 5.6809 | 0.0000 | 0.0000 | 0.0000 |
| *WF_VOC* | 0.1867 | 0.1867 | 0.0815 | 0.0000 | 0.0000 | 0.0000 |
| *WF_H2S* | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| *WF_CO2* | 0.0327 | 0.0327 | 0.0308 | 0.0000 | 0.0000 | 0.0000 |
| *WF_CH4* | 0.6722 | 0.6722 | 0.8195 | 0.0000 | 0.0000 | 0.0000 |
| *WF_Benz* | 0.0008 | 0.0008 | 0.0001 | 0.0000 | 0.0000 | 0.0000 |
| *WF_Ebenz* | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| *WF_Tol* | 0.0008 | 0.0008 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| *WF_Xyl* | 0.0002 | 0.0002 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| *WF_N2* | 0.0190 | 0.0190 | 0.0121 | 0.0000 | 0.0000 | 0.0000 |
| *WF_C2H6* | 0.0875 | 0.0875 | 0.0559 | 0.0000 | 0.0000 | 0.0000 |
| *WF_trimetpen2* | 8.24E-06 | 8.24E-06 | 3.60E-06 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_cyclohexane* | 1.07E-04 | 1.07E-04 | 4.66E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_cyclopentane* | 3.61E-04 | 3.61E-04 | 1.58E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_isobut* | 1.95E-02 | 1.95E-02 | 8.50E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_isopentane* | 6.61E-03 | 6.61E-03 | 2.89E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_methcychex* | 1.72E-04 | 1.72E-04 | 7.53E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_N_but* | 3.60E-02 | 3.60E-02 | 1.57E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_N_hex* | 1.29E-02 | 1.29E-02 | 5.62E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_N_pentane* | 8.31E-03 | 8.31E-03 | 3.63E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_C3H8ass* | 9.11E-02 | 9.11E-02 | 3.98E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_i_heptanes* | 8.43E-04 | 8.43E-04 | 3.68E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_i_hexanes* | 8.44E-04 | 8.44E-04 | 3.69E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_undef_VOC* | 9.90E-03 | 9.90E-03 | 4.33E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *MW_VOC* | 55.3283 | 55.3283 | 53.4344 | 0.0000 | 0.0000 | 0.0000 |
| *MW_Gas* | 19.8748 | 19.8748 | 17.8431 | 0.0000 | 0.0000 | 0.0000 |
| *OP_HR* | 8760.0000 | 8760.0000 | 8760.0000 | 0.0000 | 0.0000 | 0.0000 |
| *NG_Flange* | 0.00040320 | 0.00040320 | 0.00040238 | 0.00000000 | 0.00000000 | 0.00000000 |

**Table D-5: Natural Gas Production Fugitive Emissions – Flanges, continued**

| Parameter Name | Scenario ID | | | | |
|---|---|---|---|---|---|
| | 7 | 8 | 9 | 10 | 11 |
| | North-Central | Rocky Mountains | TX-LA-MS Salt Basin | West coast (onshore) | West Texas/Permian Basin |
| *Avg_NG_Prod* | 0.0000 | 58059.8950 | 1498215.5000 | 0.0000 | 0.0000 |
| *C_Valve* | 0.0000 | 13.3109 | 13.8286 | 0.0000 | 0.0000 |
| *C_Conn* | 0.0000 | 30.0666 | 39.0714 | 0.0000 | 0.0000 |
| *C_Flange* | 0.0000 | 20.5772 | 21.6857 | 0.0000 | 0.0000 |
| *C_OEL* | 0.0000 | 2.3547 | 5.2286 | 0.0000 | 0.0000 |
| *WF_VOC* | 0.0000 | 0.0335 | 0.1484 | 0.0000 | 0.0000 |
| *WF_H2S* | 0.0000 | 0.0002 | 0.0000 | 0.0000 | 0.0000 |
| *WF_CO2* | 0.0000 | 0.1235 | 0.0253 | 0.0000 | 0.0000 |
| *WF_CH4* | 0.0000 | 0.8201 | 0.7311 | 0.0000 | 0.0000 |
| *WF_Benz* | 0.0000 | 0.0001 | 0.0002 | 0.0000 | 0.0000 |
| *WF_Ebenz* | 0.0000 | 0.0000 | 0.0001 | 0.0000 | 0.0000 |
| *WF_Tol* | 0.0000 | 0.0001 | 0.0000 | 0.0000 | 0.0000 |
| *WF_Xyl* | 0.0000 | 0.0000 | 0.0001 | 0.0000 | 0.0000 |
| *WF_N2* | 0.0000 | 0.0040 | 0.0169 | 0.0000 | 0.0000 |
| *WF_C2H6* | 0.0000 | 0.0183 | 0.0778 | 0.0000 | 0.0000 |
| *WF_trimetpen2* | 0.00E+00 | 1.48E-06 | 6.55E-06 | 0.00E+00 | 0.00E+00 |
| *WF_cyclohexane* | 0.00E+00 | 1.91E-05 | 8.48E-05 | 0.00E+00 | 0.00E+00 |
| *WF_cyclopentane* | 0.00E+00 | 6.48E-05 | 2.87E-04 | 0.00E+00 | 0.00E+00 |
| *WF_isobut* | 0.00E+00 | 3.50E-03 | 1.55E-02 | 0.00E+00 | 0.00E+00 |
| *WF_isopentane* | 0.00E+00 | 1.19E-03 | 5.26E-03 | 0.00E+00 | 0.00E+00 |
| *WF_methcychex* | 0.00E+00 | 3.10E-05 | 1.37E-04 | 0.00E+00 | 0.00E+00 |
| *WF_N_but* | 0.00E+00 | 6.47E-03 | 2.87E-02 | 0.00E+00 | 0.00E+00 |
| *WF_N_hex* | 0.00E+00 | 2.31E-03 | 1.02E-02 | 0.00E+00 | 0.00E+00 |
| *WF_N_pentane* | 0.00E+00 | 1.49E-03 | 6.61E-03 | 0.00E+00 | 0.00E+00 |
| *WF_C3H8ass* | 0.00E+00 | 1.64E-02 | 7.24E-02 | 0.00E+00 | 0.00E+00 |
| *WF_i_heptanes* | 0.00E+00 | 1.51E-04 | 6.70E-04 | 0.00E+00 | 0.00E+00 |
| *WF_i_hexanes* | 0.00E+00 | 1.52E-04 | 6.71E-04 | 0.00E+00 | 0.00E+00 |
| *WF_undef_VOC* | 0.00E+00 | 1.78E-03 | 7.87E-03 | 0.00E+00 | 0.00E+00 |
| *MW_VOC* | 0.0000 | 59.2686 | 55.3283 | 0.0000 | 0.0000 |
| *MW_Gas* | 0.0000 | 18.0484 | 18.9974 | 0.0000 | 0.0000 |
| *OP_HR* | 0.0000 | 8760.0000 | 8760.0000 | 0.0000 | 0.0000 |
| *NG_Flange* | 0.00000000 | 0.00044506 | 0.00040014 | 0.00000000 | 0.00000000 |

## Table D-6: Natural Gas Production Fugitive Emissions - OEL

| *Natural Gas Production Fugitive Emissions – OEL Gas Well* | | | | | | |
|---|---|---|---|---|---|---|
| **Parameter Name** | **Scenario ID** | | | | | |
| | **1** | **2** | **3** | **4** | **5** | **6** |
| | **Appalachian Basin** | **Black Warrior Basin** | **Central** | **Ft Worth Basin (Barnett)** | **Gulf Coast (onshore)** | **Illinois/Michigan Basins** |
| ***Avg_NG_Prod*** | 13816.5340 | 23522.6827 | 42612.1886 | 88451.8006 | 88927.7682 | 12008.4996 |
| ***C_Valve*** | 13.5831 | 13.8286 | 12.3757 | 13.8286 | 13.8286 | 13.8113 |
| ***C_Conn*** | 38.5248 | 39.0714 | 36.2220 | 39.0714 | 39.0714 | 39.0330 |
| ***C_Flange*** | 18.7743 | 21.6857 | 18.8735 | 21.6857 | 21.6857 | 21.6510 |
| ***C_OEL*** | 4.6609 | 5.2286 | 5.8558 | 5.2286 | 5.2286 | 5.2358 |
| ***WF_VOC*** | 0.1867 | 0.1867 | 0.1604 | 0.1484 | 0.1484 | 0.1852 |
| ***WF_H2S*** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_CO2*** | 0.0327 | 0.0327 | 0.0143 | 0.0253 | 0.0253 | 0.0327 |
| ***WF_CH4*** | 0.6722 | 0.6722 | 0.7434 | 0.7311 | 0.7311 | 0.6742 |
| ***WF_Benz*** | 0.0008 | 0.0008 | 0.0001 | 0.0002 | 0.0002 | 0.0008 |
| ***WF_Ebenz*** | 0.0000 | 0.0000 | 0.0001 | 0.0001 | 0.0001 | 0.0000 |
| ***WF_Tol*** | 0.0008 | 0.0008 | 0.0001 | 0.0000 | 0.0000 | 0.0007 |
| ***WF_Xyl*** | 0.0002 | 0.0002 | 0.0001 | 0.0001 | 0.0001 | 0.0002 |
| ***WF_N2*** | 0.0190 | 0.0190 | 0.0145 | 0.0169 | 0.0169 | 0.0189 |
| ***WF_C2H6*** | 0.0875 | 0.0875 | 0.0670 | 0.0778 | 0.0778 | 0.0870 |
| ***WF_trimetpen2*** | 8.24E-06 | 8.24E-06 | 7.08E-06 | 6.55E-06 | 6.55E-06 | 8.18E-06 |
| ***WF_cyclohexane*** | 1.07E-04 | 1.07E-04 | 9.16E-05 | 8.48E-05 | 8.48E-05 | 1.06E-04 |
| ***WF_cyclopentane*** | 3.61E-04 | 3.61E-04 | 3.10E-04 | 2.87E-04 | 2.87E-04 | 3.58E-04 |
| ***WF_isobut*** | 1.95E-02 | 1.95E-02 | 1.67E-02 | 1.55E-02 | 1.55E-02 | 1.93E-02 |
| ***WF_isopentane*** | 6.61E-03 | 6.61E-03 | 5.68E-03 | 5.26E-03 | 5.26E-03 | 6.56E-03 |
| ***WF_methcychex*** | 1.72E-04 | 1.72E-04 | 1.48E-04 | 1.37E-04 | 1.37E-04 | 1.71E-04 |
| ***WF_N_but*** | 3.60E-02 | 3.60E-02 | 3.10E-02 | 2.87E-02 | 2.87E-02 | 3.58E-02 |
| ***WF_N_hex*** | 1.29E-02 | 1.29E-02 | 1.11E-02 | 1.02E-02 | 1.02E-02 | 1.28E-02 |
| ***WF_N_pentane*** | 8.31E-03 | 8.31E-03 | 7.14E-03 | 6.61E-03 | 6.61E-03 | 8.25E-03 |
| ***WF_C3H8ass*** | 9.11E-02 | 9.11E-02 | 7.83E-02 | 7.24E-02 | 7.24E-02 | 9.04E-02 |
| ***WF_i_heptanes*** | 8.43E-04 | 8.43E-04 | 7.24E-04 | 6.70E-04 | 6.70E-04 | 8.37E-04 |
| ***WF_i_hexanes*** | 8.44E-04 | 8.44E-04 | 7.25E-04 | 6.71E-04 | 6.71E-04 | 8.38E-04 |
| ***WF_undef_VOC*** | 9.90E-03 | 9.90E-03 | 8.51E-03 | 7.87E-03 | 7.87E-03 | 9.83E-03 |
| ***MW_VOC*** | 55.3283 | 55.3283 | 55.5986 | 55.3283 | 55.3283 | 55.2978 |
| ***MW_Gas*** | 19.8748 | 19.8748 | 18.9307 | 18.9974 | 18.9974 | 19.8442 |
| ***OP_HR*** | 7618.83766 | 8760.00000 | 8760.00000 | 8760.00000 | 8760.00000 | 8760.00000 |
| ***NG_OEL*** | 0.00207 | 0.00207 | 0.00203 | 0.00205 | 0.00205 | 0.00207 |

**Table D-6: Natural Gas Production Fugitive Emissions – OEL, continued**

| Parameter Name | Scenario ID | | | | |
|---|---|---|---|---|---|
| | 7 | 8 | 9 | 10 | 11 |
| | North-Central | Rocky Mountains | TX-LA-MS Salt Basin | West coast (onshore) | West Texas/Permian Basin |
| ***Avg_NG_Prod*** | 18489.6325 | 63670.1644 | 112913.3906 | 60539.0682 | 28294.9264 |
| ***C_Valve*** | 27.0221 | 29.6167 | 13.0969 | 13.8286 | 18.4998 |
| ***C_Conn*** | 90.0660 | 47.4532 | 37.4424 | 39.0714 | 42.4999 |
| ***C_Flange*** | 21.5539 | 38.1386 | 20.2110 | 21.6857 | 28.9997 |
| ***C_OEL*** | 2.2714 | 7.2609 | 5.5372 | 5.2286 | 3.0001 |
| ***WF_VOC*** | 0.2761 | 0.1340 | 0.1355 | 0.1867 | 0.1956 |
| ***WF_H2S*** | 0.0000 | 0.0024 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_CO2*** | 0.0327 | 0.0473 | 0.0362 | 0.0327 | 0.0450 |
| ***WF_CH4*** | 0.6722 | 0.6910 | 0.7413 | 0.6722 | 0.5628 |
| ***WF_Benz*** | 0.0008 | 0.0004 | 0.0005 | 0.0008 | 0.0000 |
| ***WF_Ebenz*** | 0.0000 | 0.0000 | 0.0001 | 0.0000 | 0.0000 |
| ***WF_Tol*** | 0.0008 | 0.0005 | 0.0000 | 0.0008 | 0.0000 |
| ***WF_Xyl*** | 0.0002 | 0.0002 | 0.0001 | 0.0002 | 0.0000 |
| ***WF_N2*** | 0.0030 | 0.0222 | 0.0154 | 0.0190 | 0.0350 |
| ***WF_C2H6*** | 0.0140 | 0.1021 | 0.0709 | 0.0875 | 0.1615 |
| ***WF_trimetpen2*** | 1.22E-05 | 5.92E-06 | 5.98E-06 | 8.24E-06 | 8.64E-06 |
| ***WF_cyclohexane*** | 1.58E-04 | 7.66E-05 | 7.74E-05 | 1.07E-04 | 1.12E-04 |
| ***WF_cyclopentane*** | 5.34E-04 | 2.59E-04 | 2.62E-04 | 3.61E-04 | 3.78E-04 |
| ***WF_isobut*** | 2.88E-02 | 1.40E-02 | 1.41E-02 | 1.95E-02 | 2.04E-02 |
| ***WF_isopentane*** | 9.78E-03 | 4.75E-03 | 4.80E-03 | 6.61E-03 | 6.93E-03 |
| ***WF_methcychex*** | 2.55E-04 | 1.24E-04 | 1.25E-04 | 1.72E-04 | 1.81E-04 |
| ***WF_N_but*** | 5.33E-02 | 2.59E-02 | 2.62E-02 | 3.60E-02 | 3.78E-02 |
| ***WF_N_hex*** | 1.90E-02 | 9.24E-03 | 9.34E-03 | 1.29E-02 | 1.35E-02 |
| ***WF_N_pentane*** | 1.23E-02 | 5.97E-03 | 6.03E-03 | 8.31E-03 | 8.71E-03 |
| ***WF_C3H8ass*** | 1.35E-01 | 6.54E-02 | 6.61E-02 | 9.11E-02 | 9.55E-02 |
| ***WF_i_heptanes*** | 1.25E-03 | 6.05E-04 | 6.12E-04 | 8.43E-04 | 8.83E-04 |
| ***WF_i_hexanes*** | 1.25E-03 | 6.06E-04 | 6.13E-04 | 8.44E-04 | 8.85E-04 |
| ***WF_undef_VOC*** | 1.47E-02 | 7.11E-03 | 7.19E-03 | 9.90E-03 | 1.04E-02 |
| ***MW_VOC*** | 53.9072 | 54.8723 | 56.9991 | 55.3283 | 50.6362 |
| ***MW_Gas*** | 20.6269 | 19.3559 | 18.9110 | 19.8748 | 20.8997 |
| ***OP_HR*** | 8760.00000 | 8760.00000 | 8760.00000 | 8760.00000 | 8760.00000 |
| ***NG_OEL*** | 0.00207 | 0.00210 | 0.00208 | 0.00207 | 0.00209 |

