New York State Oil and Gas Sector Methane Emissions Inventory

Final Report | Report Number 19-36 | July 2019

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New York State Oil and Gas Sector Methane Emissions Inventory

Final Report

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Abstract

Methane (CH_4) is a greenhouse gas that is second only to carbon dioxide (CO_2) in its contribution to global climate change. Fossil fuel production and consumption, including the extraction and processing of natural gas as well as the distribution of natural gas to homes and businesses, is a significant source of anthropogenic CH_4 emissions. The goal of this project was to support CH_4 emission reduction efforts in New York State by improving the State's understanding of CH_4 emission and CH_4 emission-accounting methodologies for the oil and natural gas sector, including upstream, midstream, and downstream sources. Informed by the literature review and guided by identified best practices, an emissions estimation tool was developed to generate a geospatially resolved, bottom-up CH_4 emissions inventory for the oil and natural gas sector for 1990–2017. In 2017, CH_4 emissions from oil and natural gas activity in New York State totaled 106,561 metric tons (MT) CH_4, equivalent to 2,664,182 $MTCO_2e$ (AR4 GWP_{100}). Downstream emissions totaled 0.477 $MMTCO_2e$ in 2017 (17.9%), midstream emissions totaled 1.807 $MMTCO_2e$ (67.8%) and upstream sources emitted 0.380 $MMTCO_2e$ (14.2%). These results reflect the fact that the State is largely a consumer of natural gas and, as such, the midstream and downstream source categories drive the majority of CH_4 emissions. Results of this study estimates CH_4 emissions to be 20% higher than previous estimates of CH_4 emissions from natural gas systems [2.22 million metric ton (MMT) CO_2e in 2015], based on prior inventories developed by the State and using 2015 as the most recent common year.

Keywords

Methane, oil, natural gas, emissions, inventory, greenhouse gas inventory, emission factors, methane inventory, downstream emissions, upstream emissions, midstream emissions, natural gas emissions, natural gas production, New York State methane inventory

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Cynthia McCarran, New York State Department of Public Service
Catherine Dickert, New York State Department of Environmental Conservation
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Acronyms and Abbreviations

AR4	Fourth Assessment Report of the IPCC (2007)
AR5	Fifth Assessment Report of the IPCC (2014)
bbl	barrels. 1 oil barrel = 42 U.S. gallons
Bcf	billion cubic feet
BHFS	Bacharach Hi Flow® Sampler
BOE	barrels of oil equivalent
BOEM	Bureau of Ocean Energy Management
Bscf	billion standard cubic feet
Btu	British thermal unit
BU	bottom-up
CAP	criteria air pollutants
CBM	coal-bed methane
CenSARA	Central States Air Resource Agencies
cf	cubic feet
CFR	Code of Federal Regulation
CH_4	methane
CI	confidence interval
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CS	compressor station
D-J	Denver-Julesburg
EDF	Environmental Defense Fund
EF	emissions factor
EIA	Energy Information Administration
EPA	United States Environmental Protection Agency

ESOGIS	Empire State Organized Geologic Information System
EU	European Union
EU-28+ISL	28 European Union countries plus Iceland
EU Inventory	Annual European Union Greenhouse Gas Inventory 1990-2016 and Inventory Report 2018
FLIGHT	Facility Level Information on Greenhouse Gases Tool
g	gram
Gg	gigagram
GHG	greenhouse gas
GHGRP	Greenhouse Gas Reporting Program
GRI	Gas Research Institute
GWP	global warming potential
GWP_{20}	global warming potential (20 year)
GWP_{100}	global warming potential (100 year)
H_2S	hydrogen sulfide
HAP	hazardous air pollutants
hp	horsepower
hr	hour
HVHF	high-volume hydraulic fracturing
IPCC	Intergovernmental Panel on Climate Change
ITRC	Interstate Technology and Regulatory Council
Kg	kilogram
lb	pound
LAUF	lost and unaccounted for
LNG	liquefied natural gas
Mcf	thousand cubic feet
Mg	megagram
MMBTU	million British thermal unit
MMcf	million cubic feet
MMT	million metric ton (1 MMT = 1 teragram)
M&R	metering and regulating
MT	metric ton
N_2O	nitrous oxide
NG	natural gas
NEI	National Emissions Inventory
NSPS	New Source Performance Standards
NYS	New York State
DEC	New York State Department of Environmental Conservation
Oil and Gas Tool	Nonpoint Oil and Gas Emission Estimation Tool

PAC	Project Advisory Committee
PHMSA	Pipeline and Hazardous Materials Safety Administration
psi	pounds per square inch
psig	pounds per square inch gauge
SCC	Source Classification Code
scf	standard cubic foot
scfd	standard cubic feet per day
SCFM	standard cubic foot per minute (1 SCFM = 19.2 gCH_4.min-1)
SEDS	State Energy Data System
SIT	State Inventory Tool
SNCR	selective non-catalytic reduction
TD	top-down
UNFCCC	United Nations Framework Convention on Climate Change
VOC	volatile organic compound

Summary

Methane (CH_4) is a greenhouse gas that is second only to carbon dioxide (CO_2) in its contribution to global climate change. Driven by human activity, CH_4 emissions are increasing in the atmosphere. CH_4 is particularly problematic because its impact on climate change is 25 times greater than CO_2 over a 100-year period, according to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC). Fossil fuel production and consumption, including the extraction and processing of natural gas as well as the distribution of natural gas to homes and businesses, is a significant source of anthropogenic CH_4 emissions.

The goal of this project is to support CH_4 emission reduction efforts in New York State by improving the State's understanding of CH_4 emission and CH_4 emission-accounting methodologies for the oil and natural gas sector, including upstream, midstream, and downstream sources. The use of improved accounting methodologies to develop an activity-driven, site-level, CH_4 emissions inventory is needed to capture the impacts of mitigation strategies for fugitive CH_4 emissions from the oil and natural gas sector. To ensure project success, a six-member Project Advisory Committee (PAC) comprised of experts with knowledge on air pollutant emissions from the oil and natural gas sector was established to provide technical oversight and peer review throughout the duration of this project.

The oil and natural gas sector in New York State is dominated by end-user consumption. In 2017, the State consumed 4.6% (1,255 billion cubic feet, Bcf) of the natural gas in the United States but produced less than 0.1% of natural gas (11.4 Bcf). The natural gas wells are primarily low-producing wells and there are no natural gas processing plants in New York State. In 2017, 299 out of 7,032 wells (4.26%) accounted for 50% of natural gas production. While oil and natural gas production are concentrated in Western New York, consumption is more evenly distributed across the State. Since production and consumption characteristics of the oil and natural gas sector differ from the national average, using national estimates for the fraction of emissions attributed to each stage in the oil and natural gas system, derives potentially spurious results. This situation highlights the importance of performing a bottom-up, activity-driven, component-level CH_4 emissions inventory for the State.

The development of this inventory focuses on the following best practices: (1) the use of appropriately scaled activity data, (2) inclusion of state-of-the-science emission factors (EFs), (3) geospatial resolution of activities and emissions, and (4) application and reporting of uncertainty factors, including high-emitting sources. In addition, New York State should consider reporting emissions in CO_2 equivalents (CO_2e) using the most recent IPCC Assessment Report (AR5) values in addition to AR4 values as well as both the long-term (100-year global warming potential, GWP_{100}) and short-term (20-year GWP_{20}) GWP factors.

A comprehensive literature review performed under this project revealed five major issues that need to be considered in order to improve CH_4 emission inventories for the oil and natural gas sector. First, the literature stresses the importance of an activity-based, component-level analysis. These methodologies meet the highest standards laid out by the IPCC and the U.S. Environmental Protection Agency (EPA). Second, this review indicated the importance of identifying appropriate EFs for the systems that are in place in the geographic region. EFs can vary significantly by region due to differences in gas pressure and gas composition as well as equipment type, material, and age. Thus, using region-specific EFs provides the most accurate results. Third, geospatial allocation of emissions is important (1) for planners and regulators to identify hotspots and (2) to link emission inventories with chemical fate and transport and health models. Fourth, the literature demonstrates significant uncertainty in estimating emissions, stressing the need to incorporate uncertainty analysis into the emissions inventory methodology. Fifth, there is a clear and pressing need to consider high-emitting sources, their causes, and the role that they play in overall emission inventories.

Informed by the literature review and guided by identified best practices, an emissions estimation tool was developed to generate a geospatially resolved, bottom-up CH_4 emissions inventory for the oil and natural gas sector for 1990–2017. CH_4 emissions from oil and natural gas activity in New York State in 2017 totaled 106,561 metric tons (MT) CH_4, equivalent to 2,664,182 $MTCO_2e$ (AR4 GWP_{100}). Results of this study estimates CH_4 emissions to be 20% higher than previous estimates of CH_4 emissions from natural gas systems [2.22 million metric ton (MMT) CO_2e in 2015], based on prior inventories developed by the State and using 2015 as the most recent common year.

Figure S-1 shows CH_4 emissions by source category broken out by upstream, midstream, and downstream source categories using AR4 GWP_{100} units. Downstream emissions totaled 0.477 $MMTCO_2e$ in 2017, accounting for 17.9% of total emissions. Unprotected steel mains are the largest single-source category, followed by residential meters and cast-iron distribution mains. Midstream emissions totaled 1.807 $MMTCO_2e$, accounting for 67.8% of emissions, with compressors (storage and transmission) comprising the largest source categories in the inventory. In fact, storage and transmission compressor stations are the two largest single-source categories identified in New York State. Upstream sources, dominated by conventional gas wells, emitted 0.380 $MMTCO_2e$, accounting for 14.2% of total CH_4 emissions. These results reflect the fact that the State is largely a consumer of natural gas and, as such, the midstream and downstream source categories drive the majority of CH_4 emissions.