**Table D-6: Natural Gas Production Fugitive Emissions – OEL, continued**

| *Natural Gas Production Fugitive Emissions – OEL CBM* | | | | | | |
|---|---|---|---|---|---|---|
| Parameter Name | Scenario ID | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 |
| | Appalachian Basin | Black Warrior Basin | Central | Ft Worth Basin (Barnett) | Gulf Coast (onshore) | Illinois/Michigan Basins |
| *Avg_NG_Prod* | 22183.3258 | 16255.6969 | 9108.2858 | 0.0000 | 0.0000 | 0.0000 |
| *C_Valve* | 13.8286 | 13.8286 | 12.7566 | 0.0000 | 0.0000 | 0.0000 |
| *C_Conn* | 39.0714 | 39.0714 | 36.6868 | 0.0000 | 0.0000 | 0.0000 |
| *C_Flange* | 21.6857 | 21.6857 | 19.5257 | 0.0000 | 0.0000 | 0.0000 |
| *C_OEL* | 5.2286 | 5.2286 | 5.6809 | 0.0000 | 0.0000 | 0.0000 |
| *WF_VOC* | 0.1867 | 0.1867 | 0.0815 | 0.0000 | 0.0000 | 0.0000 |
| *WF_H2S* | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| *WF_CO2* | 0.0327 | 0.0327 | 0.0308 | 0.0000 | 0.0000 | 0.0000 |
| *WF_CH4* | 0.6722 | 0.6722 | 0.8195 | 0.0000 | 0.0000 | 0.0000 |
| *WF_Benz* | 0.0008 | 0.0008 | 0.0001 | 0.0000 | 0.0000 | 0.0000 |
| *WF_Ebenz* | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| *WF_Tol* | 0.0008 | 0.0008 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| *WF_Xyl* | 0.0002 | 0.0002 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| *WF_N2* | 0.0190 | 0.0190 | 0.0121 | 0.0000 | 0.0000 | 0.0000 |
| *WF_C2H6* | 0.0875 | 0.0875 | 0.0559 | 0.0000 | 0.0000 | 0.0000 |
| *WF_trimetpen2* | 8.24E-06 | 8.24E-06 | 3.60E-06 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_cyclohexane* | 1.07E-04 | 1.07E-04 | 4.66E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_cyclopentane* | 3.61E-04 | 3.61E-04 | 1.58E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_isobut* | 1.95E-02 | 1.95E-02 | 8.50E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_isopentane* | 6.61E-03 | 6.61E-03 | 2.89E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_methcychex* | 1.72E-04 | 1.72E-04 | 7.53E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_N_but* | 3.60E-02 | 3.60E-02 | 1.57E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_N_hex* | 1.29E-02 | 1.29E-02 | 5.62E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_N_pentane* | 8.31E-03 | 8.31E-03 | 3.63E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_C3H8ass* | 9.11E-02 | 9.11E-02 | 3.98E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_i_heptanes* | 8.43E-04 | 8.43E-04 | 3.68E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_i_hexanes* | 8.44E-04 | 8.44E-04 | 3.69E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_undef_VOC* | 9.90E-03 | 9.90E-03 | 4.33E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *MW_VOC* | 55.3283 | 55.3283 | 53.4344 | 0.0000 | 0.0000 | 0.0000 |
| *MW_Gas* | 19.8748 | 19.8748 | 17.8431 | 0.0000 | 0.0000 | 0.0000 |
| *OP_HR* | 8760.00000 | 8760.00000 | 8760.00000 | 0.00000 | 0.00000 | 0.00000 |
| *NG_OEL* | 0.00207 | 0.00207 | 0.00206 | 0.00000 | 0.00000 | 0.00000 |

**Table D-6: Natural Gas Production Fugitive Emissions – OEL, continued**

| Parameter Name | Scenario ID | | | | |
|---|---|---|---|---|---|
| | 7 | 8 | 9 | 10 | 11 |
| | North-Central | Rocky Mountains | TX-LA-MS Salt Basin | West coast (onshore) | West Texas/Permian Basin |
| ***Avg_NG_Prod*** | 0.0000 | 58059.8950 | 1498215.5000 | 0.0000 | 0.0000 |
| ***C_Valve*** | 0.0000 | 13.3109 | 13.8286 | 0.0000 | 0.0000 |
| ***C_Conn*** | 0.0000 | 30.0666 | 39.0714 | 0.0000 | 0.0000 |
| ***C_Flange*** | 0.0000 | 20.5772 | 21.6857 | 0.0000 | 0.0000 |
| ***C_OEL*** | 0.0000 | 2.3547 | 5.2286 | 0.0000 | 0.0000 |
| ***WF_VOC*** | 0.0000 | 0.0335 | 0.1484 | 0.0000 | 0.0000 |
| ***WF_H2S*** | 0.0000 | 0.0002 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_CO2*** | 0.0000 | 0.1235 | 0.0253 | 0.0000 | 0.0000 |
| ***WF_CH4*** | 0.0000 | 0.8201 | 0.7311 | 0.0000 | 0.0000 |
| ***WF_Benz*** | 0.0000 | 0.0001 | 0.0002 | 0.0000 | 0.0000 |
| ***WF_Ebenz*** | 0.0000 | 0.0000 | 0.0001 | 0.0000 | 0.0000 |
| ***WF_Tol*** | 0.0000 | 0.0001 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_Xyl*** | 0.0000 | 0.0000 | 0.0001 | 0.0000 | 0.0000 |
| ***WF_N2*** | 0.0000 | 0.0040 | 0.0169 | 0.0000 | 0.0000 |
| ***WF_C2H6*** | 0.0000 | 0.0183 | 0.0778 | 0.0000 | 0.0000 |
| ***WF_trimetpen2*** | 0.00E+00 | 1.48E-06 | 6.55E-06 | 0.00E+00 | 0.00E+00 |
| ***WF_cyclohexane*** | 0.00E+00 | 1.91E-05 | 8.48E-05 | 0.00E+00 | 0.00E+00 |
| ***WF_cyclopentane*** | 0.00E+00 | 6.48E-05 | 2.87E-04 | 0.00E+00 | 0.00E+00 |
| ***WF_isobut*** | 0.00E+00 | 3.50E-03 | 1.55E-02 | 0.00E+00 | 0.00E+00 |
| ***WF_isopentane*** | 0.00E+00 | 1.19E-03 | 5.26E-03 | 0.00E+00 | 0.00E+00 |
| ***WF_methcychex*** | 0.00E+00 | 3.10E-05 | 1.37E-04 | 0.00E+00 | 0.00E+00 |
| ***WF_N_but*** | 0.00E+00 | 6.47E-03 | 2.87E-02 | 0.00E+00 | 0.00E+00 |
| ***WF_N_hex*** | 0.00E+00 | 2.31E-03 | 1.02E-02 | 0.00E+00 | 0.00E+00 |
| ***WF_N_pentane*** | 0.00E+00 | 1.49E-03 | 6.61E-03 | 0.00E+00 | 0.00E+00 |
| ***WF_C3H8ass*** | 0.00E+00 | 1.64E-02 | 7.24E-02 | 0.00E+00 | 0.00E+00 |
| ***WF_i_heptanes*** | 0.00E+00 | 1.51E-04 | 6.70E-04 | 0.00E+00 | 0.00E+00 |
| ***WF_i_hexanes*** | 0.00E+00 | 1.52E-04 | 6.71E-04 | 0.00E+00 | 0.00E+00 |
| ***WF_undef_VOC*** | 0.00E+00 | 1.78E-03 | 7.87E-03 | 0.00E+00 | 0.00E+00 |
| ***MW_VOC*** | 0.0000 | 59.2686 | 55.3283 | 0.0000 | 0.0000 |
| ***MW_Gas*** | 0.0000 | 18.0484 | 18.9974 | 0.0000 | 0.0000 |
| ***OP_HR*** | 0.00000 | 8760.00000 | 8760.00000 | 0.00000 | 0.00000 |
| ***NG_OEL*** | 0.00000 | 0.00228 | 0.00205 | 0.00000 | 0.00000 |

## Table D-7: Natural Gas Production Fugitive Emissions - Valves

| Natural Gas Production Fugitive Emissions – Valves Gas Well | | | | | | |
|---|---|---|---|---|---|---|
| Parameter Name | Scenario ID | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 |
| | Appalachian Basin | Black Warrior Basin | Central | Ft Worth Basin (Barnett) | Gulf Coast (onshore) | Illinois/Michigan Basins |
| ***Avg_NG_Prod*** | 13816.5340 | 23522.6827 | 42612.1886 | 88451.8006 | 88927.7682 | 12008.4996 |
| ***C_Valve*** | 13.5831 | 13.8286 | 12.3757 | 13.8286 | 13.8286 | 13.8113 |
| ***C_Conn*** | 38.5248 | 39.0714 | 36.2220 | 39.0714 | 39.0714 | 39.0330 |
| ***C_Flange*** | 18.7743 | 21.6857 | 18.8735 | 21.6857 | 21.6857 | 21.6510 |
| ***C_OEL*** | 4.6609 | 5.2286 | 5.8558 | 5.2286 | 5.2286 | 5.2358 |
| ***WF_VOC*** | 0.1867 | 0.1867 | 0.1604 | 0.1484 | 0.1484 | 0.1852 |
| ***WF_H2S*** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_CO2*** | 0.0327 | 0.0327 | 0.0143 | 0.0253 | 0.0253 | 0.0327 |
| ***WF_CH4*** | 0.6722 | 0.6722 | 0.7434 | 0.7311 | 0.7311 | 0.6742 |
| ***WF_Benz*** | 0.0008 | 0.0008 | 0.0001 | 0.0002 | 0.0002 | 0.0008 |
| ***WF_Ebenz*** | 0.0000 | 0.0000 | 0.0001 | 0.0001 | 0.0001 | 0.0000 |
| ***WF_Tol*** | 0.0008 | 0.0008 | 0.0001 | 0.0000 | 0.0000 | 0.0007 |
| ***WF_Xyl*** | 0.0002 | 0.0002 | 0.0001 | 0.0001 | 0.0001 | 0.0002 |
| ***WF_N2*** | 0.0190 | 0.0190 | 0.0145 | 0.0169 | 0.0169 | 0.0189 |
| ***WF_C2H6*** | 0.0875 | 0.0875 | 0.0670 | 0.0778 | 0.0778 | 0.0870 |
| ***WF_trimetpen2*** | 8.24E-06 | 8.24E-06 | 7.08E-06 | 6.55E-06 | 6.55E-06 | 8.18E-06 |
| ***WF_cyclohexane*** | 1.07E-04 | 1.07E-04 | 9.16E-05 | 8.48E-05 | 8.48E-05 | 1.06E-04 |
| ***WF_cyclopentane*** | 3.61E-04 | 3.61E-04 | 3.10E-04 | 2.87E-04 | 2.87E-04 | 3.58E-04 |
| ***WF_isobut*** | 1.95E-02 | 1.95E-02 | 1.67E-02 | 1.55E-02 | 1.55E-02 | 1.93E-02 |
| ***WF_isopentane*** | 6.61E-03 | 6.61E-03 | 5.68E-03 | 5.26E-03 | 5.26E-03 | 6.56E-03 |
| ***WF_methcychex*** | 1.72E-04 | 1.72E-04 | 1.48E-04 | 1.37E-04 | 1.37E-04 | 1.71E-04 |
| ***WF_N_but*** | 3.60E-02 | 3.60E-02 | 3.10E-02 | 2.87E-02 | 2.87E-02 | 3.58E-02 |
| ***WF_N_hex*** | 1.29E-02 | 1.29E-02 | 1.11E-02 | 1.02E-02 | 1.02E-02 | 1.28E-02 |
| ***WF_N_pentane*** | 8.31E-03 | 8.31E-03 | 7.14E-03 | 6.61E-03 | 6.61E-03 | 8.25E-03 |
| ***WF_C3H8ass*** | 9.11E-02 | 9.11E-02 | 7.83E-02 | 7.24E-02 | 7.24E-02 | 9.04E-02 |
| ***WF_i_heptanes*** | 8.43E-04 | 8.43E-04 | 7.24E-04 | 6.70E-04 | 6.70E-04 | 8.37E-04 |
| ***WF_i_hexanes*** | 8.44E-04 | 8.44E-04 | 7.25E-04 | 6.71E-04 | 6.71E-04 | 8.38E-04 |
| ***WF_undef_VOC*** | 9.90E-03 | 9.90E-03 | 8.51E-03 | 7.87E-03 | 7.87E-03 | 9.83E-03 |
| ***MW_VOC*** | 55.3283 | 55.3283 | 55.5986 | 55.3283 | 55.3283 | 55.2978 |
| ***MW_Gas*** | 19.8748 | 19.8748 | 18.9307 | 18.9974 | 18.9974 | 19.8442 |
| ***OP_HR*** | 7618.8377 | 8760.0000 | 8760.0000 | 8760.0000 | 8760.0000 | 8760.0000 |
| ***NG_Valve*** | 0.0047 | 0.0047 | 0.0046 | 0.0046 | 0.0046 | 0.0047 |

**Table D-7: Natural Gas Production Fugitive Emissions – Valves, continued**

| Parameter Name | Scenario ID | | | | |
|---|---|---|---|---|---|
| | 7 | 8 | 9 | 10 | 11 |
| | North-Central | Rocky Mountains | TX-LA-MS Salt Basin | West coast (onshore) | West Texas/Permian Basin |
| ***Avg_NG_Prod*** | 18489.6325 | 63670.1644 | 112913.3906 | 60539.0682 | 28294.9264 |
| ***C_Valve*** | 27.0221 | 29.6167 | 13.0969 | 13.8286 | 18.4998 |
| ***C_Conn*** | 90.0660 | 47.4532 | 37.4424 | 39.0714 | 42.4999 |
| ***C_Flange*** | 21.5539 | 38.1386 | 20.2110 | 21.6857 | 28.9997 |
| ***C_OEL*** | 2.2714 | 7.2609 | 5.5372 | 5.2286 | 3.0001 |
| ***WF_VOC*** | 0.2761 | 0.1340 | 0.1355 | 0.1867 | 0.1956 |
| ***WF_H2S*** | 0.0000 | 0.0024 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_CO2*** | 0.0327 | 0.0473 | 0.0362 | 0.0327 | 0.0450 |
| ***WF_CH4*** | 0.6722 | 0.6910 | 0.7413 | 0.6722 | 0.5628 |
| ***WF_Benz*** | 0.0008 | 0.0004 | 0.0005 | 0.0008 | 0.0000 |
| ***WF_Ebenz*** | 0.0000 | 0.0000 | 0.0001 | 0.0000 | 0.0000 |
| ***WF_Tol*** | 0.0008 | 0.0005 | 0.0000 | 0.0008 | 0.0000 |
| ***WF_Xyl*** | 0.0002 | 0.0002 | 0.0001 | 0.0002 | 0.0000 |
| ***WF_N2*** | 0.0030 | 0.0222 | 0.0154 | 0.0190 | 0.0350 |
| ***WF_C2H6*** | 0.0140 | 0.1021 | 0.0709 | 0.0875 | 0.1615 |
| ***WF_trimetpen2*** | 1.22E-05 | 5.92E-06 | 5.98E-06 | 8.24E-06 | 8.64E-06 |
| ***WF_cyclohexane*** | 1.58E-04 | 7.66E-05 | 7.74E-05 | 1.07E-04 | 1.12E-04 |
| ***WF_cyclopentane*** | 5.34E-04 | 2.59E-04 | 2.62E-04 | 3.61E-04 | 3.78E-04 |
| ***WF_isobut*** | 2.88E-02 | 1.40E-02 | 1.41E-02 | 1.95E-02 | 2.04E-02 |
| ***WF_isopentane*** | 9.78E-03 | 4.75E-03 | 4.80E-03 | 6.61E-03 | 6.93E-03 |
| ***WF_methcychex*** | 2.55E-04 | 1.24E-04 | 1.25E-04 | 1.72E-04 | 1.81E-04 |
| ***WF_N_but*** | 5.33E-02 | 2.59E-02 | 2.62E-02 | 3.60E-02 | 3.78E-02 |
| ***WF_N_hex*** | 1.90E-02 | 9.24E-03 | 9.34E-03 | 1.29E-02 | 1.35E-02 |
| ***WF_N_pentane*** | 1.23E-02 | 5.97E-03 | 6.03E-03 | 8.31E-03 | 8.71E-03 |
| ***WF_C3H8ass*** | 1.35E-01 | 6.54E-02 | 6.61E-02 | 9.11E-02 | 9.55E-02 |
| ***WF_i_heptanes*** | 1.25E-03 | 6.05E-04 | 6.12E-04 | 8.43E-04 | 8.83E-04 |
| ***WF_i_hexanes*** | 1.25E-03 | 6.06E-04 | 6.13E-04 | 8.44E-04 | 8.85E-04 |
| ***WF_undef_VOC*** | 1.47E-02 | 7.11E-03 | 7.19E-03 | 9.90E-03 | 1.04E-02 |
| ***MW_VOC*** | 53.9072 | 54.8723 | 56.9991 | 55.3283 | 50.6362 |
| ***MW_Gas*** | 20.6269 | 19.3559 | 18.9110 | 19.8748 | 20.8997 |
| ***OP_HR*** | 8760.0000 | 8760.0000 | 8760.0000 | 8760.0000 | 8760.0000 |
| ***NG_Valve*** | 0.0047 | 0.0047 | 0.0047 | 0.0047 | 0.0047 |

**Table D-7: Natural Gas Production Fugitive Emissions – Valves, continued**

| *Natural Gas Production Fugitive Emissions – Valves CBM* | | | | | | |
|---|---|---|---|---|---|---|
| Parameter Name | Scenario ID | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 |
| | Appalachian Basin | Black Warrior Basin | Central | Ft Worth Basin (Barnett) | Gulf Coast (onshore) | Illinois/Michigan Basins |
| *Avg_NG_Prod* | 22183.3258 | 16255.6969 | 9108.2858 | 0.0000 | 0.0000 | 0.0000 |
| *C_Valve* | 13.8286 | 13.8286 | 12.7566 | 0.0000 | 0.0000 | 0.0000 |
| *C_Conn* | 39.0714 | 39.0714 | 36.6868 | 0.0000 | 0.0000 | 0.0000 |
| *C_Flange* | 21.6857 | 21.6857 | 19.5257 | 0.0000 | 0.0000 | 0.0000 |
| *C_OEL* | 5.2286 | 5.2286 | 5.6809 | 0.0000 | 0.0000 | 0.0000 |
| *WF_VOC* | 0.1867 | 0.1867 | 0.0815 | 0.0000 | 0.0000 | 0.0000 |
| *WF_H2S* | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| *WF_CO2* | 0.0327 | 0.0327 | 0.0308 | 0.0000 | 0.0000 | 0.0000 |
| *WF_CH4* | 0.6722 | 0.6722 | 0.8195 | 0.0000 | 0.0000 | 0.0000 |
| *WF_Benz* | 0.0008 | 0.0008 | 0.0001 | 0.0000 | 0.0000 | 0.0000 |
| *WF_Ebenz* | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| *WF_Tol* | 0.0008 | 0.0008 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| *WF_Xyl* | 0.0002 | 0.0002 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| *WF_N2* | 0.0190 | 0.0190 | 0.0121 | 0.0000 | 0.0000 | 0.0000 |
| *WF_C2H6* | 0.0875 | 0.0875 | 0.0559 | 0.0000 | 0.0000 | 0.0000 |
| *WF_trimetpen2* | 8.24E-06 | 8.24E-06 | 3.60E-06 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_cyclohexane* | 1.07E-04 | 1.07E-04 | 4.66E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_cyclopentane* | 3.61E-04 | 3.61E-04 | 1.58E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_isobut* | 1.95E-02 | 1.95E-02 | 8.50E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_isopentane* | 6.61E-03 | 6.61E-03 | 2.89E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_methcychex* | 1.72E-04 | 1.72E-04 | 7.53E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_N_but* | 3.60E-02 | 3.60E-02 | 1.57E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_N_hex* | 1.29E-02 | 1.29E-02 | 5.62E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_N_pentane* | 8.31E-03 | 8.31E-03 | 3.63E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_C3H8ass* | 9.11E-02 | 9.11E-02 | 3.98E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_i_heptanes* | 8.43E-04 | 8.43E-04 | 3.68E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_i_hexanes* | 8.44E-04 | 8.44E-04 | 3.69E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_undef_VOC* | 9.90E-03 | 9.90E-03 | 4.33E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *MW_VOC* | 55.3283 | 55.3283 | 53.4344 | 0.0000 | 0.0000 | 0.0000 |
| *MW_Gas* | 19.8748 | 19.8748 | 17.8431 | 0.0000 | 0.0000 | 0.0000 |
| *OP_HR* | 8760.0000 | 8760.0000 | 8760.0000 | 0.0000 | 0.0000 | 0.0000 |
| *NG_Valve* | 0.0047 | 0.0047 | 0.0046 | 0.0000 | 0.0000 | 0.0000 |

**Table D-7: Natural Gas Production Fugitive Emissions – Valves, continued**

| Parameter Name | Scenario ID | | | | |
|---|---|---|---|---|---|
| | 7 | 8 | 9 | 10 | 11 |
| | North-Central | Rocky Mountains | TX-LA-MS Salt Basin | West coast (onshore) | West Texas/Permian Basin |
| ***Avg_NG_Prod*** | 0.0000 | 58059.8950 | 1498215.5000 | 0.0000 | 0.0000 |
| ***C_Valve*** | 0.0000 | 13.3109 | 13.8286 | 0.0000 | 0.0000 |
| ***C_Conn*** | 0.0000 | 30.0666 | 39.0714 | 0.0000 | 0.0000 |
| ***C_Flange*** | 0.0000 | 20.5772 | 21.6857 | 0.0000 | 0.0000 |
| ***C_OEL*** | 0.0000 | 2.3547 | 5.2286 | 0.0000 | 0.0000 |
| ***WF_VOC*** | 0.0000 | 0.0335 | 0.1484 | 0.0000 | 0.0000 |
| ***WF_H2S*** | 0.0000 | 0.0002 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_CO2*** | 0.0000 | 0.1235 | 0.0253 | 0.0000 | 0.0000 |
| ***WF_CH4*** | 0.0000 | 0.8201 | 0.7311 | 0.0000 | 0.0000 |
| ***WF_Benz*** | 0.0000 | 0.0001 | 0.0002 | 0.0000 | 0.0000 |
| ***WF_Ebenz*** | 0.0000 | 0.0000 | 0.0001 | 0.0000 | 0.0000 |
| ***WF_Tol*** | 0.0000 | 0.0001 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_Xyl*** | 0.0000 | 0.0000 | 0.0001 | 0.0000 | 0.0000 |
| ***WF_N2*** | 0.0000 | 0.0040 | 0.0169 | 0.0000 | 0.0000 |
| ***WF_C2H6*** | 0.0000 | 0.0183 | 0.0778 | 0.0000 | 0.0000 |
| ***WF_trimetpen2*** | 0.00E+00 | 1.48E-06 | 6.55E-06 | 0.00E+00 | 0.00E+00 |
| ***WF_cyclohexane*** | 0.00E+00 | 1.91E-05 | 8.48E-05 | 0.00E+00 | 0.00E+00 |
| ***WF_cyclopentane*** | 0.00E+00 | 6.48E-05 | 2.87E-04 | 0.00E+00 | 0.00E+00 |
| ***WF_isobut*** | 0.00E+00 | 3.50E-03 | 1.55E-02 | 0.00E+00 | 0.00E+00 |
| ***WF_isopentane*** | 0.00E+00 | 1.19E-03 | 5.26E-03 | 0.00E+00 | 0.00E+00 |
| ***WF_methcychex*** | 0.00E+00 | 3.10E-05 | 1.37E-04 | 0.00E+00 | 0.00E+00 |
| ***WF_N_but*** | 0.00E+00 | 6.47E-03 | 2.87E-02 | 0.00E+00 | 0.00E+00 |
| ***WF_N_hex*** | 0.00E+00 | 2.31E-03 | 1.02E-02 | 0.00E+00 | 0.00E+00 |
| ***WF_N_pentane*** | 0.00E+00 | 1.49E-03 | 6.61E-03 | 0.00E+00 | 0.00E+00 |
| ***WF_C3H8ass*** | 0.00E+00 | 1.64E-02 | 7.24E-02 | 0.00E+00 | 0.00E+00 |
| ***WF_i_heptanes*** | 0.00E+00 | 1.51E-04 | 6.70E-04 | 0.00E+00 | 0.00E+00 |
| ***WF_i_hexanes*** | 0.00E+00 | 1.52E-04 | 6.71E-04 | 0.00E+00 | 0.00E+00 |
| ***WF_undef_VOC*** | 0.00E+00 | 1.78E-03 | 7.87E-03 | 0.00E+00 | 0.00E+00 |
| ***MW_VOC*** | 0.0000 | 59.2686 | 55.3283 | 0.0000 | 0.0000 |
| ***MW_Gas*** | 0.0000 | 18.0484 | 18.9974 | 0.0000 | 0.0000 |
| ***OP_HR*** | 0.0000 | 8760.0000 | 8760.0000 | 0.0000 | 0.0000 |
| ***NG_Valve*** | 0.0000 | 0.0051 | 0.0046 | 0.0000 | 0.0000 |

## Table D-8: Natural Gas Production Pneumatic Device Venting

| *Natural Gas Production Pneumatic Device Venting Gas Well* | | | | | | |
|---|---|---|---|---|---|---|
| **Parameter Name** | **Scenario ID** | | | | | |
| | **1** | **2** | **3** | **4** | **5** | **6** |
| | **Appalachian Basin** | **Black Warrior Basin** | **Central** | **Ft Worth Basin (Barnett)** | **Gulf Coast (onshore)** | **Illinois/Michigan Basins** |
| ***AVG_NG_Prod*** | 13816.5340 | 23522.6827 | 42612.1886 | 88451.8006 | 88927.7682 | 12008.4996 |
| ***NB_Count*** | 0.3299 | 0.3299 | 0.6039 | 0.3299 | 0.3299 | 0.3268 |
| ***NB_V_VentRate*** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| ***LB_Count*** | 0.1249 | 0.2063 | 0.8711 | 2.4000 | 0.9754 | 0.1522 |
| ***LB_V_VentRate*** | 1.3900 | 1.3900 | 3.0178 | 3.1511 | 3.1511 | 1.4066 |
| ***HB_Count*** | 0.5951 | 0.3176 | 0.8444 | 0.1800 | 0.1589 | 0.2293 |
| ***HB_V_VentRate*** | 37.3000 | 37.3000 | 32.0682 | 32.0682 | 32.0682 | 37.2507 |
| ***IB_Count*** | 0.1036 | 0.1711 | 0.8680 | 1.0900 | 2.2559 | 0.1299 |
| ***IB_V_VentRate*** | 13.5000 | 13.5000 | 7.3623 | 8.5774 | 8.5774 | 13.4966 |
| ***WF_VOC*** | 0.1867 | 0.1867 | 0.1604 | 0.1484 | 0.1484 | 0.1852 |
| ***WF_H2S*** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_CO2*** | 0.0327 | 0.0327 | 0.0143 | 0.0253 | 0.0253 | 0.0327 |
| ***WF_CH4*** | 0.6722 | 0.6722 | 0.7434 | 0.7311 | 0.7311 | 0.6742 |
| ***WF_Benz*** | 0.0008 | 0.0008 | 0.0001 | 0.0002 | 0.0002 | 0.0008 |
| ***WF_Ebenz*** | 0.0000 | 0.0000 | 0.0001 | 0.0001 | 0.0001 | 0.0000 |
| ***WF_Tol*** | 0.0008 | 0.0008 | 0.0001 | 0.0000 | 0.0000 | 0.0007 |
| ***WF_Xyl*** | 0.0002 | 0.0002 | 0.0001 | 0.0001 | 0.0001 | 0.0002 |
| ***WF_N2*** | 0.0190 | 0.0190 | 0.0145 | 0.0169 | 0.0169 | 0.0189 |
| ***WF_C2H6*** | 0.0875 | 0.0875 | 0.0670 | 0.0778 | 0.0778 | 0.0870 |
| ***WF_trimetpen2*** | 8.24E-06 | 8.24E-06 | 7.08E-06 | 6.55E-06 | 6.55E-06 | 8.18E-06 |
| ***WF_cyclohexane*** | 1.07E-04 | 1.07E-04 | 9.16E-05 | 8.48E-05 | 8.48E-05 | 1.06E-04 |
| ***WF_cyclopentane*** | 3.61E-04 | 3.61E-04 | 3.10E-04 | 2.87E-04 | 2.87E-04 | 3.58E-04 |
| ***WF_isobut*** | 1.95E-02 | 1.95E-02 | 1.67E-02 | 1.55E-02 | 1.55E-02 | 1.93E-02 |
| ***WF_isopentane*** | 6.61E-03 | 6.61E-03 | 5.68E-03 | 5.26E-03 | 5.26E-03 | 6.56E-03 |
| ***WF_methcychex*** | 1.72E-04 | 1.72E-04 | 1.48E-04 | 1.37E-04 | 1.37E-04 | 1.71E-04 |
| ***WF_N_but*** | 3.60E-02 | 3.60E-02 | 3.10E-02 | 2.87E-02 | 2.87E-02 | 3.58E-02 |
| ***WF_N_hex*** | 1.29E-02 | 1.29E-02 | 1.11E-02 | 1.02E-02 | 1.02E-02 | 1.28E-02 |
| ***WF_N_pentane*** | 8.31E-03 | 8.31E-03 | 7.14E-03 | 6.61E-03 | 6.61E-03 | 8.25E-03 |
| ***WF_C3H8ass*** | 9.11E-02 | 9.11E-02 | 7.83E-02 | 7.24E-02 | 7.24E-02 | 9.04E-02 |
| ***WF_i_heptanes*** | 8.43E-04 | 8.43E-04 | 7.24E-04 | 6.70E-04 | 6.70E-04 | 8.37E-04 |
| ***WF_i_hexanes*** | 8.44E-04 | 8.44E-04 | 7.25E-04 | 6.71E-04 | 6.71E-04 | 8.38E-04 |
| ***WF_undef_VOC*** | 9.90E-03 | 9.90E-03 | 8.51E-03 | 7.87E-03 | 7.87E-03 | 9.83E-03 |
| ***MW_VOC*** | 5.53E+01 | 5.53E+01 | 5.56E+01 | 5.53E+01 | 5.53E+01 | 5.51E+01 |
| ***MW_Gas*** | 19.8748 | 19.8748 | 18.9306 | 18.9974 | 18.9974 | 19.8392 |
| ***OP_HR*** | 7213.1032 | 8760.0000 | 8760.0000 | 8760.0000 | 8760.0000 | 8760.0000 |