Figure S-1. CH_4 Emissions by Source Category and Grouped by Upstream, Midstream, and Downstream Stages in New York State in 2017

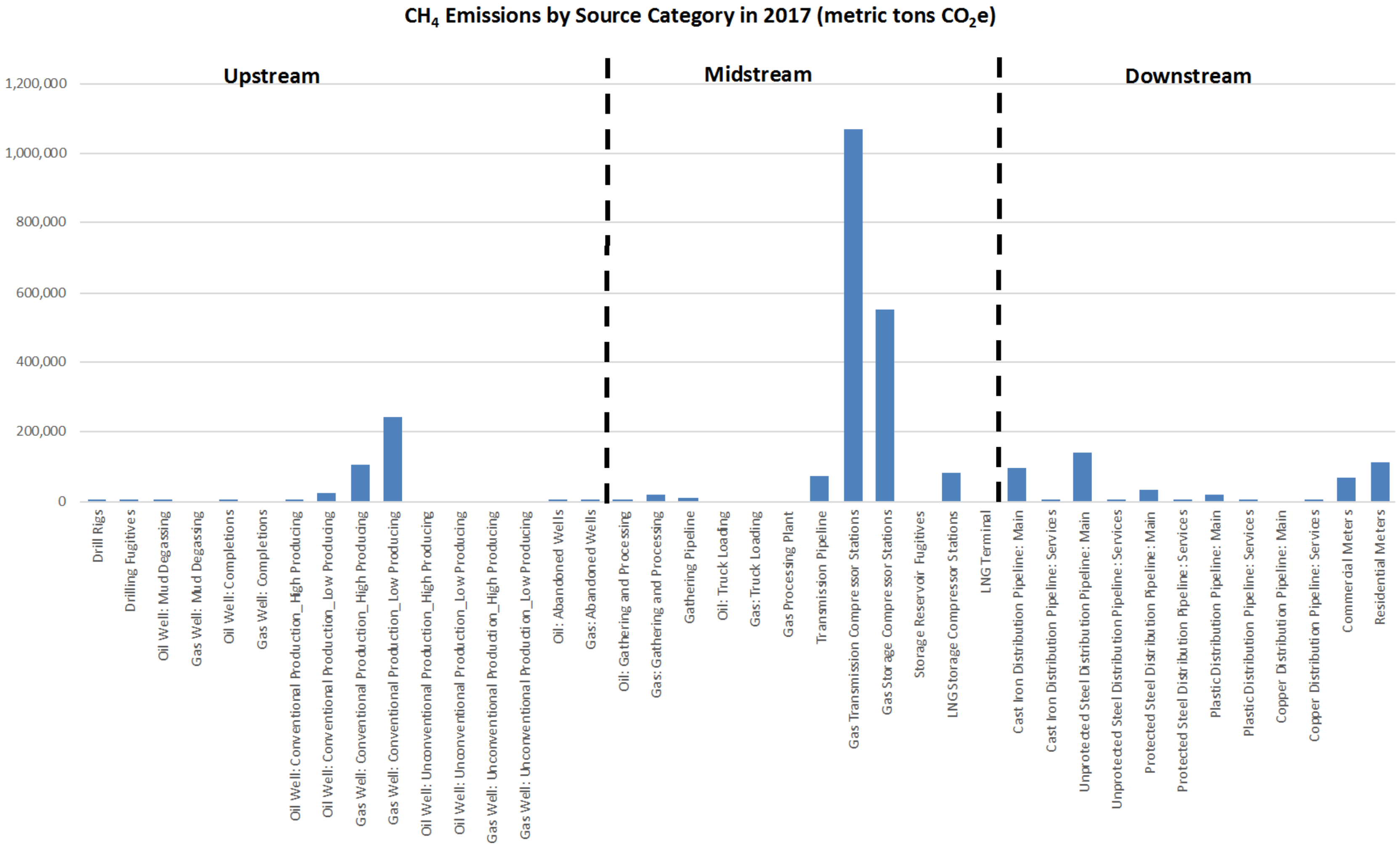


Figure S-2 shows the distribution of emissions by county. The counties with the largest emissions correspond to the high oil and natural gas exploration and production areas in Western New York and to areas of high population, gas services, and consumption around New York City and Long Island. As shown in Figure ES-2, Erie County had the highest total CH_4 emissions in 2017, accounting for 11.3% of statewide CH_4 emissions from the oil and natural gas sector, followed by Steuben County (11.0%). Erie County had the second-highest gas production in New York State, as well as the largest miles of transmission pipeline (381.9 miles) and second-highest number of compressor stations (five gas transmission compressor stations and six gas storage compressor stations), resulting in high-midstream emissions. Steuben County ranked highest in conventional gas production and in number of compressor stations (five gas transmission compressor stations and seven gas storage compressor stations) and second-highest in miles of transmission pipeline (320.4 miles), resulting in high-upstream and midstream emissions. The top five counties (Erie, Steuben, Chautauqua, Cattaraugus, and Allegany) accounted for 41.7% of statewide CH_4 emissions in 2017.

Figure S-2. Map of CH_4 Emissions by County in New York State in 2017 (AR4 GWP_{100})

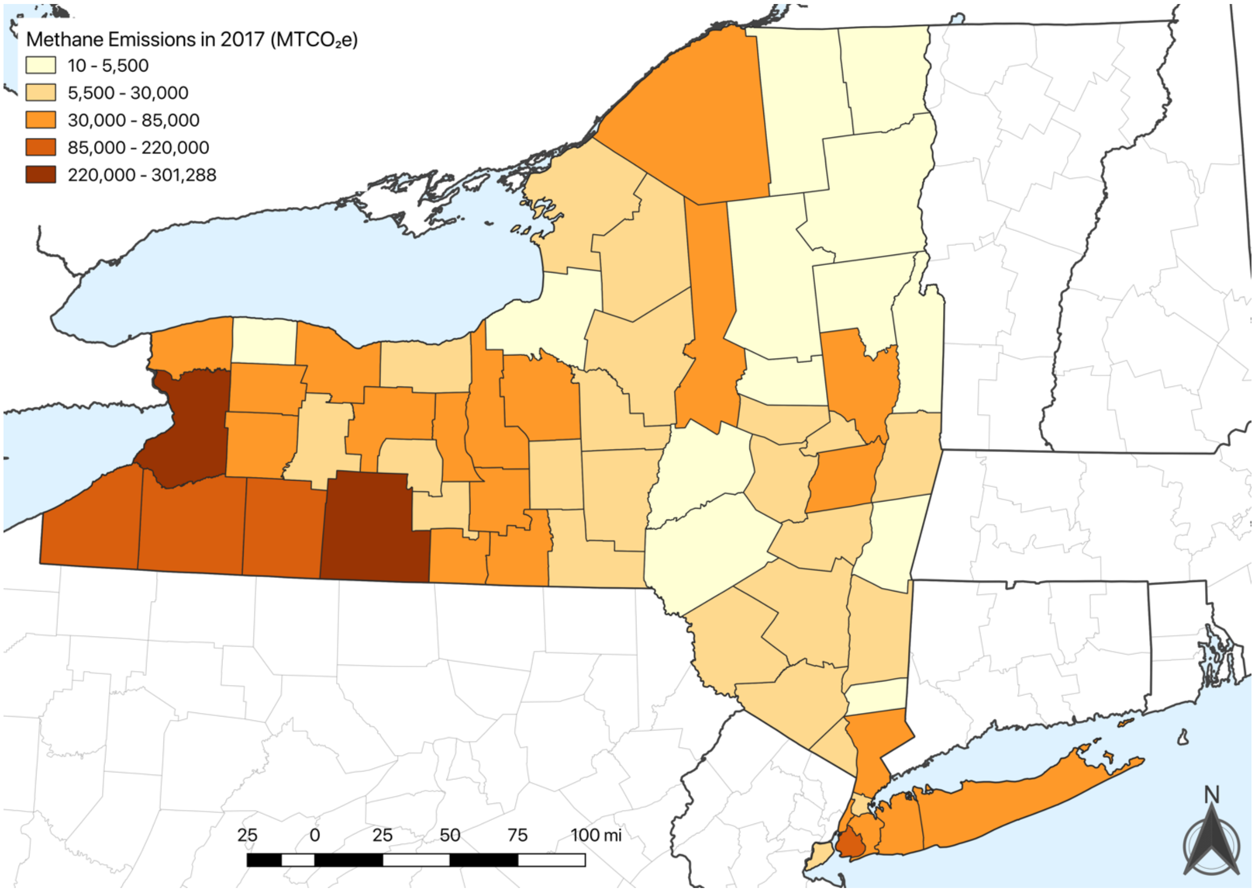
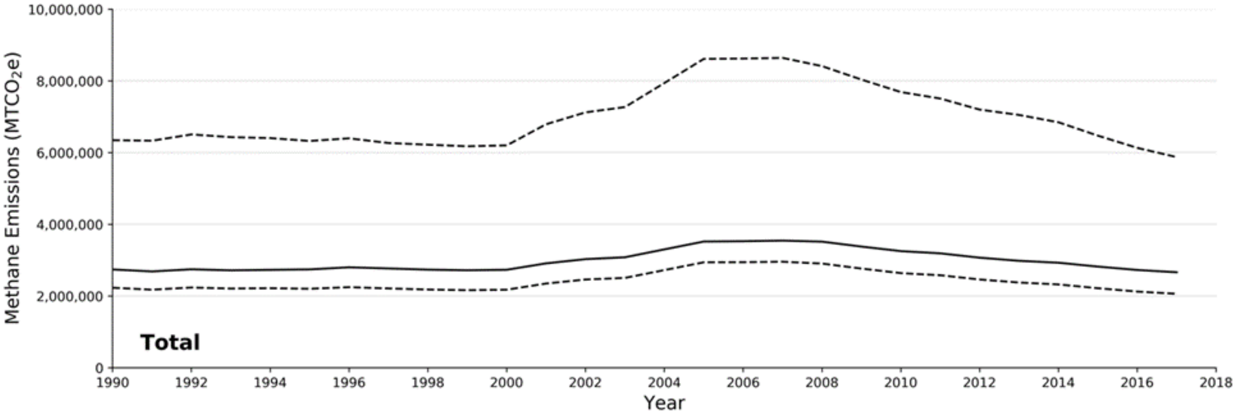


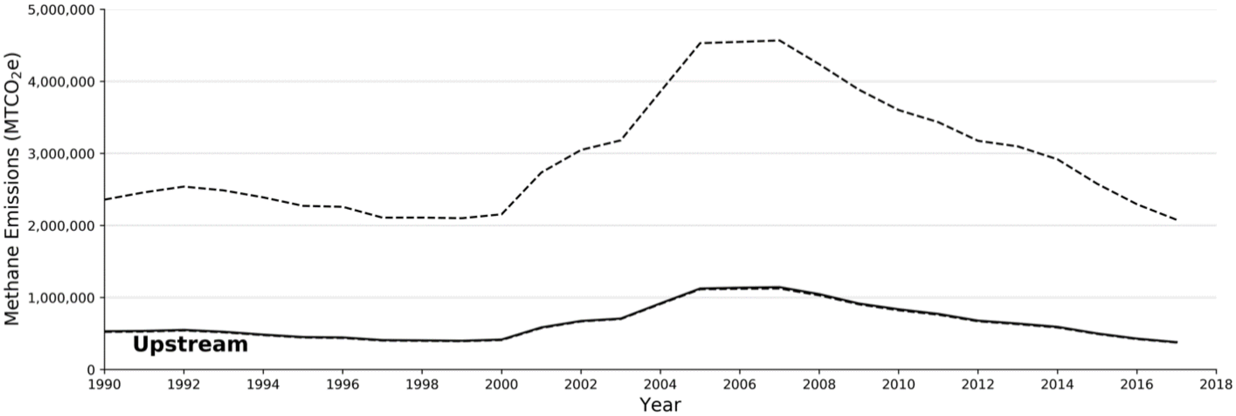
Figure S-3 shows that total CH_4 emissions in New York State from 1990–2017 followed a generally increasing trend from 1990 until peaking at 3.546 $MMTCO_2e$ in 2007. Since 2007 CH_4 emissions have decreased each year and are currently at levels last seen in 2000. Total CH_4 emissions decreased 11.5% since their peak in 2007. The lower- and upper-bound emission estimates (Figure ES-3, dashed lines) were determined by selecting the lower and upper bound of the EF uncertainty range. As such, the lower- and upper-bound emission estimates may be thought of as representing the lower and upper limit of emissions for the oil and natural gas sector. These upper-bound estimates also reflect literature estimates of EFs for many source categories with identified high-emitting sources. As such, the uncertainty bounds likely capture the possible range of uncertainty that arises from accounting for high-emitting sources in the State. This is especially notable in the upstream and downstream source categories, where upper-bound emission estimates are four times and twice the best estimate values, respectively—reflecting the wide range of uncertainty that arises from incorporating EFs that are derived with high-emitting sources in the sample population.