**Table D-8: Natural Gas Production Pneumatic Device Venting, continued**

| Parameter Name | Scenario ID | | | | |
|---|---|---|---|---|---|
| | 7 | 8 | 9 | 10 | 11 |
| | North-Central | Rocky Mountains | TX-LA-MS Salt Basin | West coast (onshore) | West Texas/Permian Basin |
| ***AVG_NG_Prod*** | 18489.6325 | 63670.1644 | 112913.3906 | 60539.0682 | 28294.9264 |
| ***NB_Count*** | 0.0000 | 0.1112 | 0.1979 | 0.3299 | 0.0000 |
| ***NB_V_VentRate*** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| ***LB_Count*** | 0.3363 | 2.6781 | 0.5854 | 0.2974 | 0.2200 |
| ***LB_V_VentRate*** | 4.6194 | 1.9925 | 3.1511 | 1.3900 | 3.1511 |
| ***HB_Count*** | 1.3747 | 0.8289 | 0.8448 | 0.4579 | 0.0600 |
| ***HB_V_VentRate*** | 38.9472 | 27.8226 | 32.0682 | 37.3000 | 32.0682 |
| ***IB_Count*** | 1.1919 | 0.1404 | 0.4206 | 0.2467 | 0.9100 |
| ***IB_V_VentRate*** | 23.6589 | 8.3673 | 8.5774 | 13.5000 | 8.5774 |
| ***WF_VOC*** | 0.2761 | 0.1340 | 0.1355 | 0.1867 | 0.1956 |
| ***WF_H2S*** | 0.0000 | 0.0024 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_CO2*** | 0.0327 | 0.0473 | 0.0362 | 0.0327 | 0.0450 |
| ***WF_CH4*** | 0.6722 | 0.6910 | 0.7413 | 0.6722 | 0.5628 |
| ***WF_Benz*** | 0.0008 | 0.0004 | 0.0005 | 0.0008 | 0.0000 |
| ***WF_Ebenz*** | 0.0000 | 0.0000 | 0.0001 | 0.0000 | 0.0000 |
| ***WF_Tol*** | 0.0008 | 0.0005 | 0.0000 | 0.0008 | 0.0000 |
| ***WF_Xyl*** | 0.0002 | 0.0002 | 0.0001 | 0.0002 | 0.0000 |
| ***WF_N2*** | 0.0030 | 0.0222 | 0.0154 | 0.0190 | 0.0350 |
| ***WF_C2H6*** | 0.0140 | 0.1021 | 0.0709 | 0.0875 | 0.1615 |
| ***WF_trimetpen2*** | 1.22E-05 | 5.92E-06 | 5.98E-06 | 8.24E-06 | 8.64E-06 |
| ***WF_cyclohexane*** | 1.58E-04 | 7.66E-05 | 7.74E-05 | 1.07E-04 | 1.12E-04 |
| ***WF_cyclopentane*** | 5.34E-04 | 2.59E-04 | 2.62E-04 | 3.61E-04 | 3.78E-04 |
| ***WF_isobut*** | 2.88E-02 | 1.40E-02 | 1.41E-02 | 1.95E-02 | 2.04E-02 |
| ***WF_isopentane*** | 9.78E-03 | 4.75E-03 | 4.80E-03 | 6.61E-03 | 6.93E-03 |
| ***WF_methcychex*** | 2.55E-04 | 1.24E-04 | 1.25E-04 | 1.72E-04 | 1.81E-04 |
| ***WF_N_but*** | 5.33E-02 | 2.59E-02 | 2.62E-02 | 3.60E-02 | 3.78E-02 |
| ***WF_N_hex*** | 1.90E-02 | 9.24E-03 | 9.34E-03 | 1.29E-02 | 1.35E-02 |
| ***WF_N_pentane*** | 1.23E-02 | 5.97E-03 | 6.03E-03 | 8.31E-03 | 8.71E-03 |
| ***WF_C3H8ass*** | 1.35E-01 | 6.54E-02 | 6.61E-02 | 9.11E-02 | 9.55E-02 |
| ***WF_i_heptanes*** | 1.25E-03 | 6.05E-04 | 6.12E-04 | 8.43E-04 | 8.83E-04 |
| ***WF_i_hexanes*** | 1.25E-03 | 6.06E-04 | 6.13E-04 | 8.44E-04 | 8.85E-04 |
| ***WF_undef_VOC*** | 1.47E-02 | 7.11E-03 | 7.19E-03 | 9.90E-03 | 1.04E-02 |
| ***MW_VOC*** | 5.53E+01 | 5.51E+01 | 5.53E+01 | 5.53E+01 | 5.06E+01 |
| ***MW_Gas*** | 20.6830 | 19.3596 | 18.8854 | 19.8748 | 20.8996 |
| ***OP_HR*** | 8760.0000 | 8760.0000 | 8760.0000 | 8760.0000 | 8760.0000 |

**Table D-8: Natural Gas Production Pneumatic Device Venting, continued**

| *Natural Gas Production Pneumatic Device Venting CBM* | | | | | | |
|---|---|---|---|---|---|---|
| Parameter Name | Scenario ID | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 |
| | Appalachian Basin | Black Warrior Basin | Central | Ft Worth Basin (Barnett) | Gulf Coast (onshore) | Illinois/Michigan Basins |
| *AVG_NG_Prod* | 22183.3258 | 16255.6969 | 9108.2858 | 0.0000 | 0.0000 | 0.0000 |
| *NB_Count* | 0.3299 | 0.3299 | 0.1368 | 0.0000 | 0.0000 | 0.0000 |
| *NB_V_VentRate* | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| *LB_Count* | 0.1587 | 0.2063 | 0.9362 | 0.0000 | 0.0000 | 0.0000 |
| *LB_V_VentRate* | 1.3900 | 1.3900 | 3.1511 | 0.0000 | 0.0000 | 0.0000 |
| *HB_Count* | 0.2444 | 0.3176 | 1.1292 | 0.0000 | 0.0000 | 0.0000 |
| *HB_V_VentRate* | 37.3000 | 37.3000 | 32.0682 | 0.0000 | 0.0000 | 0.0000 |
| *IB_Count* | 0.1317 | 0.1711 | 1.0018 | 0.0000 | 0.0000 | 0.0000 |
| *IB_V_VentRate* | 13.5000 | 13.5000 | 11.2516 | 0.0000 | 0.0000 | 0.0000 |
| *WF_VOC* | 0.1867 | 0.1867 | 0.0815 | 0.0000 | 0.0000 | 0.0000 |
| *WF_H2S* | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| *WF_CO2* | 0.0327 | 0.0327 | 0.0308 | 0.0000 | 0.0000 | 0.0000 |
| *WF_CH4* | 0.6722 | 0.6722 | 0.8195 | 0.0000 | 0.0000 | 0.0000 |
| *WF_Benz* | 0.0008 | 0.0008 | 0.0001 | 0.0000 | 0.0000 | 0.0000 |
| *WF_Ebenz* | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| *WF_Tol* | 0.0008 | 0.0008 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| *WF_Xyl* | 0.0002 | 0.0002 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| *WF_N2* | 0.0190 | 0.0190 | 0.0121 | 0.0000 | 0.0000 | 0.0000 |
| *WF_C2H6* | 0.0875 | 0.0875 | 0.0559 | 0.0000 | 0.0000 | 0.0000 |
| *WF_trimetpen2* | 8.24E-06 | 8.24E-06 | 3.60E-06 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_cyclohexane* | 1.07E-04 | 1.07E-04 | 4.66E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_cyclopentane* | 3.61E-04 | 3.61E-04 | 1.58E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_isobut* | 1.95E-02 | 1.95E-02 | 8.50E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_isopentane* | 6.61E-03 | 6.61E-03 | 2.89E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_methcychex* | 1.72E-04 | 1.72E-04 | 7.53E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_N_but* | 3.60E-02 | 3.60E-02 | 1.57E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_N_hex* | 1.29E-02 | 1.29E-02 | 5.62E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_N_pentane* | 8.31E-03 | 8.31E-03 | 3.63E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_C3H8ass* | 9.11E-02 | 9.11E-02 | 3.98E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_i_heptanes* | 8.43E-04 | 8.43E-04 | 3.68E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_i_hexanes* | 8.44E-04 | 8.44E-04 | 3.69E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *WF_undef_VOC* | 9.90E-03 | 9.90E-03 | 4.33E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *MW_VOC* | 5.53E+01 | 5.53E+01 | 5.34E+01 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| *MW_Gas* | 19.8748 | 19.8748 | 17.8431 | 0.0000 | 0.0000 | 0.0000 |
| *OP_HR* | 8760.0000 | 8760.0000 | 8760.0000 | 0.0000 | 0.0000 | 0.0000 |

**Table D-8: Natural Gas Production Pneumatic Device Venting, continued**

| Parameter Name | Scenario ID | | | | |
|---|---|---|---|---|---|
| | 7 | 8 | 9 | 10 | 11 |
| | North-Central | Rocky Mountains | TX-LA-MS Salt Basin | West coast (onshore) | West Texas/Permian Basin |
| ***AVG_NG_Prod*** | 0.0000 | 58059.8950 | 1498215.5000 | 0.0000 | 0.0000 |
| ***NB_Count*** | 0.0000 | 0.0649 | 0.3299 | 0.0000 | 0.0000 |
| ***NB_V_VentRate*** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| ***LB_Count*** | 0.0000 | 1.6067 | 0.8649 | 0.0000 | 0.0000 |
| ***LB_V_VentRate*** | 0.0000 | 1.2570 | 3.1511 | 0.0000 | 0.0000 |
| ***HB_Count*** | 0.0000 | 0.5745 | 1.3319 | 0.0000 | 0.0000 |
| ***HB_V_VentRate*** | 0.0000 | 37.2450 | 32.0682 | 0.0000 | 0.0000 |
| ***IB_Count*** | 0.0000 | 0.2959 | 0.7175 | 0.0000 | 0.0000 |
| ***IB_V_VentRate*** | 0.0000 | 13.8502 | 8.5774 | 0.0000 | 0.0000 |
| ***WF_VOC*** | 0.0000 | 0.0335 | 0.1484 | 0.0000 | 0.0000 |
| ***WF_H2S*** | 0.0000 | 0.0002 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_CO2*** | 0.0000 | 0.1235 | 0.0253 | 0.0000 | 0.0000 |
| ***WF_CH4*** | 0.0000 | 0.8201 | 0.7311 | 0.0000 | 0.0000 |
| ***WF_Benz*** | 0.0000 | 0.0001 | 0.0002 | 0.0000 | 0.0000 |
| ***WF_Ebenz*** | 0.0000 | 0.0000 | 0.0001 | 0.0000 | 0.0000 |
| ***WF_Tol*** | 0.0000 | 0.0001 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_Xyl*** | 0.0000 | 0.0000 | 0.0001 | 0.0000 | 0.0000 |
| ***WF_N2*** | 0.0000 | 0.0040 | 0.0169 | 0.0000 | 0.0000 |
| ***WF_C2H6*** | 0.0000 | 0.0183 | 0.0778 | 0.0000 | 0.0000 |
| ***WF_trimetpen2*** | 0.00E+00 | 1.48E-06 | 6.55E-06 | 0.00E+00 | 0.00E+00 |
| ***WF_cyclohexane*** | 0.00E+00 | 1.91E-05 | 8.48E-05 | 0.00E+00 | 0.00E+00 |
| ***WF_cyclopentane*** | 0.00E+00 | 6.48E-05 | 2.87E-04 | 0.00E+00 | 0.00E+00 |
| ***WF_isobut*** | 0.00E+00 | 3.50E-03 | 1.55E-02 | 0.00E+00 | 0.00E+00 |
| ***WF_isopentane*** | 0.00E+00 | 1.19E-03 | 5.26E-03 | 0.00E+00 | 0.00E+00 |
| ***WF_methcychex*** | 0.00E+00 | 3.10E-05 | 1.37E-04 | 0.00E+00 | 0.00E+00 |
| ***WF_N_but*** | 0.00E+00 | 6.47E-03 | 2.87E-02 | 0.00E+00 | 0.00E+00 |
| ***WF_N_hex*** | 0.00E+00 | 2.31E-03 | 1.02E-02 | 0.00E+00 | 0.00E+00 |
| ***WF_N_pentane*** | 0.00E+00 | 1.49E-03 | 6.61E-03 | 0.00E+00 | 0.00E+00 |
| ***WF_C3H8ass*** | 0.00E+00 | 1.64E-02 | 7.24E-02 | 0.00E+00 | 0.00E+00 |
| ***WF_i_heptanes*** | 0.00E+00 | 1.51E-04 | 6.70E-04 | 0.00E+00 | 0.00E+00 |
| ***WF_i_hexanes*** | 0.00E+00 | 1.52E-04 | 6.71E-04 | 0.00E+00 | 0.00E+00 |
| ***WF_undef_VOC*** | 0.00E+00 | 1.78E-03 | 7.87E-03 | 0.00E+00 | 0.00E+00 |
| ***MW_VOC*** | 0.00E+00 | 5.93E+01 | 5.53E+01 | 0.00E+00 | 0.00E+00 |
| ***MW_Gas*** | 0.0000 | 18.0485 | 18.9974 | 0.0000 | 0.0000 |
| ***OP_HR*** | 0.0000 | 8760.0000 | 8760.0000 | 0.0000 | 0.0000 |