Figure S-3. Total Emissions Including Best Estimate and Upper and Lower Bounds (AR4 GWP_{100})



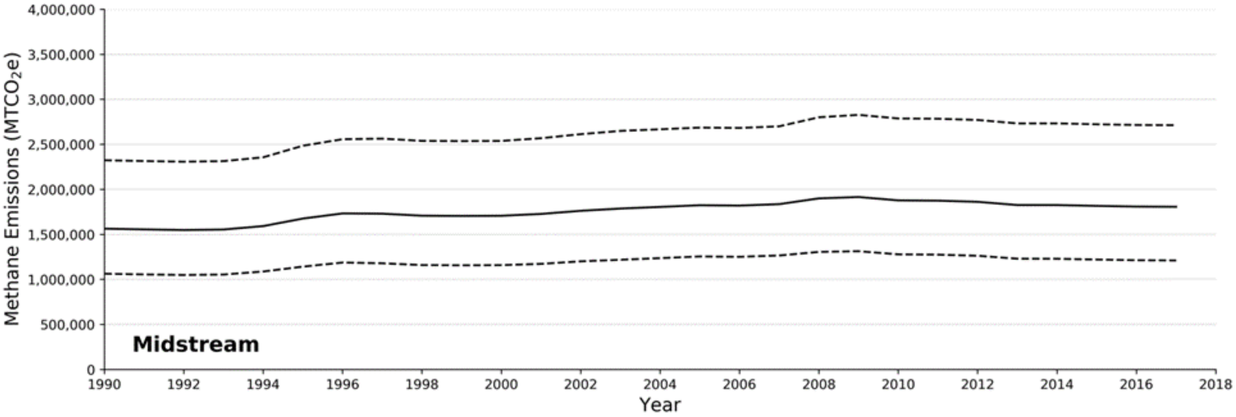
Upstream CH_4 emissions (Figure S-4), though smaller in magnitude than midstream and downstream emissions, have shown greater variation over time, more closely mirroring the cyclical nature of oil and gas exploration and well completions in the State. Upstream CH_4 emissions peaked at 1.143 $MMTCO_2e$ in 2007, corresponding with the observed peak in natural gas prices and production and well completions. Since 2007, well completions have fallen to near zero and natural gas production is around one-fifth of the peak production, resulting in an overall decline in emissions associated with upstream source categories. Overall upstream emissions decreased 28.5% from 1990–2017, and by 66.8% from 2007–2017.

Figure S-4. Upstream Emissions Including Upper and Lower Bounds (AR4 GWP_{100})



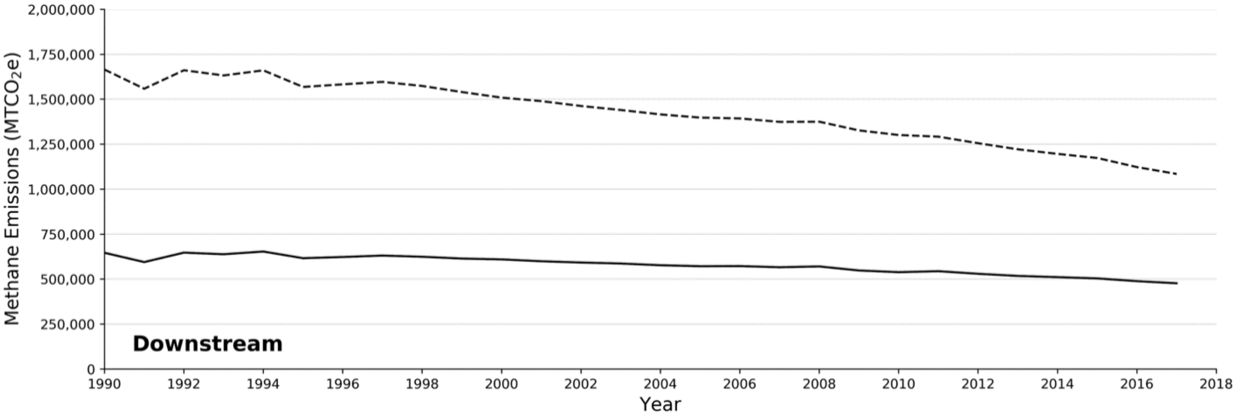
Midstream CH_4 emissions (Figure S-5) increased from 1990–2017 by 15.5%. However, since 2009 midstream emissions have declined by 5.7% as a result of declining natural gas production and subsequent midstream throughput in New York State. Midstream emissions are largely a function of transmission and storage compressor stations and transmission pipelines. New York State Department of Environmental Conservation (DEC) data, used to verify compressor station counts in this inventory, show increasing compressor counts and throughput, resulting in increasing midstream CH_4 emissions. Midstream emissions increased 15.5% from 1990–2017. Although natural gas production in New York State has declined since 2006, this trend closely follows increased natural gas consumption, which has risen by 16.2%, from 1,080 Bcf in 2005 to 1,255 Bcf in 2017. Correspondingly, emissions from transmission compressor stations have risen in order to accommodate increased natural gas throughput in the State.

Figure S-5. Midstream Emissions Including Upper and Lower Bounds (AR4 GWP_{100})



Downstream CH_4 emissions (Figure S-6) decreased by 26.2% from 1990–2017. The two largest source categories in downstream emissions, cast-iron and unprotected steel distribution main pipelines, have both decreased since 1990, since they have largely been replaced with plastic distribution mains. Plastic mains have much lower leak rates and therefore a lower EF, resulting in the downward trend observed in Figure ES-6. Additionally, increasing consumption in New York State has driven increases in the number of residential services and meters, though this growth is outweighed by the transition from cast-iron and unprotected steel distribution lines to plastic.

FigureS-6. Downstream Emissions Including Upper and Lower Bounds (AR4 GWP_{100})



The CH_4 emissions estimates presented throughout this report use AR4 GWP_{100} estimates, though recent literature has indicated that it is important to consider the short-lived effects of CH_4, described by the GWP_{20}. Under AR4, the GWP_{100} for CH_4 is 25, and the GWP_{20} is 72. AR4 estimates from 2007 were updated in 2014 in IPCC's AR5, which increased the GWP_{100} to 28, and GWP_{20} to 86.

The activity patterns identified in this inventory correspond to national trends in CH_4 emissions. To validate this emissions inventory, comparisons were made with EPA's nationwide inventory and with adjacent state inventories. Comparison to the national inventory shows New York State CH_4 emissions to be equivalent to 1.62% of the total national oil and natural gas inventory. Comparison with inventories from adjacent states shows New York State oil and gas emissions to be approximately one-quarter of emissions from the same source categories in Pennsylvania, which has much higher upstream production and similar downstream consumption.

Based on the four areas of best practices and recommendations developed under this project, the inventory presents a marked improvement compared to prior iterations of the oil and natural gas sector emissions in the New York State GHG Inventory. Table S-1 summarizes the best practice recommendations, implementation of these recommendations when developing the current inventory, and areas for future inventory improvements.

Table S-1. Summary of Best Practice Recommendations, Implementation of Best Practices, and Areas for Future Inventory Improvements

✓	**Recommendation #1** New York State should develop a more detailed set of activity data, including site- and component-level data, for its CH_4 inventory in order to create an inventory with the detail needed to capture the impacts of CH_4 mitigation strategies targeted at the site- or component-level. **Implementation in Current Inventory:** Applied the best available activity data, using publicly available inputs as well as data provided by New York State agencies. **Areas for Future Improvement:** • Collect/compile data on the number and location of transmission and storage compressor stations in New York State, including stations that only have electric compressors. • Collect/compile data on the county-level miles of distribution pipeline by pipeline material. • Collect/compile data on the county-level number of residential and commercial/industrial gas meters.
✓	**Recommendation #2** New York State should estimate and apply EFs for upstream and downstream oil and gas activities in the State using best available data, validated by both bottom-up and top-down studies, and specific to geographic location. **Implementation in Current Inventory:** Applied the best available EFs from the published literature. **Areas for Future Improvement:** • Develop New York State-specific EFs for well pads during production. • Develop New York State-specific EFs for transmission and storage compressor stations. • Develop an EF for fugitive emissions from storage reservoirs.
✓	**Recommendation #3** New York State should align available geospatial data with inventory data as much as possible to create a geospatial emissions inventory that allows greater consideration of identifying hot spots and air quality concerns, and verification of emission inventories with empirical data. **Implementation in Current Inventory:** Results are presented geospatially, allocated to the county level, with the ability to produce sub-county results for many segments. **Areas for Future Improvement:** • Collect air quality data on ambient CH_4 concentrations throughout New York State and use the observed concentrations to verify emission estimates.

Table S-1 continued

✓	**Recommendation #4** New York State should conduct uncertainty analysis when calculating and reporting its CH_4 inventory. At a minimum, that uncertainty analysis should account for uncertainties in published EFs, but it could also include an assessment of high-emitting sources across the State. New York State should develop and apply models that help account for the existence of high-emitting sources either in cases where emission releases are known (e.g., reported leakage) or in cases where emission releases are not known (e.g., estimated leakage based on pipeline age or material). **Implementation in Current Inventory:** Assessed uncertainty in the applied EFs to identify the most likely range of CH_4 emissions from the oil and natural gas sector. With better information on the statistical distribution of high-emitting sources, this inventory methodology may also be applied to explicitly include high-emitting sources. **Areas for Future Improvement:** • Develop a better understanding of the distribution of high-emitting sources and the frequency of operation in the high-emitting state.

The inventory developed under this project incorporates findings from the most current empirical research and utilizes the most accurate, current, and inventory-appropriate available data sources. The application of state-of-the-art practices and EFs represents a significant methodological advancement over other available tools. Other available inventory tools are often based on out-of-date EFs that do not reflect the modern oil and natural gas sector. By applying established best practices based on a thorough review of the literature and expert consultation, this inventory establishes a rigorous and robust CH_4 emissions baseline in New York State. These inventory results, and the accompanying inventory tool, provide important resources for supporting rulemaking and regulations in order to reduce CH_4 emissions from the oil and natural gas sector. This inventory lays the foundation for a geospatially refined inventory that can capture the impacts of future mitigation strategies for CH_4 emissions from the oil and natural gas sector as well as the impacts of current regulations, such as EPA's proposed changes to the 2016 New Source Performance Standards for the oil and gas industry. In addition, the inventory tool provides New York State with the flexibility to revise the current inventory, or generate future inventories, by updating activity data and EFs as current data become available and as future advancements in the industry lead to technological changes.

1 Introduction

1.1 Overview

The goal of this project is to support methane (CH_4) emission reduction efforts in New York State by improving the State's understanding of CH_4 emissions and CH_4 emission-accounting methodologies for the oil and natural gas sector, including upstream, midstream, and downstream sources from the wellhead to the customer meter. Additionally, it will be necessary to capture from this sector the impacts of mitigation strategies for fugitive CH_4 emissions through improved accounting methodologies to develop an activity-driven, site-level, CH_4 emissions inventory. Consequently, the inventory developed under this project incorporates findings from the most current empirical research and utilizes the most accurate, current, and inventory-appropriate available data sources.

Specific objectives of this project include (1) assessing the State's current oil and natural gas sector CH_4 emissions inventory, (2) performing a literature review of CH_4 emission-accounting methodologies and associated analyses and studies, (3) developing an improved CH_4 emission-accounting methodology, and (4) implementing the methodology to create an improved CH_4 emissions inventory for the oil and natural gas sector in the State.

The assessment includes an analysis of key research and data gaps as well as cataloging emission source types applicable to New York State. To the extent possible, the assessment documents information on the potential relative contribution of emission source types to overall fugitive CH_4 emissions. The assessment is informed by the following questions:

- What types of sources are not taken into account?
- Are some missing sources insignificant and therefore reasonable to exclude?
- Which sources create the biggest environmental impacts?
- What data quality issues exist for each data source?
- Are there ways to improve the resolution of the analysis to demonstrate the effects that State policies (such as changes to flaring or well plugging) might have on actual CH_4 emissions?

The literature review links with the assessment and includes an evaluation of how existing annual emission accounting methodologies can incorporate the results of new scientific studies of fugitive CH_4 emissions. For example, one question informing the literature review is how standardized inventories best account for the non-normal distribution of emissions resulting from high-emitting sources (i.e., “super-emitters”). The CH_4 emission accounting methodology and associated emission inventory for oil and natural gas activities in New York State are derived using bottom-up (BU) best practices and best available data identified from the assessment and literature review.

1.2 Project Advisory Committee

To ensure project success, a Project Advisory Committee (PAC) was established to provide technical oversight and peer review throughout the duration of the project. The PAC consisted of six voluntary members with knowledge on air pollutant emissions from the oil and natural gas sector. Each member’s name, affiliation, and title are presented in Table 1.

Table 1. List of PAC Members

Committee Member	Affiliation	Title
Cynthia McCarran	New York State Department of Public Service	Deputy Director, Office of Electric, Gas, and Water
Catherine Dickert	New York State Department of Environmental Conservation	Director of Mineral Resources
Kevin Speicher	New York State Department of Public Service	Chief, Natural Gas and Hazardous Liquid Pipeline Safety
Ona Papageorgiou	New York State Department of Environmental Conservation	Environmental Engineer
David Lyon	Environmental Defense Fund	Scientist
Jennifer Snyder	U.S. Environmental Protection Agency	Environmental Engineer

The PAC served as advisors to the research team, its members actively contributing their expertise and knowledge in the oil and natural gas sector. The research team relied on the PAC’s input to help ensure that the project remained scientifically rigorous and accurate and that deliverables fulfilled the project objectives. During the course of this project, three meetings were held with the PAC to solicit feedback on the draft inventory and this report. In addition, the research team routinely reached out to PAC members for guidance on CH_4 emission inventory development. New York State Energy Research and Development Authority (NYSERDA) would like to thank the PAC members for their valuable contributions throughout this project.

The project also received support and guidance from Dr. Anthony Marchese, Professor of Mechanical Engineering at Colorado State University and an expert in CH_4 emissions derived from the oil and natural gas sector.

The remainder of the report is organized by sections and presents an assessment of the current CH_4 emission inventory and key findings (section 2), an overview of the literature review and key findings (section 3), the methodology used to develop the improved CH_4 emission inventory (section 4), an analysis and summary of the improved CH_4 emission inventory (section 5), information on performing future projections of CH_4 emissions (section 6), conclusions (section 7), details of EPA Subpart W methodology (appendix A), and supporting tables from the literature review (appendix B).

2 Methane Emissions Inventory Assessment

2.1 Summary

The 2015 New York State Greenhouse Gas (GHG) Inventory (NYSERDA and DEC 2018) provides estimates of CH_4 emissions across various sectors and activities in the State, including emissions from the oil and natural gas sector. This section of the report provides an assessment of the CH_4 estimate from New York State's 2015 GHG Inventory on oil and gas systems, drawing on recent literature to identify areas in which the inventory can be improved to more accurately account for CH_4 emissions using the latest science and activity data. The opportunities for the greatest improvement center around four key areas as follows:

- Applying a more detailed BU activity-based analysis, with validation from top-down (TD) studies.
- Using emission factors (EFs) for activities within the oil and natural gas sector, informed by the peer-reviewed literature and studies most applicable to the equipment in place in wells and geographic regions of New York State.
- Including uncertainty analysis to provide a range of possible emissions, with special consideration of high-emitting sources, sometimes referred to as super-emitters.
- Presenting the inventory using at least two different global warming potential (GWP) calculations (GWP100 and GWP_{20}, i.e., global warming potential for 100 years and 20 years, respectively).

These improvements are discussed in the following table and discussion in more detail.

2.1.1 Relevant Inventory Products

Repeated reference is made throughout this report to a few select inventory products. As a convenience to the reader, Table 2 provides an overview of and reference to these products.

Table 2. Glossary of Relevant Inventory Products

EPA Greenhouse Gas Reporting Program (GHGRP): This program collects GHG data from self-reporting facilities with emissions of 25,000 tons of carbon dioxide equivalent (CO_2e) each year. Subpart W of the GHGRP specifically covers CH_4 emissions from 10 segments in the petroleum and natural gas industry (EPA 2017).
New York State Greenhouse Gas Inventory, 1990–2015: The 2018 iteration of the New York State Greenhouse Gas Inventory contains estimated emissions up to 2015 (NYSERDA and DEC 2018).
U.S. Greenhouse Gas Emissions and Sinks, 1990–2016: This document provides an overview of U.S. GHG emissions, including CH_4 emissions from oil and natural gas systems (EPA 2018a).
United States Environmental Protection Agency (EPA) Nonpoint Oil and Gas Emission Estimation Tool: The EPA Nonpoint Oil and Gas Emission Estimation Tool (Oil and Gas Tool) contains information used to develop a nonpoint (i.e., originating from many diffuse sources) source emissions inventory for upstream oil and natural gas activities across the 54 source categories (EPA 2014).
EPA State Inventory and Projection Tool (SIT): The Natural Gas and Oil Module of the EPA tool, SIT, contains data updated to include 2016, which allows states to independently develop state-level emission inventories, and covers CH_4 and carbon dioxide (CO_2) emissions from natural gas and petroleum systems.

Section 2.2 of this report provides a characterization of New York State's oil and natural gas sector. Section 2.3 provides information on the State's current CH_4 inventory approach and the weaknesses inherent in that approach. Section 2.4 provides information on alternative approaches and tools used by the federal government or other states to enhance CH_4 inventory development. Section 2.5 brings together the two previous sections to propose a new model for New York State that includes more precise activity data, EFs, geospatial issues, and uncertainty analysis (including the issue of high-emitting sources). Section 2.6 discusses the impact of GWP factors and recommends the use of at least two GWP values in future inventory development. Section 2.7 provides a summary of best practices for developing an improved CH_4 emissions inventory for the oil and natural gas sector in the State.

2.2 Characterization of New York State's Oil and Natural Gas Sector

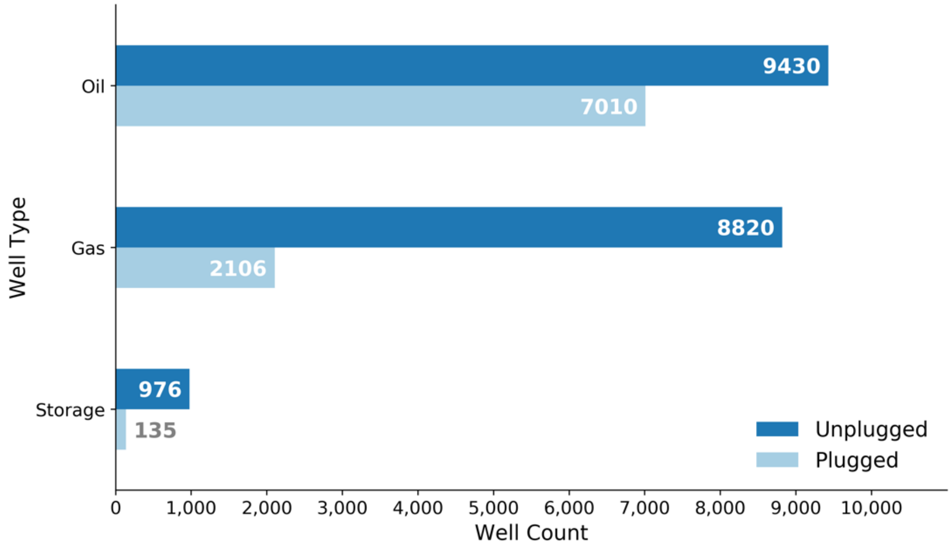
This section begins with a characterization of oil and gas wells, then moves into a discussion of oil and gas production and concludes with an overview of associated oil and gas infrastructure.

2.2.1 Oil and Gas Wells in New York State

As of February 2019, New York State had 8,820 unplugged natural gas wells and 9,430 unplugged oil wells (DEC 2018a). In addition, the State had 7,010 plugged oil wells, 2,106 plugged gas wells (Figure 1), 976 unplugged storage wells, and 135 plugged storage wells. (Plugged wells are wells that are no longer in use and the borehole has been plugged with cement or another impermeable substance to isolate the underlying hydrocarbon formation from contaminating the environment.)