## Table D-9: Natural Gas Extraction Produced Water Tank Venting

| *Natural Gas Extraction Produced Water Tank Venting Gas Well* | | | | | | |
|---|---|---|---|---|---|---|
| **Parameter Name** | **Scenario ID** | | | | | |
| | **1** | **2** | **3** | **4** | **5** | **6** |
| | **Appalachian Basin** | **Black Warrior Basin** | **Central** | **Ft Worth Basin (Barnett)** | **Gulf Coast (onshore)** | **Illinois/Michigan Basins** |
| ***MCF_Prod*** | 22306.3846 | 24710.7112 | 46011.4744 | 88493.8009 | 88942.4006 | 11832.3374 |
| ***PW_Prod*** | 220.6283 | 139.4932 | 3270.6326 | 13902.1831 | 10377.6408 | 6808.2080 |
| ***Tank_Frac*** | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| ***EF_CH4*** | 0.1120 | 0.1120 | 0.1120 | 0.1120 | 0.1120 | 0.1120 |
| ***WF_VOC*** | 0.1567 | 0.1567 | 0.2397 | 0.1567 | 0.1567 | 0.1567 |
| ***WF_CO2*** | 0.0255 | 0.0255 | 0.0076 | 0.0255 | 0.0255 | 0.0255 |
| ***WF_CH4*** | 0.7245 | 0.7245 | 0.6294 | 0.7245 | 0.7245 | 0.7245 |
| ***WF_H2S*** | 0.0000 | 0.0000 | 0.0001 | 0.0000 | 0.0000 | 0.0000 |
| ***MW_VOC*** | 55.3283 | 55.3283 | 56.5857 | 55.3283 | 55.3283 | 55.3283 |
| ***WF_Benz*** | 0.0002 | 0.0002 | 0.0001 | 0.0002 | 0.0002 | 0.0002 |
| ***WF_Ebenz*** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_Tol*** | 0.0001 | 0.0001 | 0.0002 | 0.0001 | 0.0001 | 0.0001 |
| ***WF_Xyl*** | 0.0001 | 0.0001 | 0.0002 | 0.0001 | 0.0001 | 0.0001 |
| ***WF_trimetpen2*** | 6.92E-06 | 6.92E-06 | 1.06E-05 | 6.92E-06 | 6.92E-06 | 6.92E-06 |
| ***WF_cyclohexane*** | 8.95E-05 | 8.95E-05 | 1.37E-04 | 8.95E-05 | 8.95E-05 | 8.95E-05 |
| ***WF_cyclopentane*** | 3.03E-04 | 3.03E-04 | 4.63E-04 | 3.03E-04 | 3.03E-04 | 3.03E-04 |
| ***WF_isobut*** | 1.63E-02 | 1.63E-02 | 2.50E-02 | 1.63E-02 | 1.63E-02 | 1.63E-02 |
| ***WF_isopentane*** | 5.55E-03 | 5.55E-03 | 8.49E-03 | 5.55E-03 | 5.55E-03 | 5.55E-03 |
| ***WF_methcychex*** | 1.45E-04 | 1.45E-04 | 2.21E-04 | 1.45E-04 | 1.45E-04 | 1.45E-04 |
| ***WF_N_but*** | 3.03E-02 | 3.03E-02 | 4.63E-02 | 3.03E-02 | 3.03E-02 | 3.03E-02 |
| ***WF_N_hex*** | 1.08E-02 | 1.08E-02 | 1.65E-02 | 1.08E-02 | 1.08E-02 | 1.08E-02 |
| ***WF_N_pentane*** | 6.98E-03 | 6.98E-03 | 1.07E-02 | 6.98E-03 | 6.98E-03 | 6.98E-03 |
| ***WF_C3H8ass*** | 7.65E-02 | 7.65E-02 | 1.17E-01 | 7.65E-02 | 7.65E-02 | 7.65E-02 |
| ***WF_i_heptanes*** | 7.07E-04 | 7.07E-04 | 1.08E-03 | 7.07E-04 | 7.07E-04 | 7.07E-04 |
| ***WF_i_hexanes*** | 7.09E-04 | 7.09E-04 | 1.08E-03 | 7.09E-04 | 7.09E-04 | 7.09E-04 |
| ***WF_undef_VOC*** | 8.31E-03 | 8.31E-03 | 1.27E-02 | 8.31E-03 | 8.31E-03 | 8.31E-03 |
| ***MW_Gas*** | 18.6702 | 18.6702 | 20.0951 | 18.6702 | 18.6702 | 18.6702 |

**Table D-9: Natural Gas Extraction Produced Water Tank Venting, continued**

| Parameter Name | Scenario ID | | | | |
|---|---|---|---|---|---|
| | 7 | 8 | 9 | 10 | 11 |
| | North-Central | Rocky Mountains | TX-LA-MS Salt Basin | West coast (onshore) | West Texas/Permian Basin |
| ***MCF_Prod*** | 18808.2732 | 63826.5870 | 112869.9792 | 60550.3647 | 28293.4826 |
| ***PW_Prod*** | 908.9628 | 3636.2494 | 7501.2875 | 761.6255 | 3112.8509 |
| ***Tank_Frac*** | 0.8624 | 0.9891 | 1.0000 | 1.0000 | 1.0000 |
| ***EF_CH4*** | 0.1120 | 0.1225 | 0.1120 | 0.1120 | 0.1120 |
| ***WF_VOC*** | 0.1567 | 0.1531 | 0.1460 | 0.1567 | 0.2074 |
| ***WF_CO2*** | 0.0255 | 0.0249 | 0.0340 | 0.0255 | 0.0477 |
| ***WF_CH4*** | 0.7245 | 0.7236 | 0.7396 | 0.7245 | 0.5975 |
| ***WF_H2S*** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| ***MW_VOC*** | 55.3283 | 55.3496 | 56.6172 | 55.3283 | 50.6360 |
| ***WF_Benz*** | 0.0002 | 0.0002 | 0.0005 | 0.0002 | 0.0000 |
| ***WF_Ebenz*** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_Tol*** | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0000 |
| ***WF_Xyl*** | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0000 |
| ***WF_trimetpen2*** | 6.92E-06 | 6.76E-06 | 6.45E-06 | 6.92E-06 | 9.16E-06 |
| ***WF_cyclohexane*** | 8.95E-05 | 8.75E-05 | 8.34E-05 | 8.95E-05 | 1.18E-04 |
| ***WF_cyclopentane*** | 3.03E-04 | 2.96E-04 | 2.82E-04 | 3.03E-04 | 4.01E-04 |
| ***WF_isobut*** | 1.63E-02 | 1.60E-02 | 1.52E-02 | 1.63E-02 | 2.16E-02 |
| ***WF_isopentane*** | 5.55E-03 | 5.42E-03 | 5.17E-03 | 5.55E-03 | 7.34E-03 |
| ***WF_methcychex*** | 1.45E-04 | 1.41E-04 | 1.35E-04 | 1.45E-04 | 1.92E-04 |
| ***WF_N_but*** | 3.03E-02 | 2.96E-02 | 2.82E-02 | 3.03E-02 | 4.00E-02 |
| ***WF_N_hex*** | 1.08E-02 | 1.06E-02 | 1.01E-02 | 1.08E-02 | 1.43E-02 |
| ***WF_N_pentane*** | 6.98E-03 | 6.82E-03 | 6.50E-03 | 6.98E-03 | 9.23E-03 |
| ***WF_C3H8ass*** | 7.65E-02 | 7.47E-02 | 7.13E-02 | 7.65E-02 | 1.01E-01 |
| ***WF_i_heptanes*** | 7.07E-04 | 6.91E-04 | 6.59E-04 | 7.07E-04 | 9.37E-04 |
| ***WF_i_hexanes*** | 7.09E-04 | 6.93E-04 | 6.60E-04 | 7.09E-04 | 9.38E-04 |
| ***WF_undef_VOC*** | 8.31E-03 | 8.12E-03 | 7.75E-03 | 8.31E-03 | 1.10E-02 |
| ***MW_Gas*** | 18.6702 | 18.6175 | 18.6033 | 18.6702 | 20.0942 |

**Table D-9: Natural Gas Extraction Produced Water Tank Venting, continued**

| *Natural Gas Extraction Produced Water Tank Venting CBM* | | | | | | |
|---|---|---|---|---|---|---|
| Parameter Name | Scenario ID | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 |
| | Appalachian Basin | Black Warrior Basin | Central | Ft Worth Basin (Barnett) | Gulf Coast (onshore) | Illinois/Michigan Basins |
| ***MCF_Prod*** | 20358.2941 | 16255.6969 | 37502.7029 | 0.0000 | 0.0000 | 0.0000 |
| ***PW_Prod*** | 3716.8118 | 9626.5552 | 23266.4616 | 0.0000 | 0.0000 | 0.0000 |
| ***Tank_Frac*** | 1.0000 | 1.0000 | 1.0000 | 0.0000 | 0.0000 | 0.0000 |
| ***EF_CH4*** | 0.1120 | 0.1120 | 0.1120 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_VOC*** | 0.1567 | 0.1567 | 0.1567 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_CO2*** | 0.0255 | 0.0255 | 0.0255 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_CH4*** | 0.7245 | 0.7245 | 0.7245 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_H2S*** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| ***MW_VOC*** | 55.3283 | 55.3283 | 55.3283 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_Benz*** | 0.0002 | 0.0002 | 0.0002 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_Ebenz*** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_Tol*** | 0.0001 | 0.0001 | 0.0001 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_Xyl*** | 0.0001 | 0.0001 | 0.0001 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_trimetpen2*** | 6.92E-06 | 6.92E-06 | 6.92E-06 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_cyclohexane*** | 8.95E-05 | 8.95E-05 | 8.95E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_cyclopentane*** | 3.03E-04 | 3.03E-04 | 3.03E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_isobut*** | 1.63E-02 | 1.63E-02 | 1.63E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_isopentane*** | 5.55E-03 | 5.55E-03 | 5.55E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_methcychex*** | 1.45E-04 | 1.45E-04 | 1.45E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_N_but*** | 3.03E-02 | 3.03E-02 | 3.03E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_N_hex*** | 1.08E-02 | 1.08E-02 | 1.08E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_N_pentane*** | 6.98E-03 | 6.98E-03 | 6.98E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_C3H8ass*** | 7.65E-02 | 7.65E-02 | 7.65E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_i_heptanes*** | 7.07E-04 | 7.07E-04 | 7.07E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_i_hexanes*** | 7.09E-04 | 7.09E-04 | 7.09E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***WF_undef_VOC*** | 8.31E-03 | 8.31E-03 | 8.31E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| ***MW_Gas*** | 18.6702 | 18.6702 | 18.6702 | 0.0000 | 0.0000 | 0.0000 |

**Table D-9: Natural Gas Extraction Produced Water Tank Venting, continued**

| Parameter Name | Scenario ID | | | | |
|---|---|---|---|---|---|
| | 7 | 8 | 9 | 10 | 11 |
| | North-Central | Rocky Mountains | TX-LA-MS Salt Basin | West coast (onshore) | West Texas/Permian Basin |
| ***MCF_Prod*** | 0.0000 | 58059.8950 | 1498215.5000 | 0.0000 | 0.0000 |
| ***PW_Prod*** | 0.0000 | 26642.8230 | 77139.0000 | 0.0000 | 0.0000 |
| ***Tank_Frac*** | 0.0000 | 1.0000 | 1.0000 | 0.0000 | 1.0000 |
| ***EF_CH4*** | 0.0000 | 0.1120 | 0.1120 | 0.0000 | 0.1120 |
| ***WF_VOC*** | 0.0000 | 0.1567 | 0.1567 | 0.0000 | 0.2073 |
| ***WF_CO2*** | 0.0000 | 0.0255 | 0.0255 | 0.0000 | 0.0477 |
| ***WF_CH4*** | 0.0000 | 0.7245 | 0.7245 | 0.0000 | 0.5966 |
| ***WF_H2S*** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| ***MW_VOC*** | 0.0000 | 55.3283 | 55.3283 | 0.0000 | 50.6360 |
| ***WF_Benz*** | 0.0000 | 0.0002 | 0.0002 | 0.0000 | 0.0000 |
| ***WF_Ebenz*** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| ***WF_Tol*** | 0.0000 | 0.0001 | 0.0001 | 0.0000 | 0.0000 |
| ***WF_Xyl*** | 0.0000 | 0.0001 | 0.0001 | 0.0000 | 0.0000 |
| ***WF_trimetpen2*** | 0.00E+00 | 6.92E-06 | 6.92E-06 | 0.00E+00 | 9.16E-06 |
| ***WF_cyclohexane*** | 0.00E+00 | 8.95E-05 | 8.95E-05 | 0.00E+00 | 1.18E-04 |
| ***WF_cyclopentane*** | 0.00E+00 | 3.03E-04 | 3.03E-04 | 0.00E+00 | 4.01E-04 |
| ***WF_isobut*** | 0.00E+00 | 1.63E-02 | 1.63E-02 | 0.00E+00 | 2.16E-02 |
| ***WF_isopentane*** | 0.00E+00 | 5.55E-03 | 5.55E-03 | 0.00E+00 | 7.34E-03 |
| ***WF_methcychex*** | 0.00E+00 | 1.45E-04 | 1.45E-04 | 0.00E+00 | 1.92E-04 |
| ***WF_N_but*** | 0.00E+00 | 3.03E-02 | 3.03E-02 | 0.00E+00 | 4.00E-02 |
| ***WF_N_hex*** | 0.00E+00 | 1.08E-02 | 1.08E-02 | 0.00E+00 | 1.43E-02 |
| ***WF_N_pentane*** | 0.00E+00 | 6.98E-03 | 6.98E-03 | 0.00E+00 | 9.23E-03 |
| ***WF_C3H8ass*** | 0.00E+00 | 7.65E-02 | 7.65E-02 | 0.00E+00 | 1.01E-01 |
| ***WF_i_heptanes*** | 0.00E+00 | 7.07E-04 | 7.07E-04 | 0.00E+00 | 9.36E-04 |
| ***WF_i_hexanes*** | 0.00E+00 | 7.09E-04 | 7.09E-04 | 0.00E+00 | 9.38E-04 |
| ***WF_undef_VOC*** | 0.00E+00 | 8.31E-03 | 8.31E-03 | 0.00E+00 | 1.10E-02 |
| ***MW_Gas*** | 0.0000 | 18.6702 | 18.6702 | 0.0000 | 20.0989 |