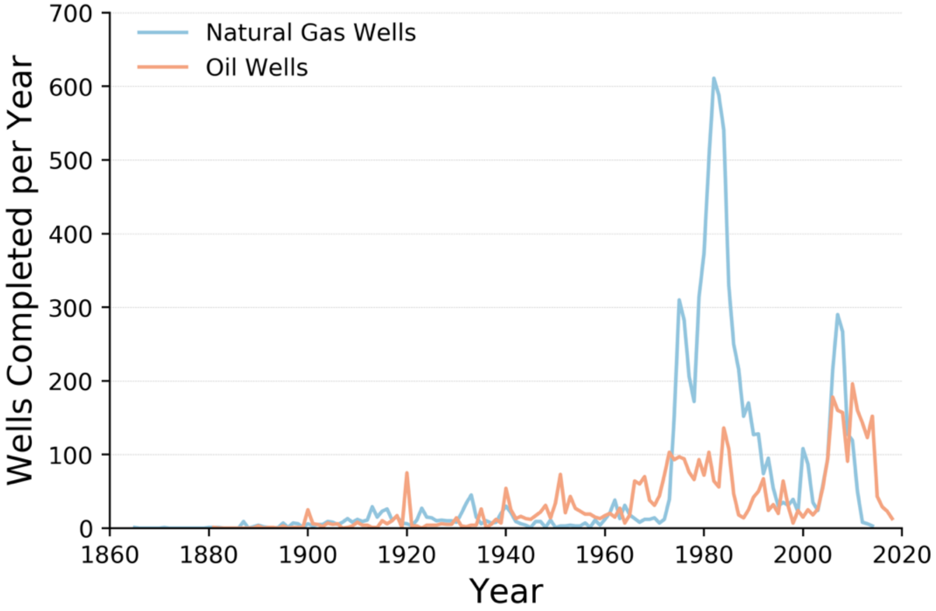
Figure 1. Number of Open Hole and Plugged Wells in New York State as of February 2019

Source: New York State Department of Environmental Conservation (DEC) downloadable well data



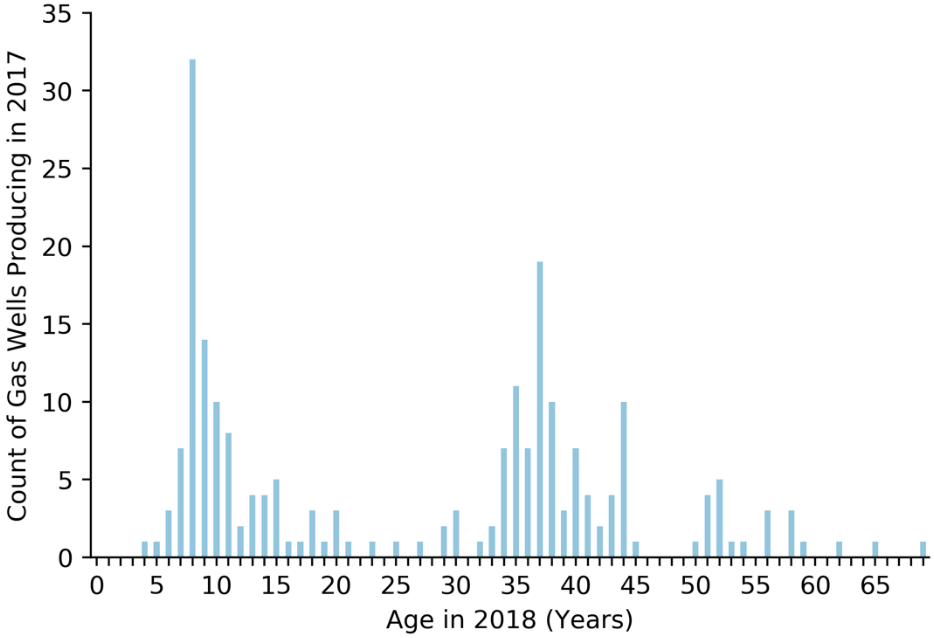
Gas well development in New York State increased significantly in the 1970s, reaching a peak in 1982 when 611 wells were drilled and put into production, followed by a decline in activity until the mid-2000s. This was followed by a secondary spike in installations from 2006–2008 (Figure 2). After 2008, natural gas well completions fell to fewer than 10 per year. High-volume hydraulic fracturing (HVHF), or fracking, was banned in the State in 2014. Oil well completions also followed a cyclical pattern, with increased activity from 1973–1985 and again from 2006–2014. Much of this activity follows oil and natural gas price patterns, with higher activity during periods of high-fuel prices, and lower activity during periods of low-fuel prices. The deregulation of oil and natural gas markets also played a role in increasing production and consumption of natural gas while reducing prices.

Figure 2. Number of Oil and Natural Gas Wells Completed per Year in New York State



The age distribution of natural gas wells producing in New York State in 2017 (Figure 3) followed a similar bimodal pattern to that seen in Figure 2. Well count data for 2018 show a primary peak of wells aged around 9 and 10 years old, and a secondary peak of wells aged between 34 and 45 years old. Comparing Figure 2 and Figure 3, age and completions follow a similar bimodal pattern, with peaks in age corresponding to peaks in completions, indicating that older wells can remain in production for a long time. Well age data showed that, although there were far more completions in the 1970s and 1980s, 42% of currently operational wells were completed in the last 15 years, with 90% of wells under 45 years old.

Figure 3. Age Distribution of Gas Wells Producing in 2017



2.2.2 New York State Oil and Natural Gas Production

Natural gas production far outweighs oil production in New York State as shown in Figure 4. Natural gas production peaked at 55.34 billion cubic feet (Bcf) or 9.78 million barrels of oil equivalent (BOE) in 2006 (1 BOE = 5.65853 thousand cubic feet, Mcf), while oil production peaked at 386,192 barrels (bbl) in 2008. Natural gas production declined from 55.34 Bcf in 2006 to 11.39 Bcf, or 2.01 million BOE in 2017. Oil production has also declined in the State since the mid-2000s from a peak of 386,192 bbl in 2008 to 183,609 bbl in 2017. There are no in-state oil refineries, and all of the oil produced is refined out of State, primarily in Pennsylvania (DEC 2006).

As shown in Figure 5, 299 out of 7,032 wells (4.26%) accounted for 50% of natural gas production in New York State in 2017, 21.3% of the wells accounted for 75% of natural gas production, and almost all (99%) of natural gas production came from 4,760 (67.7%) of wells. These data demonstrate that a comparatively small number of wells produce the majority of natural gas, and that production is not evenly distributed across those wells. Oil wells also showed a similarly skewed distribution, with 401 out of 4,738 (8.5%) wells accounting for 50% of production, 944 (19.9%) wells accounting for 75% of production, and 2,537 (53.5%) wells accounting for 99% of production in 2017.

Figure 4. Oil and Natural Gas Production in New York State

Note: The axis scale for natural gas production (left) is 10x larger than the axis scale for oil production (right).

1 BOE = 5.65853 Mcf natural gas[1]

Source: (DEC 2018b)

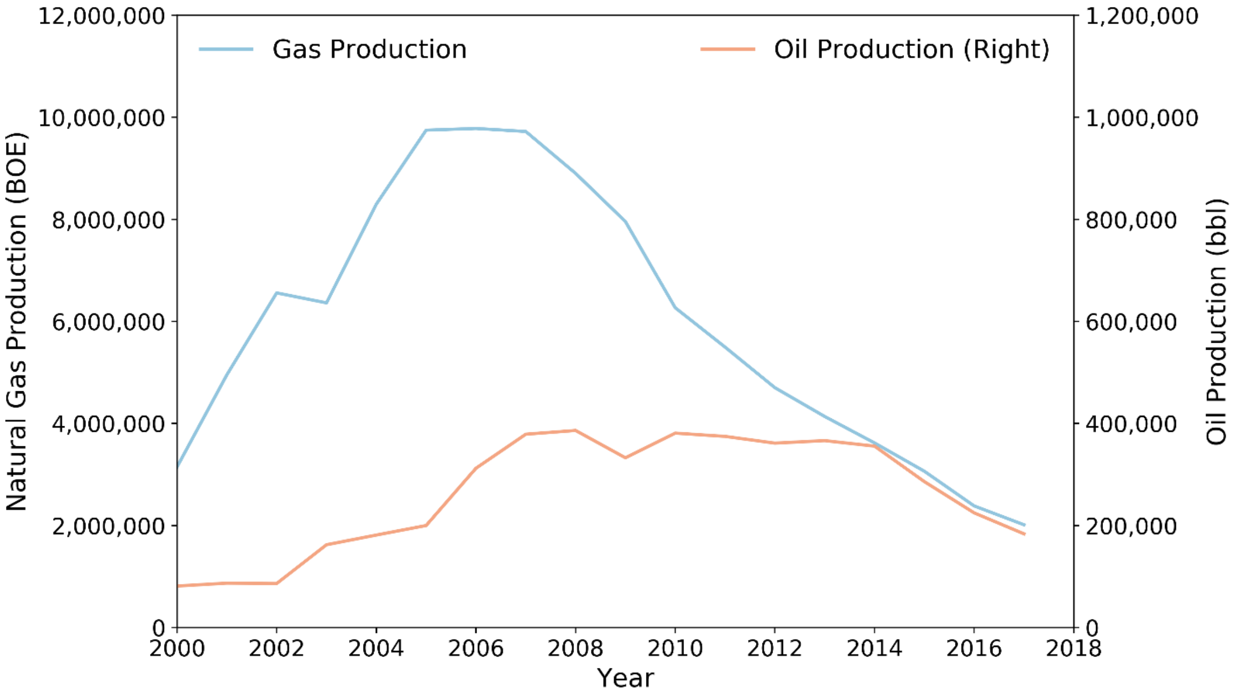
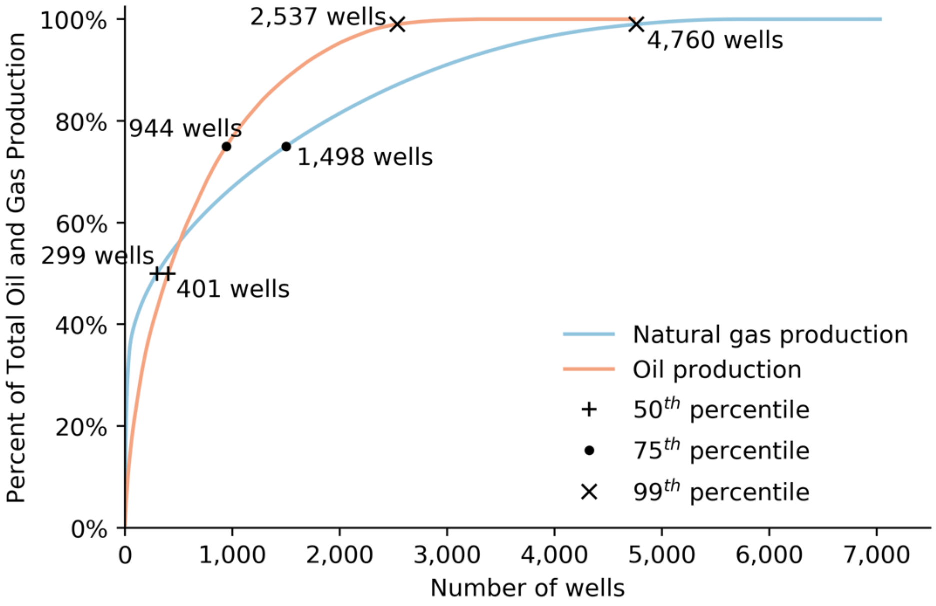