## Table D-10: Natural Gas Extraction Condensate Tank Venting and Flaring

| *Natural Gas Extraction Condensate Tank Venting and Flaring Gas Well* | | | | | | |
|---|---|---|---|---|---|---|
| **Parameter Name** | **Scenario ID** | | | | | |
| | **1** | **2** | **3** | **4** | **5** | **6** |
| | **Appalachian Basin** | **Black Warrior Basin** | **Central** | **Ft Worth Basin (Barnett)** | **Gulf Coast (onshore)** | **Illinois/Michigan Basins** |
| ***Flare_Frac*** | 0.5000 | 0.5000 | 0.4970 | 0.1204 | 0.1442 | 0.5005 |
| ***C_Capture*** | 97.6529 | 100.0000 | 100.0000 | 100.0000 | 86.8045 | 99.4797 |
| ***C_Eff*** | 78.1223 | 80.0000 | 97.9999 | 98.0000 | 85.0684 | 79.6178 |
| ***Flare_Eff*** | 0.7629 | 0.8000 | 0.9800 | 0.9800 | 0.7384 | 0.7920 |
| ***EF_VOC*** | 9.3340 | 9.3340 | 6.0962 | 9.7600 | 11.0000 | 9.3031 |
| ***WF_VOC*** | 0.5537 | 0.5537 | 0.5223 | 0.5537 | 0.5537 | 0.5526 |
| ***WF_CH4*** | 0.2227 | 0.2227 | 0.3462 | 0.2227 | 0.2227 | 0.2251 |
| ***WF_Benz*** | 0.0017 | 0.0017 | 0.0014 | 0.0017 | 0.0017 | 0.0017 |
| ***WF_Ebenz*** | 0.0003 | 0.0003 | 0.0013 | 0.0003 | 0.0003 | 0.0003 |
| ***WF_Tol*** | 0.0022 | 0.0022 | 0.0033 | 0.0022 | 0.0022 | 0.0021 |
| ***WF_Xyl*** | 0.0013 | 0.0013 | 0.0035 | 0.0013 | 0.0013 | 0.0013 |
| ***WF_trimetpen2*** | 2.45E-05 | 2.45E-05 | 2.31E-05 | 2.45E-05 | 2.45E-05 | 2.44E-05 |
| ***WF_cyclohexane*** | 3.16E-04 | 3.16E-04 | 2.98E-04 | 3.16E-04 | 3.16E-04 | 3.16E-04 |
| ***WF_cyclopentane*** | 1.07E-03 | 1.07E-03 | 1.01E-03 | 1.07E-03 | 1.07E-03 | 1.07E-03 |
| ***WF_isobut*** | 5.78E-02 | 5.78E-02 | 5.45E-02 | 5.78E-02 | 5.78E-02 | 5.76E-02 |
| ***WF_isopentane*** | 1.96E-02 | 1.96E-02 | 1.85E-02 | 1.96E-02 | 1.96E-02 | 1.96E-02 |
| ***WF_methcychex*** | 5.12E-04 | 5.12E-04 | 4.83E-04 | 5.12E-04 | 5.12E-04 | 5.10E-04 |
| ***WF_N_but*** | 1.07E-01 | 1.07E-01 | 1.01E-01 | 1.07E-01 | 1.07E-01 | 1.07E-01 |
| ***WF_N_hex*** | 3.82E-02 | 3.82E-02 | 3.60E-02 | 3.82E-02 | 3.82E-02 | 3.81E-02 |
| ***WF_N_pentane*** | 2.47E-02 | 2.47E-02 | 2.33E-02 | 2.47E-02 | 2.47E-02 | 2.46E-02 |
| ***WF_C3H8ass*** | 2.70E-01 | 2.70E-01 | 2.55E-01 | 2.70E-01 | 2.70E-01 | 2.70E-01 |
| ***WF_i_heptanes*** | 2.50E-03 | 2.50E-03 | 2.36E-03 | 2.50E-03 | 2.50E-03 | 2.50E-03 |
| ***WF_i_hexanes*** | 2.50E-03 | 2.50E-03 | 2.36E-03 | 2.50E-03 | 2.50E-03 | 2.50E-03 |
| ***WF_undef_VOC*** | 2.94E-02 | 2.94E-02 | 2.77E-02 | 2.94E-02 | 2.94E-02 | 2.93E-02 |
| ***AG_HV*** | 2321.4272 | 2321.4272 | 2097.6625 | 2321.4272 | 2321.4272 | 2321.3195 |
| ***MCF_Prod*** | 13816.7285 | 23522.6827 | 42679.8338 | 88444.2760 | 88927.7682 | 11199.3791 |
| ***COND_Prod*** | 18.5493 | 41.3832 | 334.1357 | 128.8459 | 2343.5274 | 40.6790 |
| ***AG_MW*** | 33.6267 | 33.6267 | 30.3953 | 33.6267 | 33.6267 | 33.5815 |

**Table D-10: Natural Gas Extraction Condensate Tank Venting and Flaring**

| Parameter Name | Scenario ID | | | | |
|---|---|---|---|---|---|
| | 7 | 8 | 9 | 10 | 11 |
| | North-Central | Rocky Mountains | TX-LA-MS Salt Basin | West coast (onshore) | West Texas/Permian Basin |
| ***Flare_Frac*** | 0.1380 | 0.4954 | 0.3171 | 0.5000 | 0.1990 |
| ***C_Capture*** | 100.0000 | 99.9700 | 83.0094 | 51.9663 | 100.0000 |
| ***C_Eff*** | 90.0000 | 92.2649 | 75.4512 | 41.5730 | 98.0000 |
| ***Flare_Eff*** | 0.9000 | 0.9224 | 0.6263 | 0.2160 | 0.9800 |
| ***EF_VOC*** | 14.7209 | 14.1013 | 6.3354 | 9.3340 | 7.0778 |
| ***WF_VOC*** | 0.3140 | 0.7209 | 0.6004 | 0.5537 | 0.5537 |
| ***WF_CH4*** | 0.1263 | 0.1556 | 0.2080 | 0.2227 | 0.2227 |
| ***WF_Benz*** | 0.0010 | 0.0029 | 0.0022 | 0.0017 | 0.0017 |
| ***WF_Ebenz*** | 0.0002 | 0.0109 | 0.0003 | 0.0003 | 0.0003 |
| ***WF_Tol*** | 0.0012 | 0.0041 | 0.0025 | 0.0022 | 0.0022 |
| ***WF_Xyl*** | 0.0007 | 0.0209 | 0.0014 | 0.0013 | 0.0013 |
| ***WF_trimetpen2*** | 1.39E-05 | 3.18E-05 | 2.65E-05 | 2.45E-05 | 2.45E-05 |
| ***WF_cyclohexane*** | 1.79E-04 | 4.12E-04 | 3.43E-04 | 3.16E-04 | 3.16E-04 |
| ***WF_cyclopentane*** | 6.07E-04 | 1.39E-03 | 1.16E-03 | 1.07E-03 | 1.07E-03 |
| ***WF_isobut*** | 3.28E-02 | 7.52E-02 | 6.26E-02 | 5.78E-02 | 5.78E-02 |
| ***WF_isopentane*** | 1.11E-02 | 2.55E-02 | 2.13E-02 | 1.96E-02 | 1.96E-02 |
| ***WF_methcychex*** | 2.90E-04 | 6.66E-04 | 5.55E-04 | 5.12E-04 | 5.12E-04 |
| ***WF_N_but*** | 6.06E-02 | 1.39E-01 | 1.16E-01 | 1.07E-01 | 1.07E-01 |
| ***WF_N_hex*** | 2.16E-02 | 4.97E-02 | 4.14E-02 | 3.82E-02 | 3.82E-02 |
| ***WF_N_pentane*** | 1.40E-02 | 3.21E-02 | 2.67E-02 | 2.47E-02 | 2.47E-02 |
| ***WF_C3H8ass*** | 1.53E-01 | 3.52E-01 | 2.93E-01 | 2.70E-01 | 2.70E-01 |
| ***WF_i_heptanes*** | 1.42E-03 | 3.26E-03 | 2.71E-03 | 2.50E-03 | 2.50E-03 |
| ***WF_i_hexanes*** | 1.42E-03 | 3.26E-03 | 2.72E-03 | 2.50E-03 | 2.50E-03 |
| ***WF_undef_VOC*** | 1.67E-02 | 3.83E-02 | 3.19E-02 | 2.94E-02 | 2.94E-02 |
| ***AG_HV*** | 1807.0000 | 2592.7849 | 2368.6555 | 2321.4272 | 2321.4272 |
| ***MCF_Prod*** | 18489.6325 | 63670.1644 | 112913.3906 | 60539.0682 | 28293.8293 |
| ***COND_Prod*** | 157.3151 | 387.1827 | 249.9368 | 47.5082 | 200.8162 |
| ***AG_MW*** | 32.7057 | 46.4273 | 35.7858 | 33.6267 | 33.6267 |

**Table D-10: Natural Gas Extraction Condensate Tank Venting and Flaring, continued**

| *Natural Gas Extraction Condensate Tank Venting and Flaring CBM* | | | | | | |
|---|---|---|---|---|---|---|
| **Parameter Name** | **Scenario ID** | | | | | |
| | **1** | **2** | **3** | **4** | **5** | **6** |
| | **Appalachian Basin** | **Black Warrior Basin** | **Central** | **Ft Worth Basin (Barnett)** | **Gulf Coast (onshore)** | **Illinois/Michigan Basins** |
| ***Flare_Frac*** | No production | 0.5000 | 0.3092 | No production | No production | No production |
| ***C_Capture*** | No production | 100.0000 | 99.4064 | No production | No production | No production |
| ***C_Eff*** | No production | 80.0000 | 97.4183 | No production | No production | No production |
| ***Flare_Eff*** | No Production | 0.8000 | 0.9684 | No Production | No Production | No Production |
| ***EF_VOC*** | No production | 9.3340 | 9.5249 | No production | No production | No production |
| ***WF_VOC*** | No production | 0.5537 | 0.5509 | No production | No production | No production |
| ***WF_CH4*** | No production | 0.4021 | 0.4176 | No production | No production | No production |
| ***WF_Benz*** | No production | 0.0031 | 0.0030 | No production | No production | No production |
| ***WF_Ebenz*** | No production | 0.0006 | 0.0006 | No production | No production | No production |
| ***WF_Tol*** | No production | 0.0022 | 0.0021 | No production | No production | No production |
| ***WF_Xyl*** | No production | 0.0013 | 0.0012 | No production | No production | No production |
| ***WF_trimetpen2*** | No production | 2.45E-05 | 2.43E-05 | No production | No production | No production |
| ***WF_cyclohexane*** | No production | 3.16E-04 | 3.15E-04 | No production | No production | No production |
| ***WF_cyclopentane*** | No production | 1.07E-03 | 1.06E-03 | No production | No production | No production |
| ***WF_isobut*** | No production | 5.78E-02 | 5.75E-02 | No production | No production | No production |
| ***WF_isopentane*** | No production | 1.96E-02 | 1.95E-02 | No production | No production | No production |
| ***WF_methcychex*** | No production | 5.12E-04 | 5.09E-04 | No production | No production | No production |
| ***WF_N_but*** | No production | 1.07E-01 | 1.06E-01 | No production | No production | No production |
| ***WF_N_hex*** | No production | 3.82E-02 | 3.80E-02 | No production | No production | No production |
| ***WF_N_pentane*** | No production | 2.47E-02 | 2.45E-02 | No production | No production | No production |
| ***WF_C3H8ass*** | No production | 2.70E-01 | 2.69E-01 | No production | No production | No production |
| ***WF_i_heptanes*** | No production | 2.50E-03 | 2.49E-03 | No production | No production | No production |
| ***WF_i_hexanes*** | No production | 2.50E-03 | 2.49E-03 | No production | No production | No production |
| ***WF_undef_VOC*** | No production | 2.94E-02 | 2.92E-02 | No production | No production | No production |
| ***AG_HV*** | No production | 2321.4272 | 2320.5951 | No production | No production | No production |
| ***MCF_Prod*** | 22183.3258 | 16255.6969 | 23970.4960 | No production | No production | No production |
| ***COND_Prod*** | 0.0000 | 0.0170 | 22.4195 | No production | No production | No production |
| ***AG_MW*** | No production | 33.6267 | 33.4134 | No production | No production | No production |

**Table D-10: Natural Gas Extraction Condensate Tank Venting and Flaring, continued**

| Parameter Name | Scenario ID | | | | |
|---|---|---|---|---|---|
| | 7 | 8 | 9 | 10 | 11 |
| | North-Central | Rocky Mountains | TX-LA-MS Salt Basin | West coast (onshore) | West Texas/Permian Basin |
| ***Flare_Frac*** | No production | 0.4595 | 0.5000 | No production | No production |
| ***C_Capture*** | No production | 100.0000 | 100.0000 | No production | No production |
| ***C_Eff*** | No production | 91.8660 | 80.0000 | No production | No production |
| ***Flare_Eff*** | No Production | 0.9187 | 0.8000 | No Production | No Production |
| ***EF_VOC*** | No production | 12.9931 | 11.0000 | No production | No production |
| ***WF_VOC*** | No production | 0.8055 | 0.5537 | No production | No production |
| ***WF_CH4*** | No production | 0.1567 | 0.4021 | No production | No production |
| ***WF_Benz*** | No production | 0.0030 | 0.0031 | No production | No production |
| ***WF_Ebenz*** | No production | 0.0240 | 0.0006 | No production | No production |
| ***WF_Tol*** | No production | 0.0062 | 0.0022 | No production | No production |
| ***WF_Xyl*** | No production | 0.0375 | 0.0013 | No production | No production |
| ***WF_trimetpen2*** | No production | 3.56E-05 | 2.45E-05 | No production | No production |
| ***WF_cyclohexane*** | No production | 4.60E-04 | 3.16E-04 | No production | No production |
| ***WF_cyclopentane*** | No production | 1.56E-03 | 1.07E-03 | No production | No production |
| ***WF_isobut*** | No production | 8.40E-02 | 5.78E-02 | No production | No production |
| ***WF_isopentane*** | No production | 2.85E-02 | 1.96E-02 | No production | No production |
| ***WF_methcychex*** | No production | 7.44E-04 | 5.12E-04 | No production | No production |
| ***WF_N_but*** | No production | 1.56E-01 | 1.07E-01 | No production | No production |
| ***WF_N_hex*** | No production | 5.55E-02 | 3.82E-02 | No production | No production |
| ***WF_N_pentane*** | No production | 3.59E-02 | 2.47E-02 | No production | No production |
| ***WF_C3H8ass*** | No production | 3.93E-01 | 2.70E-01 | No production | No production |
| ***WF_i_heptanes*** | No production | 3.64E-03 | 2.50E-03 | No production | No production |
| ***WF_i_hexanes*** | No production | 3.64E-03 | 2.50E-03 | No production | No production |
| ***WF_undef_VOC*** | No production | 4.27E-02 | 2.94E-02 | No production | No production |
| ***AG_HV*** | No production | 2705.9085 | 2321.4272 | No production | No production |
| ***MCF_Prod*** | No production | 58059.8950 | 1498215.5000 | No production | No production |
| ***COND_Prod*** | No production | 5.9969 | 1161.5000 | No production | No production |
| ***AG_MW*** | No production | 59.9946 | 33.6267 | No production | No production |