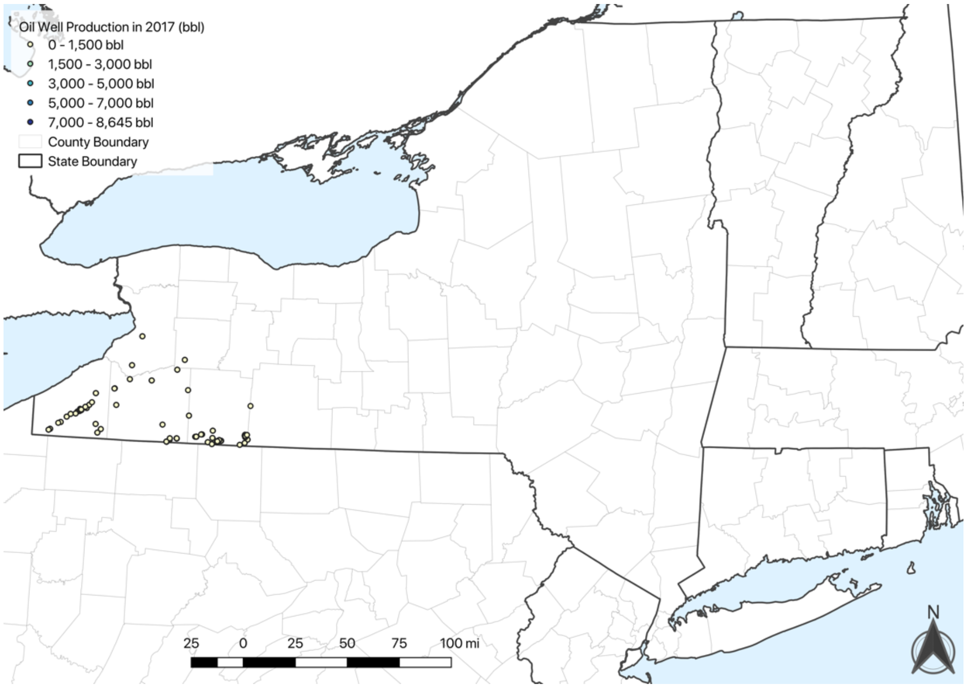
Figure 5. Relationship between Percent of Total Cumulative Oil and Natural Gas Production in 2017 and the Number of Wells in New York State



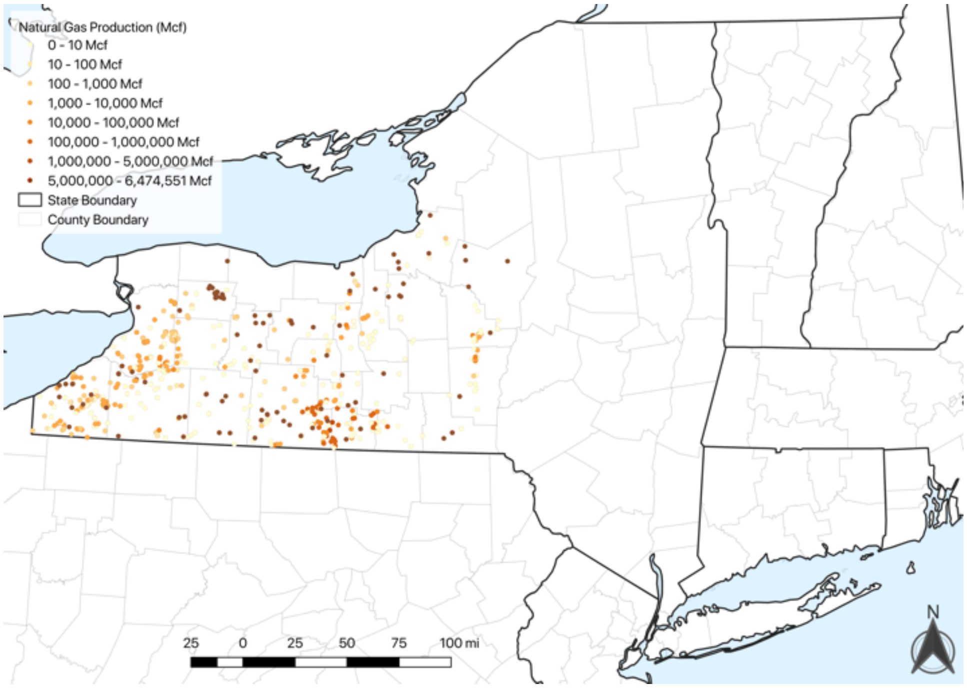
As shown in Figure 6, oil and natural gas production occur largely in Western New York, west of the line delineating the eastern boundary of Broome, Chenango, Madison, Oneida, and Lewis counties. Oil production is concentrated in the far west of New York State, in Allegany, Cattaraugus, Chautauqua, Wyoming, and Erie counties.

Figure 6. Oil and Natural Gas Well Locations and Production in New York State in 2017

(Oil)



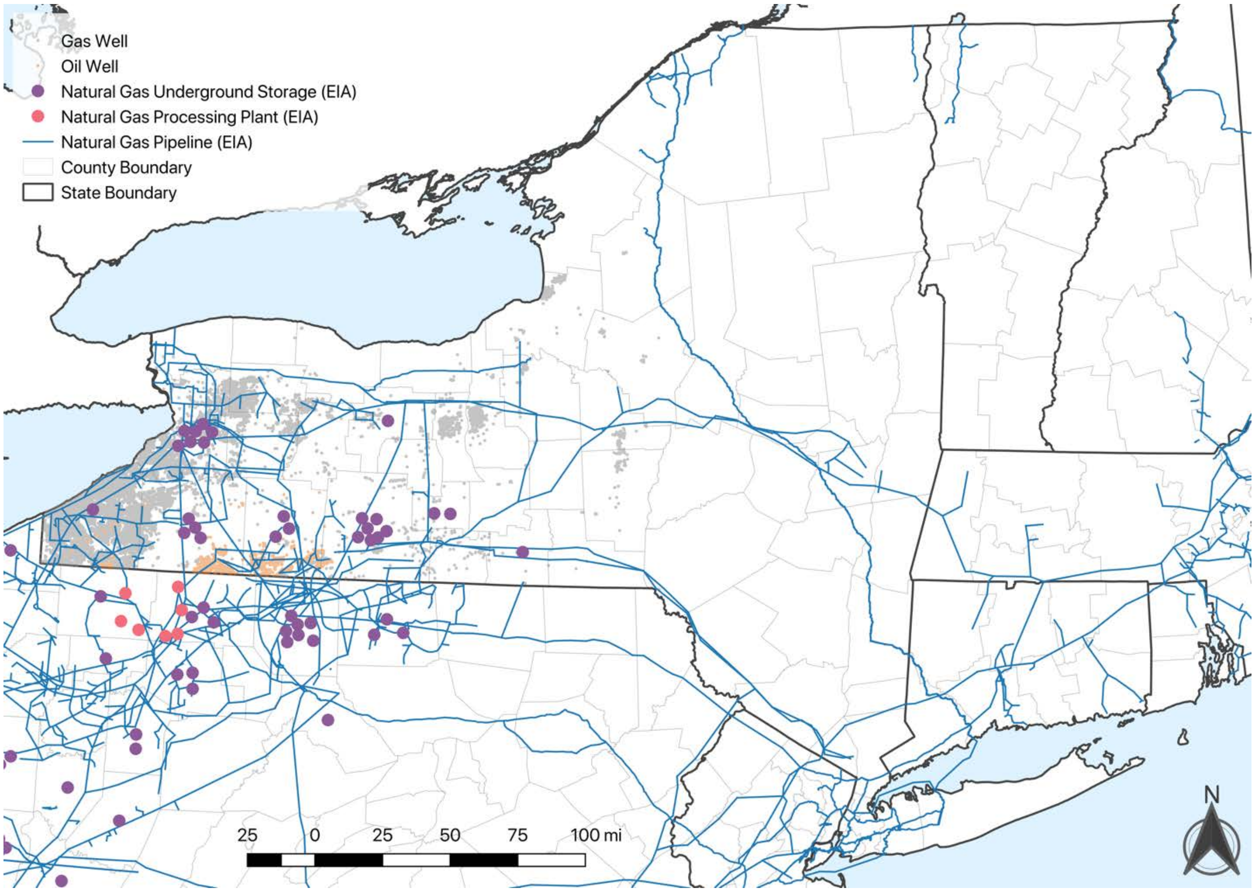
(Natural Gas)



2.2.3 New York State Oil and Natural Gas Infrastructure

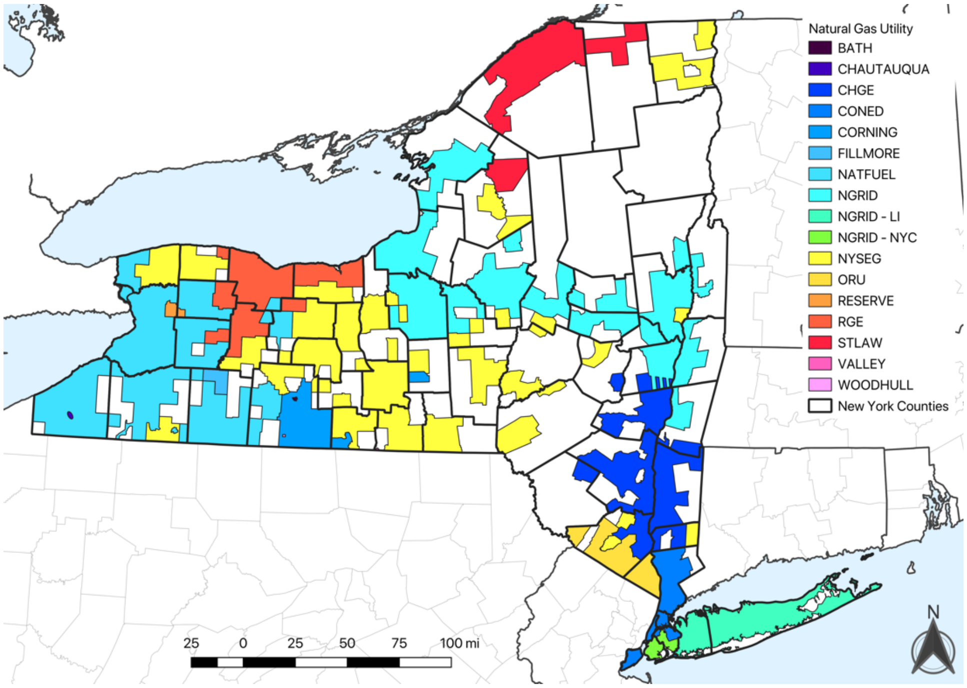
As shown in Figure 7, oil and natural gas activities are concentrated in the western portion of the State. This region has the greatest density of wells and underground natural gas storage facilities. Storage fields are located in former solution salt caverns and depleted reservoirs. The Energy Information Administration (EIA) data lists no natural gas processing plants in New York State, with the closest processing plants located in northwestern Pennsylvania. The greatest density of interstate and intrastate natural gas transmission pipelines, as identified by EIA, is located in Western New York in close proximity to the production and storage wells for removal and delivery. Transmission pipelines are well-connected to Pennsylvania and have linkages to Canada in the west and north. Two main pipeline trunks extend east-west across New York State, with one along the southern Pennsylvania border, connecting to pipelines in the New York City Metropolitan Area and the other connecting farther north to pipelines in the Albany and Buffalo regions.

Figure 7. Locations of Oil and Natural Gas Wells, Natural Gas Processing Plants, Natural Gas Pipelines, Natural Gas Underground Storage, and Shale Plays in New York State and Surrounding States



New York State has 17 natural gas utility service territories (Figure 8). These service territories cover around 94% of the households identified by the U.S. Census Bureau. According to the Census, 54% of households inside natural gas utility service areas use natural gas as their primary home heating source. In addition, EIA data[2] show 407,659 commercial and industrial end users of natural gas in New York State. Based on census data, which show 535,037 registered businesses in the State in 2016 with 96.9% of businesses within natural gas utility service areas, 78.6% of businesses inside natural gas utility service areas use natural gas.

Figure 8. New York State Gas Utility Service Territories



2.3 New York State's Current Methane Inventory: Approach and Weaknesses

The State's approach to quantifying CH_4 emissions from the oil and natural gas sector represents a simplified throughput-based, aggregated approach (Allen 2014, 2016) that relies on national CH_4 inventory estimates combined with State and national-level natural gas consumption data (NYSERDA and DEC 2018). As reflected in the inventory calculation spreadsheet (provided by NYSERDA), New York State takes the ratio of State-to-national natural gas use and multiplies that by total U.S. CH_4 emissions from the natural gas sector [as reported by the EPA in its national GHG Inventory report (EPA 2018b)] to quantify State emissions. The formula used is described in Equation 1.

Equation 1 $$E_{NY} = E_{US} \cdot \frac{NG_{NY}}{NG_{US}}$$

where:

- E_{NY} represents the CH_4 emissions from the State's natural gas systems in million metric tons of CO_2 equivalents ($MMTCO_2e$).
- E_{US} represents the CH_4 emissions from the national natural gas system as estimated by the EPA in its national GHG Inventory in $MMTCO_2e$.
- NG_{NY} represents the amount of gas consumption in New York State in Bcf.
- NG_{US} represents the amount of gas consumption in the nation in Bcf, as reported by the U.S. Department of Energy's EIA.

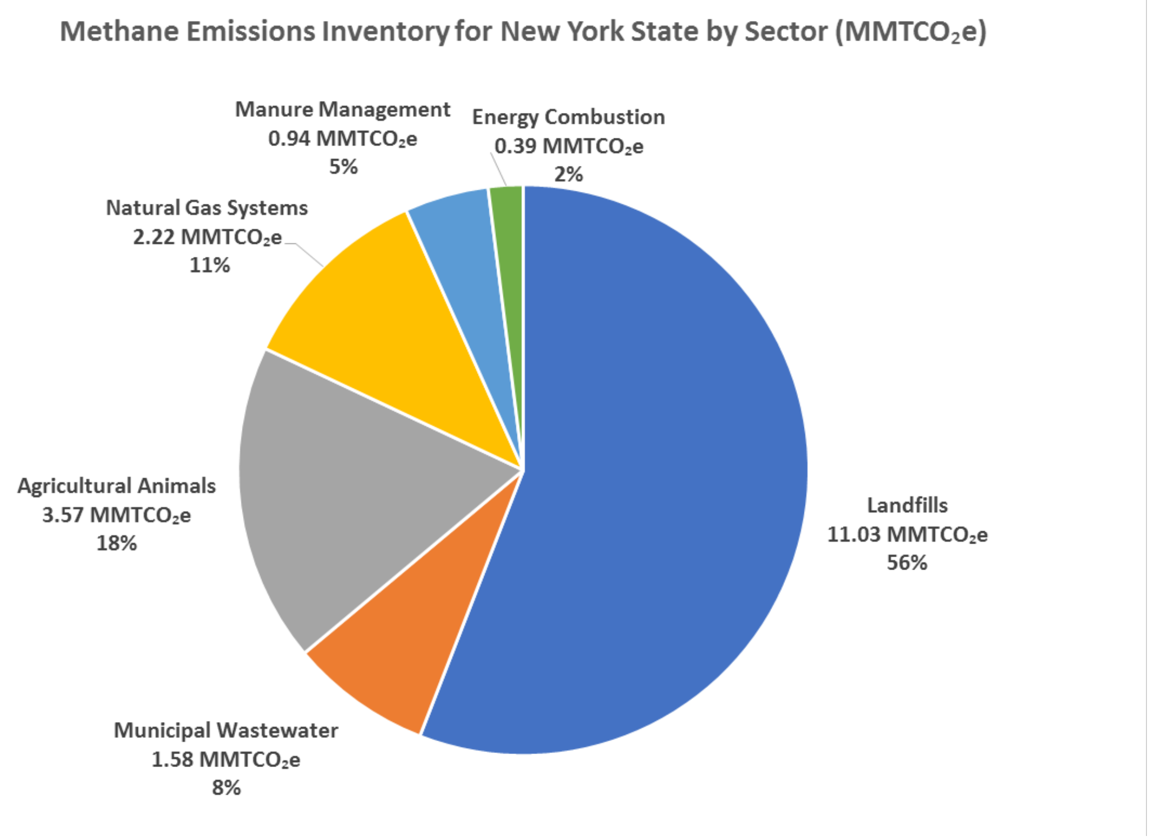
The State inventory applies this methodology to natural gas consumption. EIA statistics[3] and data from the State Energy Data System (SEDS)[4] show that total nationwide natural gas consumption in 2015 was 27,244 Bcf. SEDS reports New York State natural gas consumption in 2015 was 1,353 Bcf. Therefore, the NG_{NY}/NG_{US} consumption ratio used to scale national emissions was 4.97% (i.e., 1,353 Bcf/27,244 Bcf). EPA (2018a) estimates that 2015 emissions from the entire natural gas supply chain to be 46.1 $MMTCO_2e$. Using the NG_{NY}/NG_{US} consumption ratio yields an estimate of 2.29 $MMTCO_2e$ for the State in 2015. (Note that this estimate differs from the published estimate of 2.22 $MMTCO_2e$ due to EPA revisions to transmission, storage, and distribution emissions.) These emission estimates for natural gas systems account for 11% of the CH_4 emissions in the 2018 New York State GHG Inventory as shown in Figure 9.

Discrepancies between data reported by EPA's national inventory, using data from the GHGRP and other sources, and the New York State inventory are explained by differences in the methodologies underlying the two inventories. The EPA inventory applies BU, activity-based methods, to estimate nationwide emissions; while the State inventory uses a scaling factor, based on consumption comparisons, to adjust the national inventory to the State. As such, any underlying differences in ratios of upstream, midstream, and downstream emissions are unaccounted for, as the methodology assumes New York State is essentially a scaled-down version of the whole country.

Figure 9. New York State CH_4 Emissions for 2015 by Sector

Using the GWP_{100} factor from the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) from the New York State 2018 Greenhouse Gas Inventory.

Source: (NYSERDA and DEC 2018)



In comparison, CH_4 emissions from EPA's GHGRP (reported in Envirofacts) estimate total New York State petroleum and natural gas system emissions accounted for 1.334 $MMTCO_2e$. The EPA GHGRP reporting requirements include GHG emissions from sources emitting 25,000 $MTCO_2e$ each year in 41 categories.[5] GHGRP Subpart W outlines petroleum and natural gas system reporting requirements and methodology but does not include a number of sectors in the petroleum and natural gas system, including transmission and distribution pipelines, and customer meters. As such, the GHGRP covers many of the largest sources of emissions but does not address emissions from smaller emission sources and does not cover all segments in the petroleum and natural gas system.

The approach used by New York State has its benefits. The calculations are straightforward, and the approach is transparent. However, there are at least three drawbacks to the current approach:

- New York State's simplified approach does not account for potentially unique aspects of the State's oil and natural gas sector; instead it scales national emissions by consumption, an approach that may overestimate or underestimate the actual emissions. For example, unlike other states, New York State does not currently allow HVHF. This will distort EFs as HVHF has been shown to have higher per-well CH_4 emissions than other methods. As another example, data from EPA's GHGRP Subpart W indicate that 93.6% of CH4 emissions in New York State originate from local natural gas distribution companies, with 4.0% from transmission and compression and 2.3% from underground natural gas storage. These differ from EPA's reported national averages that show 16% of emissions originating from distribution, 27% from transmission and storage, 11% from processing, and 46% from production.
- Because the approach is highly aggregated and is not resolved by either component-level or geography, the State loses the opportunity to more precisely target its CH_4 reduction policies and programs.
- The approach does not account for the uncertainty inherent in EFs and activity data.

Without addressing these and other concerns, New York State will be challenged to accurately assess CH_4 emissions, emission changes in the State, and the impacts of reduction measures under such programs as the Methane Reduction Plan (DEC 2017). For these reasons, New York State should consider moving to a BU, activity-driven, component-level CH_4 emissions inventory using State-specific data.

2.4 Best Practices for State Methane Inventory Development

This section identifies a number of widely applied inventory tools developed by the EPA that can provide guidance on best practices for estimating emissions. These tools include EPA's SIT, GHGRP, and Oil and Gas Tool.

2.4.1 EPA's State Inventory Tool

There is no single best approach for conducting statewide CH_4 inventories for the oil and natural gas sector; however, some guidance does exist (Blackhurst et al. 2011). That guidance includes the use of consistent reporting categories, disaggregating segments, incorporating uncertainty and variability, and establishing benchmarks against which future inventories and emission reduction plans may be judged.

The EPA has provided some state-level tools that capture important elements of this sector through its SIT,[6] which includes a Natural Gas and Oil Module. The SIT is used by a number of states to generate state-level GHG inventories, including all states that border New York State (Connecticut, New Jersey, Massachusetts, Pennsylvania, Rhode Island, and Vermont).