## Table D-11: Direct Land Use GHG, No Reversion

| Parameter Name | Scenario ID | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| | *Alabama* | *Arizona* | *Arkansas* | *California* | *Colorado* | *Connecticut* | *Delaware* | *Florida* | *Georgia* |
| Grassland [dimensionless] | 0.093 | 0.697 | 0.109 | 0.430 | 0.493 | 0.021 | 0.028 | 0.232 | 0.043 |
| Forest [dimensionless] | 0.797 | 0.288 | 0.617 | 0.421 | 0.312 | 0.893 | 0.462 | 0.653 | 0.804 |
| Agriculture [dimensionless] | 0.110 | 0.016 | 0.273 | 0.149 | 0.195 | 0.086 | 0.510 | 0.115 | 0.153 |
| EF_GHG_grass [kg/m2] | 3.825 | 1.213 | 2.490 | 3.322 | 1.923 | 8.925 | 2.865 | 4.570 | 3.580 |
| EF_GHG_forest [kg/m2] | 39.689 | 17.369 | 42.338 | 70.717 | 30.757 | 59.637 | 54.520 | 46.506 | 37.719 |
| EF_GHG_ag [kg/m2] | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Parameter Name** | **Scenario ID** | | | | | | | | |
| | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| | *Idaho* | *Illinois* | *Indiana* | *Iowa* | *Kansas* | *Kentucky* | *Louisiana* | *Maine* | *Maryland* |
| Grassland [dimensionless] | 0.436 | 0.064 | 0.087 | 0.077 | 0.349 | 0.154 | 0.091 | 0.006 | 0.112 |
| Forest [dimensionless] | 0.420 | 0.144 | 0.240 | 0.089 | 0.045 | 0.512 | 0.692 | 0.968 | 0.578 |
| Agriculture [dimensionless] | 0.144 | 0.792 | 0.674 | 0.834 | 0.606 | 0.334 | 0.217 | 0.026 | 0.310 |
| EF_GHG_grass [kg/m2] | 5.799 | 3.331 | 2.107 | 4.065 | 3.599 | 3.981 | 2.577 | 9.842 | 3.454 |
| EF_GHG_forest [kg/m2] | 45.613 | 50.502 | 51.619 | 43.357 | 33.581 | 45.839 | 38.158 | 50.338 | 56.877 |
| EF_GHG_ag [kg/m2] | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Parameter Name** | **Scenario ID** | | | | | | | | |
| | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 |
| | *Massachusetts* | *Michigan* | *Minnesota* | *Mississippi* | *Missouri* | *Montana* | *Nebraska* | *Nevada* | *New Hampshire* |
| Grassland [dimensionless] | 0.022 | 0.059 | 0.074 | 0.076 | 0.212 | 0.550 | 0.504 | 0.808 | 0.020 |
| Forest [dimensionless] | 0.909 | 0.662 | 0.380 | 0.720 | 0.373 | 0.237 | 0.027 | 0.180 | 0.958 |
| Agriculture [dimensionless] | 0.069 | 0.279 | 0.546 | 0.204 | 0.416 | 0.213 | 0.469 | 0.013 | 0.022 |
| EF_GHG_grass [kg/m2] | 9.843 | 3.649 | 3.675 | 3.565 | 2.867 | 3.187 | 2.836 | 0.934 | 8.821 |
| EF_GHG_forest [kg/m2] | 59.200 | 45.756 | 34.402 | 49.171 | 42.997 | 40.252 | 32.348 | 17.872 | 61.357 |
| EF_GHG_ag [kg/m2] | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

**Table D-11: Direct Land Use GHG, No Reversion, continued**

| Parameter Name | Scenario ID | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 |
| | *New Jersey* | *New Mexico* | *New York* | *North Carolina* | *North Dakota* | *Ohio* | *Oklahoma* | *Oregon* | *Pennsylvania* |
| Grassland [dimensionless] | 0.025 | 0.750 | 0.106 | 0.051 | 0.296 | 0.094 | 0.478 | 0.410 | 0.050 |
| Forest [dimensionless] | 0.735 | 0.216 | 0.712 | 0.748 | 0.017 | 0.374 | 0.195 | 0.501 | 0.716 |
| Agriculture [dimensionless] | 0.239 | 0.034 | 0.182 | 0.201 | 0.687 | 0.532 | 0.328 | 0.089 | 0.234 |
| EF_GHG_grass [kg/m2] | 4.738 | 1.275 | 5.200 | 3.776 | 3.856 | 2.313 | 2.815 | 5.127 | 4.631 |
| EF_GHG_forest [kg/m2] | 49.976 | 21.962 | 51.060 | 62.740 | 34.164 | 46.011 | 28.292 | 76.386 | 56.694 |
| EF_GHG_ag [kg/m2] | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

| Parameter Name | Scenario ID | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 |
| | *Rhode Island* | *South Carolina* | *South Dakota* | *Tennessee* | *Texas* | *Utah* | *Vermont* | *Virginia* | *Washington* |
| Grassland [dimensionless] | 0.023 | 0.051 | 0.520 | 0.095 | 0.665 | 0.595 | 0.050 | 0.117 | 0.202 |
| Forest [dimensionless] | 0.911 | 0.819 | 0.037 | 0.632 | 0.112 | 0.366 | 0.858 | 0.729 | 0.571 |
| Agriculture [dimensionless] | 0.065 | 0.130 | 0.444 | 0.273 | 0.223 | 0.040 | 0.093 | 0.154 | 0.227 |
| EF_GHG_grass [kg/m2] | 9.252 | 3.512 | 3.432 | 3.700 | 2.260 | 2.064 | 7.668 | 3.922 | 8.924 |
| EF_GHG_forest [kg/m2] | 52.639 | 39.921 | 28.215 | 49.758 | 26.343 | 23.172 | 60.645 | 54.738 | 83.678 |
| EF_GHG_ag [kg/m2] | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

| Parameter Name | Scenario ID | | |
|---|---|---|---|
| | 46 | 47 | 48 |
| | *West Virginia* | *Wisconsin* | *Wyoming* |
| Grassland [dimensionless] | 0.089 | 0.095 | 0.819 |
| Forest [dimensionless] | 0.845 | 0.555 | 0.140 |
| Agriculture [dimensionless] | 0.066 | 0.350 | 0.041 |
| EF_GHG_grass [kg/m2] | 4.954 | 3.154 | 1.768 |
| EF_GHG_forest [kg/m2] | 57.448 | 43.339 | 35.282 |
| EF_GHG_ag [kg/m2] | 0.000 | 0.000 | 0.000 |

**Table D-12: Combustion of Natural Gas (only one scenario used in model)**

| Parameter Name | Scenario ID: 90<br>Internal Combustion Engines, Commercial/Institutional, Natural Gas, Turbine, Uncontrolled |
|---|---|
| Acenaphthene | 4.2394E-11 |
| Acenaphthylene | 4.2394E-11 |
| Acetaldehyde | 9.6563E-07 |
| Acrolein | 1.5450E-07 |
| Ammonia | 0.0000E+00 |
| Anthracene | 5.6525E-11 |
| Arsenic | 4.7104E-09 |
| Barium | 1.0363E-07 |
| Benzene | 2.8969E-07 |
| Benzo (a) anthracene | 4.2394E-11 |
| Benzo (a) pyrene | 2.8262E-11 |
| Benzo (b) fluoranthene | 4.2394E-11 |
| Benzo (e) pyrene | 0.0000E+00 |
| Benzo (g,h,i) perylene | 2.8262E-11 |
| Benzo (k) fluoranthene | 4.2394E-11 |
| Beryllium | 2.8262E-10 |
| Biphenyl | 0.0000E+00 |
| 1,3-Butadiene | 1.0381E-08 |
| n-Butane | 4.9459E-05 |
| Cadmium | 2.5907E-08 |
| Carbon dioxide | 2.6555E+00 |
| Carbon monoxide | 1.9795E-03 |
| Carbon tetrachloride | 0.0000E+00 |
| Chlorobenzene | 0.0000E+00 |
| Chloroform | 0.0000E+00 |
| Chromium | 3.2973E-08 |
| Chrysene | 4.2394E-11 |
| Cobalt | 1.9784E-09 |
| Copper | 2.0019E-08 |
| Cyanide | 0.0000E+00 |
| Cyclohexane | 0.0000E+00 |
| Cyclopentane | 0.0000E+00 |
| Dibenzo(a,h) anthracene | 2.8262E-11 |
| Dichlorobenzene, mixed isomers | 2.8262E-08 |
| 1,1-Dichloroethane | 0.0000E+00 |
| Dichloromethane | 0.0000E+00 |
| 1,3-Dichloropropene | 0.0000E+00 |

| Parameter Name | Scenario ID: 90<br>Internal Combustion Engines, Commercial/Institutional, Natural Gas, Turbine, Uncontrolled |
|---|---|
| Dimethylbenz(a)anthracene | 3.7683E-10 |

**Table D-12: Combustion of Natural Gas (only one scenario used in model), continued**

| Parameter Name | Scenario ID: 90<br>Internal Combustion Engines, Commercial/Institutional, Natural Gas, Turbine, Uncontrolled |
|---|---|
| Ethane | 7.3011E-05 |
| Ethyl chloride | 0.0000E+00 |
| Ethylbenzene | 7.7250E-07 |
| Ethylene dibromide | 0.0000E+00 |
| Ethylene dichloride | 0.0000E+00 |
| Fluoranthene | 7.0656E-11 |
| Fluorene | 6.5945E-11 |
| Formaldehyde | 1.7140E-05 |
| Indeno(1,2,3-cd)pyrene | 4.2394E-11 |
| Isobutane | 0.0000E+00 |
| Isobutyraldehyde | 0.0000E+00 |
| Isomers of xylene | 1.5450E-06 |
| Lead | 1.1776E-08 |
| Manganese | 8.9497E-09 |
| Mercury | 6.1235E-09 |
| Methane | 2.0761E-04 |
| Methyl alcohol | 0.0000E+00 |
| 2-Methyl Naphthalene | 5.6525E-10 |
| 3-Methylcholanthrene | 4.2394E-11 |
| Methylcyclohexane | 0.0000E+00 |
| Molybdenum | 2.5907E-08 |
| N-Hexane | 4.2394E-05 |
| N-Nonane | 0.0000E+00 |
| N-Octane | 0.0000E+00 |
| N-Pentane | 6.1235E-05 |
| Naphthalene | 3.1383E-08 |
| Nickel | 4.9459E-08 |
| Nitrogen oxides (NOx) | 7.7250E-03 |
| Nitrous oxide | 7.2422E-05 |
| Perchloroethylene | 0.0000E+00 |
| Perylene | 0.0000E+00 |
| Phenanthrene | 4.0038E-10 |

| | |
|---|---|
| Phenol | 0.0000E+00 |
| Phosphorus | 0.0000E+00 |
| >PM10 | 4.4749E-05 |
| PM2.5-PM10 | 0.0000E+00 |
| PM2.5 | 0.0000E+00 |
| Polycyclic aromatic hydrocarbons (PAH) | 5.3110E-08 |

**Table D-12: Combustion of Natural Gas (only one scenario used in model), continued**

| Parameter Name | **Scenario ID: 90** Internal Combustion Engines, Commercial/Institutional, Natural Gas, Turbine, Uncontrolled |
|---|---|
| Propylene oxide | 7.0008E-07 |
| Propane | 3.7683E-05 |
| Propylene dichloride | 0.0000E+00 |
| Pyrene | 1.1776E-10 |
| Selenium | 5.6525E-10 |
| Styrene | 0.0000E+00 |
| Sulfur dioxide | 1.4131E-05 |
| Sulfur oxides (SOx) | 0.0000E+00 |
| 1,1,2,2-Tetrachloroethane | 0.0000E+00 |
| Toluene | 3.1383E-06 |
| Total organic compounds (TOC) | 2.6555E-04 |
| 1,1,2-Trichloroethane | 0.0000E+00 |
| 1,2,3-Trimethylbenzene | 0.0000E+00 |
| 1,2,4-Trimethylbenzene | 0.0000E+00 |
| 1,3,5-Trimethylbenzene | 0.0000E+00 |
| 2,2,4-Trimethylpentane | 0.0000E+00 |
| Vanadium | 5.4169E-08 |
| Vinyl chloride | 0.0000E+00 |
| Volatile organic compounds (VOC) | 5.0696E-05 |
| Zinc | 6.8301E-07 |

**Table D-13: Natural gas distribution**

| Parameter Name | Value | Min. Value | Max. Value | Unit |
|---|---|---|---|---|
| loss | 0.00476 | | | kg |

**Table D-14: Natural Gas Well Completion**

| Parameter Name | Value | Min. Value | Max. Value | Unit |
|---|---|---|---|---|
| Vent_completion | 705 | | | kg |
| Product_rate | 1257 | 1006 | 1508 | kg/d |
| Life_well | 30 | | | yr |

**Table D-15: Natural Gas Well Workovers**

| Parameter Name | Value | Min. Value | Max. Value | Unit |
|---|---|---|---|---|
| Vent_episode | 46.7 | | | kg/episode |
| Freq_episode | 0.037 | | | episode/yr |
| Product_rate | 1257 | | | kg/d |

**Table D-16: Indirect Land Use GHG**

| Flow Name | Value | Total | Units per RF |
|---|---|---|---|
| Indirect land transformation | 1 | 1.00 | m2 |
| Carbon dioxide | 1 | 24.60 | kg |

**Table D-17: Diesel, Production, Transport, and Refining**

| Parameter Name | Value | Unit |
|---|---|---|
| S2_F_TRAIN_DIS | 1.2 | miles |
| S2_TRK_TANK_DIS | 2.7 | miles |
| S2_WATDOMDISZ | 331.0 | miles |
| S2_WATFOREDISZ | 4309.0 | miles |
| S2D_PIPE_LENGTH | 328.3 | miles |
| S2F_PIPE_LENGTH | 66.3 | miles |
| S3_FENERGY | 2.49E-01 | [unitless] |
| S3_FH2 | 3.77E-01 | [unitless] |
| S3_RHO_BBL | 1.35E+02 | kg/bbl |

**Table D-18: U.S. National Average Electricity Grid Mix 2007**

| Parameter Name | Value | Min. Value | Max. Value | Unit |
|---|---|---|---|---|
| Coal | 4.83E-01 | | | MWh |
| Fuel_Oil | 1.58E-02 | | | MWh |
| Natural_Gas | 2.16E-01 | | | MWh |
| Nuclear | 1.94E-01 | | | MWh |
| Hydro | 6.68E-02 | | | MWh |
| Biomass | 1.30E-02 | | | MWh |
| Wind | 8.26E-03 | | | MWh |
| Solar | 1.46E-04 | | | MWh |
| Geothermal | 3.49E-03 | | | MWh |

**Table D-19: Natural Gas Well Construction and Installation**

| Parameter Name | Value | Min. Value | Max. Value | Unit |
|---|---|---|---|---|
| Drill_speed | 17.8 | 14.2 | 21.3 | m/h |
| Drill_depth | 457 | 305 | 610 | m |
| Product_rate | 1257 | | | kg/d |
| Life_well | 30 | 24 | 36 | yr |
| Drill_power | 0.45 | | | MW |
| Diesel_rate | 221 | | | kg/MWh |
| EF_NOx | 14.6 | | | kg/MWh |
| EF_CO | 3.35 | | | kg/MWh |
| EF_SOx | 0.246 | | | kg/MWh |
| EF_CO2 | 706 | | | kg/MWh |
| EF_PM | 0.426 | | | kg/MWh |
| EF_CH4 | 0.0386 | | | kg/MWh |
| EF_VOC | 0.390 | | | kg/MWh |
| Casing_density | 36 | 26.78010108 | 44.6335018 | kg/m |

**Table D-20: Natural Gas, Average Associated, Extraction**

| Flow Name | Total | Units per RF |
|---|---|---|
| Water | 7.21E-01 | kg |
| Energy resources | 1.11E+00 | kg |

**Table D-21: Natural Gas, Marginal Associated, Extraction**

| Flow Name | Total | Units per RF |
|---|---|---|
| Water | 6.91E-01 | kg |
| Energy resources | 1.11E+00 | kg |

**Table D-22: Coal Bed Methane Natural Gas, Water Use and Water Quality**

| Parameter Name | Value | Min. Value | Max. Value | Units |
|---|---|---|---|---|
| Waterprod | 4.282 | 0.201 | 12.119 | kg/kg |
| EF_W_Barium | 6.20E-06 | | | kg/kg |
| EF_W_HCO3 | 4.38E-03 | 6.16E-04 | 2.38E-02 | kg/kg |
| EF_W_Ca | 1.07E-04 | 3.06E-06 | 6.12E-04 | kg/kg |
| EF_W_Cl | 2.16E-03 | 1.24E-05 | 3.47E-03 | kg/kg |
| EF_W_Mg | 3.54E-05 | 1.22E-06 | 3.52E-04 | kg/kg |
| EF_W_Mn | 3.20E-07 | | | kg/kg |
| EF_W_Na | 2.08E-03 | 2.30E-04 | 9.66E-03 | kg/kg |
| EF_W_SO4 | 8.72E-06 | 0.00E+00 | 4.08E-05 | kg/kg |
| EF_W_TDS | 8.85E-03 | 9.19E-04 | 3.65E-02 | kg/kg |

**Table D-23: Barnett Shale Natural Gas, Water Use and Water Quality**

| Parameter Name | Value | Min. Value | Max. Value | Units |
|---|---|---|---|---|
| Wateruse_g | 0.486 | 0.372 | 0.627 | kg/kg |
| Wateruse_s | 0.324 | 0.248 | 0.418 | kg/kg |
| perc_flowback | 0.250 | | | dimensionless |
| EF_W_Calcium | 0.006 | 0.001 | 0.010 | kg/L |
| EF_W_Cl | 0.059 | 0.023 | 0.096 | kg/L |
| EF_W_Iron | 0.000 | 0.000 | 0.000 | kg/L |
| EF_W_Magnesium | 0.001 | 0.000 | 0.001 | kg/L |
| EF_W_Silica | 0.000 | 0.000 | 0.000 | kg/L |
| EF_W_Sulfate | 0.000 | 0.000 | 0.000 | kg/L |
| EF_W_TDS | 0.108 | 0.040 | 0.176 | kg/L |
| h2otreat_redux | 0.900 | | | dimensionless |

**Table D-24: Conventional Onshore Natural Gas, Water Use and Water Quality**

| Parameter Name | Value | Units |
|---|---|---|
| Wateruse_g | 0.306 | kg/kg |
| Wateruse_s | 0.306 | kg/kg |
| Waterprod | 1.146 | kg/kg |
| EF_W_Boron | 1.83E-06 | kg/kg |
| EF_W_Cl | 3.60E-04 | kg/kg |
| EF_W_TDS | 3.75E-03 | kg/kg |
| EF_W_Sulfates | 1.45E-03 | kg/kg |
| EF_W_OilGrease | 2.56E-05 | kg/kg |

**Table D-25: Conventional Offshore Natural Gas, Water Use and Water Quality**

| Parameter Name | Value | Units |
|---|---|---|
| Waterprod | 0.657 | kg/kg |
| EF_W_BOD | 9.48E-04 | kg/kg |
| EF_W_TOC | 5.83E-04 | kg/kg |
| EF_W_N | 4.27E-05 | kg/kg |
| EF_W_P | 5.65E-07 | kg/kg |
| EF_W_Salt | 4.50E-02 | kg/kg |

**Table D-26: Water Use for Marcellus Shale Gas Extraction**

| Parameter Name | Value | Units |
|---|---|---|
| NG_product | 9.716E+07 | kg/(well-life) |
| Wateruse_drill | 3.028E+05 | kg/(well-life) |
| Wateruse_1frac | 1.438E+07 | kg/(well-treatment) |
| NumFrac | 4.750E+00 | dimensionless |
| prop_Gwater | 0.0155 | dimensionless |
| prop_Swater | 0.9845 | dimensionless |
| FBrate | 0.3458 | dimensionless |
| FB_recycled | 0.2180 | dimensionless |
| FB_WWTP | 0.3910 | dimensionless |
| FB_crystallized | 0.3910 | dimensionless |
| Water_recycling | 0.0300 | dimensionless |

**Table D-27: Marcellus Shale Water Treatment at a WWTP**

| Parameter Name | Value | Unit |
|---|---|---|
| dist_WWTP | 1.000E+02 | km |
| diesel_rate | 2.904E-05 | L/(kg-km) |
| WWTP_elec | 4.491E-04 | kWh/kg |
| WWTP_N2O | 1.377E-06 | kg/kg water |
| WWTP_CH4 | 3.700E-06 | kg/kg water |
| WWTP_CO2 | 3.391E-04 | kg/kg water |
| EF_TSS | 1.224E-04 | kg/kg water |
| EF_TDS | 7.851E-02 | kg/kg water |
| EF_TKN | 9.246E-05 | kg/kg water |
| EF_Ammonia | 8.253E-05 | kg/kg water |
| EF_BOD | 1.218E-04 | kg/kg water |
| EF_TOC | 5.768E-05 | kg/kg water |
| EF_DOC | 9.890E-05 | kg/kg water |
| EF_Oil and Grease | 4.960E-06 | kg/kg water |
| EF_Bromide | 5.001E-04 | kg/kg water |
| EF_Sulfite | 1.888E-05 | kg/kg water |
| EF_Total P | 1.223E-06 | kg/kg water |

**Table D-28: Marcellus Shale Water Treatment with Crystallization**

| Parameter Name | Value | Unit |
|---|---|---|
| dist_crystal | 100 | km |
| diesel_rate | 2.90E-05 | L/(kg-km) |
| Crystal_elec | 5.42E-02 | kWh/kg water |
| EF_TDS | 1.96E-01 | kg/kg water |
| FB_Cryst | 1.00E+00 | kg |
| WtrOut_Cryst | 9.50E-01 | dimensionless |

**Table D-29: Gasoline, Production, Transport, and Refining**

| Parameter Name | Value | Unit |
|---|---|---|
| S2_F_TRAIN_DIS | 1.20E+00 | miles |
| S2_TRK_TANK_DIS | 2.70E+00 | miles |
| S2_WATDOMDISZ | 3.31E+02 | miles |
| S2_WATFOREDISZ | 4.31E+03 | miles |
| S2D_PIPE_LENGTH | 3.28E+02 | miles |
| S2F_PIPE_LENGTH | 6.63E+01 | miles |
| S3_FENERGY | 4.74E-01 | [unitless] |
| S3_FH2 | 4.30E-01 | [unitless] |
| S3_RHO_BBL | 1.17E+02 | kg/bbl |

**Table D-30: Offshore Natural Gas Rig, Crew Transport**

| Parameter Name | Value | Units |
|---|---|---|
| EF_CO2 | 3.45E+02 | kg/kg |
| EF_CH4 | 3.44E-01 | kg/kg |
| EF_N2O | 3.61E-02 | kg/kg |
| fuel_helicopter | 1.17E+02 | kg/day |
| Product_rate | 53342 | kg/day |

**Table D-31: Hydraulic Fracturing Water Delivery**

| Parameter Name | Value | Unit |
|---|---|---|
| distance | 100 | km |
| diesel_rate | 2.904E-05 | L/(kg-km) |
| EF_VOC | 2.787E-04 | kg/L |
| EF_CO | 1.116E-03 | kg/L |
| EF_NOX | 3.322E-03 | kg/L |
| EF_PM10 | 1.321E-04 | kg/L |
| EF_SOX | 3.347E-04 | kg/L |
| EF_CH4 | 5.284E-05 | kg/L |
| EF_N2O | 6.791E-05 | kg/L |
| EF_CO2 | 2.651E+00 | kg/L |

**Table D-32: Natural Gas Sweetening, Amine Process Acid Gas Removal**

| Parameter Name | Value | Units |
|---|---|---|
| CO2_vented | 8.68E-02 | kg/kg |
| Fuel_NG | 2.26E-05 | kg/kg |
| EF_CO2 | 2.86E+00 | kg/kg |
| EF_CH4c | 5.62E-02 | kg/kg |
| vent_CH4 | 9.72E-04 | kg/kg |
| EF_N2O | 1.56E-02 | kg/kg |
| EF_NOx | 2.38E-03 | kg/kg |
| EF_CO | 2.00E-03 | kg/kg |
| EF_Pb | 1.19E-08 | kg/kg |
| EF_PM | 1.81E-04 | kg/kg |
| EF_SO2 | 1.43E-05 | kg/kg |
| EF_VOC | 1.31E-04 | kg/kg |

**Table D-33: Natural Gas Dehydration**

| Parameter Name | Value | Units |
|---|---|---|
| NG_fuel_total | 1.48E-04 | kg/kg |
| dehydGHG_CH4c | 8.09E-09 | kg/kg |
| dehydGHG_CH4v | 3.37E-04 | kg/kg |

**Table D-34: U.S. National Average Electricity Grid Mix 2007**

| Parameter Name | Value | Unit |
|---|---|---|
| Coal | 4.83E-01 | MWh |
| Fuel_Oil | 1.58E-02 | MWh |
| Natural_Gas | 2.16E-01 | MWh |
| Nuclear | 1.94E-01 | MWh |
| Hydro | 6.68E-02 | MWh |
| Biomass | 1.30E-02 | MWh |
| Wind | 8.26E-03 | MWh |
| Solar | 1.46E-04 | MWh |
| Geothermal | 3.49E-03 | MWh |

**Table D-35: Wellhead Compressor, Electrically-Powered Centrifugal, 500 HP**

| Parameter Name | Value | Units |
|---|---|---|
| Comp_heatrate | 1.76E-04 | MWh/kg |
| Motor_eff | 0.95 | dimensionless |
| CH4vent | 6.90E-03 | kg/kg |

**Table D-36: Wellhead Compressor, Gas-Powered Reciprocating, 200 HP**

| Parameter Name | Value | Units |
|---|---|---|
| Comp_heatrate | 1.76E-04 | MWh/kg |
| Recip_through | 217 | kg/MWh |
| EFrecipGHG_CO2 | 2.69 | kg/kg |
| EFrecipGHG_CH4 | 3.06E-02 | kg/kg |
| EFrecipCAP_NOx | 9.98E-02 | kg/kg |
| EFrecipCAP_CO | 7.75E-03 | kg/kg |
| EFrecipCAP_SO2 | 1.44E-05 | kg/kg |
| EFrecipCAP_PM | 2.44E-04 | kg/kg |
| EFrecipCAP_VOC | 2.89E-03 | kg/kg |

**Table D-37: Wellhead Compressor, Gas-Powered Centrifugal, 200 HP**

| Parameter Name | Value | Units |
|---|---|---|
| Comp_heatrate | 1.76E-04 | MWh/kg |
| Centrif_through | 201 | kg/MWh |
| CH4vent | 6.90E-03 | kg/kg |

**Table D-38: Natural Gas Compressors, Assembly**

| Parameter Name | Value | Min. Value | Max. Value | Unit |
|---|---|---|---|---|
| Gas_recip | 1.00 | 0 | 1 | dimensionless |
| Gas_centrif | 0.00 | 0 | 1 | dimensionless |
| Elec_centif | 0.00 | 0 | 1 | dimensionless |

**Table D-39: Onshore Pipeline, Installation/Deinstallation**

| Parameter Name | Value | Units |
|---|---|---|
| Diesel_I | 9.20E+03 | L |
| CO2_I | 3.12E+04 | kg |
| VOC_I | 2.35E+01 | kg |
| NOX_I | 3.19E+02 | kg |
| SO2_I | 1.08E+01 | kg |
| PM_I | 6.32E+01 | kg |
| CO_I | 1.11E+02 | kg |
| CH4_I | 1.41E+00 | kg |
| Nitrous_I | 6.32E-01 | kg |
| Ammonia_I | 1.01E+00 | kg |
| Mercury_I | 1.09E-02 | kg |
| HCl_I | 1.02E+00 | kg |
| Arsenic_I | 8.76E-03 | kg |
| Cadmium_I | 8.21E-03 | kg |
| Chromium_I | 3.28E-03 | kg |
| ChromiumVI_I | 5.48E-04 | kg |
| Copper_I | 2.25E-02 | kg |
| Lead_I | 4.54E-02 | kg |
| Manganese_I | 1.70E-02 | kg |
| Nickel_I | 2.14E-02 | kg |
| Selenium_I | 1.20E-02 | kg |
| Zinc_I | 1.23E-01 | kg |
| Deinstallation | 0.1 | [unitless] |

**Table D-40: Pipeline NG Operation**

| Parameter Name | Value | Unit |
|---|---|---|
| DISTANCE | 971 | km |
| SHARE_TURBINE | 0.19 | dimensionless |
| SHARE_MOTOR | 0.03 | dimensionless |
| NG_FUEL_RATE | 1.01E-05 | kg/kg-km |
| EF_CO2_RECIP | 2.69E+00 | kg/kg |
| EF_CO2_TURBINE | 2.69E+00 | kg/kg |
| EF_N2O_RECIP | 0.00E+00 | kg/kg |
| EF_N2O_TURBINE | 7.34E-05 | kg/kg |
| EF_CH4_RECIP | 3.06E-02 | kg/kg |
| EF_CH4_TURBINE | 2.10E-04 | kg/kg |
| EF_NOx_RECIP | 9.98E-02 | kg/kg |
| EF_NOx_TURBINE | 3.18E-03 | kg/kg |
| EF_CO_RECIP | 7.75E-03 | kg/kg |
| EF_CO_TURBINE | 7.34E-04 | kg/kg |
| EF_SO2_RECIP | 1.44E-05 | kg/kg |
| EF_SO2_TURBINE | 8.31E-05 | kg/kg |
| EF_PM_RECIP | 2.44E-04 | kg/kg |
| EF_PM_TURBINE | 1.61E-04 | kg/kg |
| EF_NMVOC_RECIP | 2.89E-03 | kg/kg |
| EF_NMVOC_TURBINE | 5.14E-05 | kg/kg |
| MOTOR_EFF | 0.95 | dimensionless |
| MOTOR_POWER | 10.48 | MW |
| MOTOR_CAPACITY | 0.75 | dimensionless |
| MOTOR_THROUGH | 582640 | kg/hr |
| fugitiveCH4 | 5.37E-06 | kg/kg-km |

Timothy J. Skone, P.E.
skonet@netl.doe.gov

Joe Marriott, Ph.D.
joseph.marriott@contr.netl.doe.gov

**www.netl.doe.gov**

Pittsburgh, PA • Morgantown, WV • Albany, OR • Sugar Land, TX • Anchorage, AK

(800) 553-7681