The Natural Gas and Oil Module of the SIT collects information on EFs for natural gas production and distribution sources as shown in Table 3. The EPA SIT focuses on five primary areas related to the natural gas supply chain: (1) production, (2) transmission and storage, (3) distribution pipeline, (4) distribution services, and (5) venting and flaring. See Figure 13 for an image of the natural gas supply chain.

With respect to uncertainty analysis, the SIT specifies the following:

> The main sources of uncertainty…relate to the emission factors… Statistical uncertainties arise from natural variation in measurements, equipment types, operational variability and survey and statistical methodologies. The main emission factor…is determined by bundling together the factors of several individual components and sources. In the process of aggregation, the uncertainties of each individual component get pooled to generate a larger uncertainty for the simplified emission factor.[7]

The SIT goes on to suggest that the approach taken to estimate EFs is “relatively accurate” at the national level but may be different at the state level. Thus, as discussed in section 2.5 in this report, one of our primary recommendations from this assessment is for New York State to invest in collecting better EF data at the State level.

Table 3. Source Categories and Default EFs from the EPA SIT for Oil and Natural Gas Systems in New York State

Source: https://www.phmsa.dot.gov/data-and-statistics/pipeline/pipeline-mileage-and-facilities and EPA SIT Oil and Natural Gas Systems Module

Source Category	Source Type	Default EF	EF Units (2015)
Petroleum Systems	Oil production	453.5	kg CH_4 1,000 bbl^{-1} yr^{-1}
	Oil refining	4.33	kg CH_4 1,000 bbl^{-1} yr^{-1}
	Oil transportation	3.88	kg CH_4 1,000 bbl^{-1} yr^{-1}
Natural Gas Production	Onshore wells	4.10	$MTCH_4$ $well^{-1}$ yr^{-1}
Gathering and Processing	Gathering pipeline	0.4	$MTCH_4$ $mile^{-1}$ yr^{-1}
Natural Gas Processing	Gas processing plant	1,249.95	$MTCH_4$ $plant^{-1}$ yr^{-1}
LNG Storage	Liquefied natural gas (LNG) storage compressor stations	1,184.99	$MTCH_4$ $plant^{-1}$ yr^{-1}
Natural Gas Transmission	Transmission pipeline	0.62	$MTCH_4$ $mile^{-1}$ yr^{-1}
	Gas transmission compressor stations	983.66	$MTCH_4$ $station^{-1}$ yr^{-1}
Natural Gas Storage	Gas storage compressor stations	964.15	$MTCH_4$ $station^{-1}$ yr^{-1}
Natural Gas Distribution Pipeline	Cast-iron distribution pipeline	5.80	$MTCH_4$ $mile^{-1}$ yr^{-1}
	Unprotected steel distribution pipeline	2.12	$MTCH_4$ $mile^{-1}$ yr^{-1}
	Protected steel distribution pipeline	0.06	$MTCH_4$ $mile^{-1}$ yr^{-1}
	Plastic distribution pipeline	0.37	$MTCH_4$ $mile^{-1}$ yr^{-1}
	Total miles of distribution pipeline (alternative)	0.54	$MTCH_4$ $mile^{-1}$ yr^{-1}
Natural Gas Distribution Services	Total number of services	0.02	$MTCH_4$ $service^{-1}$ yr^{-1}
	Number of unprotected steel services	0.03	$MTCH_4$ $service^{-1}$ yr^{-1}
	Number of protected steel services	0.003	$MTCH_4$ $service^{-1}$ yr^{-1}
Natural Gas Venting and Flaring	Amount of natural gas vented	0	$MTCH_4$ $BBTU^{-1}$ yr^{-1}
	Percent of vented natural gas flared	80	Percent

2.4.2 Greenhouse Gas Reporting Program: Subpart W Calculation Tool

EPA's GHGRP, Subpart W for Petroleum and Natural Gas Systems, collects data from owners or operators of petroleum and natural gas systems that emit greater than 25,000 $MTCO_2e$ of GHGs per year. Owners and operators collect GHG data and estimate emissions using the Subpart W Calculation Tool, which are then reported to EPA's GHGRP and made available through EPA's Facility Level Information on Greenhouse Gases Tool (FLIGHT; EPA 2018b) and Envirofacts.[8]

Subpart W provides a more detailed framework for emissions estimation compared to the SIT, including estimated emissions from equipment components such as valves, flanges, and connectors. Subpart W uses two methodologies for determining EFs: (1) Non-Method 21 factors and (2) Method 21 factors. Method 21[9] is an EPA protocol for monitoring specific volatile organic compounds (VOCs), including CH_4, from process equipment using portable instrumentation. It should be noted that many of Subpart W EFs are derived from older studies.

By evaluating the activity data and EFs associated with Subpart W reporting, one can begin to understand the advantages that a more detailed inventory can provide. Using Subpart W-type reporting, states can identify those specific areas of the oil and natural gas production, processing, transmission, storage, and distribution systems that have the greatest impact on the emissions inventory. This allows states to target policies and programs specifically to those areas. A more detailed description of the Subpart W methodology is provided in appendix A, along with a breakdown of Subpart W EFs for natural gas systems in the eastern United States. The Subpart W oil and natural gas sector reporting facilities for New York State for 2016 are shown in Figure 10 and Table 4. Emissions reported by facilities emitting greater than 25,000 $MTCO_2e$ per year in the State show that local distribution companies account for 93.6% of CH_4 emissions reported, transmission compressor stations account for 4%, and natural gas storage 2.3%.

Figure 10. Oil and Natural Gas Facilities Reporting to Subpart W in 2017

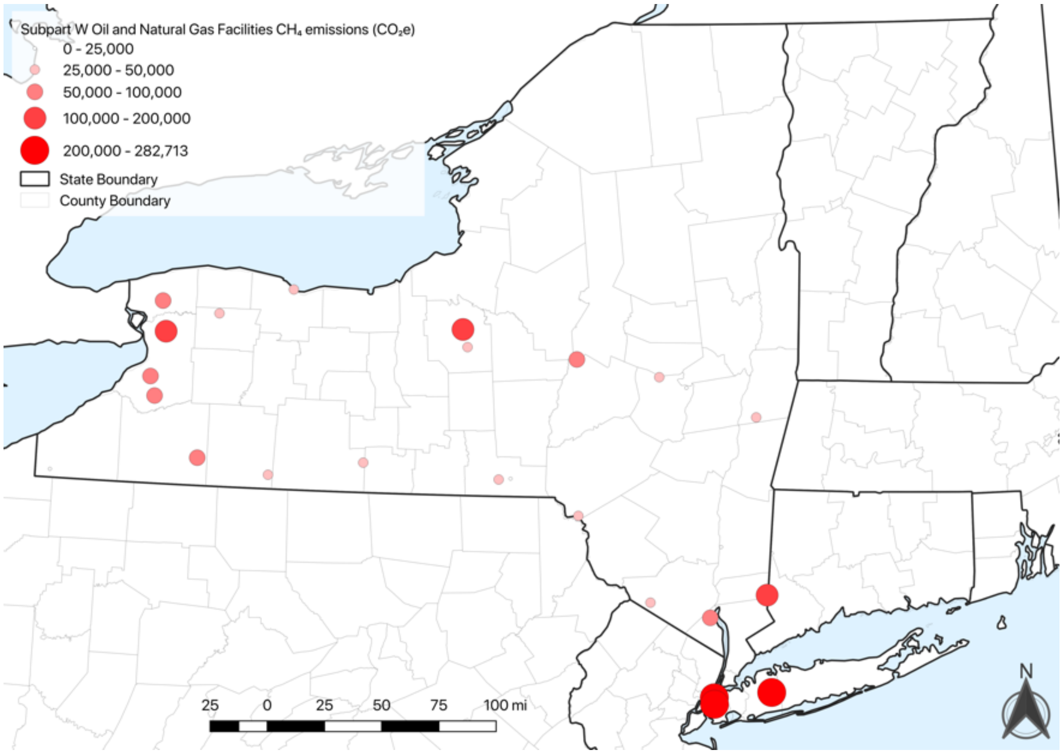


Table 4. List of All Facilities Reporting for 2016 under Subpart W

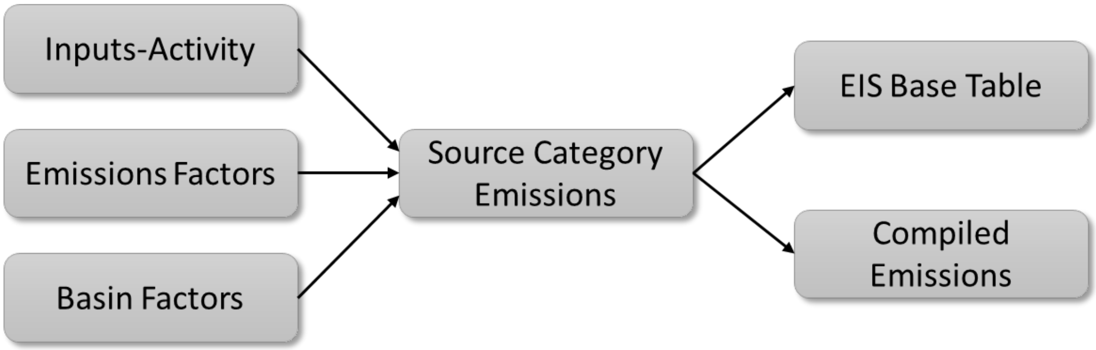
Table Shows Name, City, and County Location and Total CH_4 Emissions [metric ton (MT) CO_2e]

Year	Facility Name	City Name	County Name	CH_4 Emissions ($MTCO_2e$)
2016	Con Edison Natural Gas Delivery System	New York	New York	244,810
2016	Central Hudson Gas and Electric Corp.	Poughkeepsie	Dutchess	26,002
2016	Empire Oakfield Station	Oakfield	Genesee	1,732
2016	Hancock Compressor Station	Hancock	Delaware	2,063
2016	Iroquois Gas Wright Compressor Station	Delanson	Schoharie	2,971
2016	Keyspan Gas East Corporation	Hicksville	Nassau	286,080
2016	Minisink Compressor Station	Westtown	Orange	1,931
2016	Millennium Pipeline Company Compressor	Corning	Steuben	729
2016	NFGSC Concord Station	Springville	Erie	21,141
2016	NFGSC Hinsdale Station	Hinsdale	Cattaraugus	3,186
2016	NFGSC Independence Station	Andover	Allegany	26,512
2016	Niagara Mohawk Power Corporation	Syracuse	Onondaga	201,123
2016	National Fuel Gas Distribution Corporation	Williamsville	Erie	183,614
2016	New York State Electric and Gas	Binghamton	Broome	41,813
2016	Rochester Gas & Electric Corp.	Rochester	Monroe	36,520
2016	Southeast	Brewster	Putnam	4,943
2016	Stony Point	Stony Point	Rockland	3,949
2016	TGP Station 229 Hamburg	Eden	Erie	4,515
2016	TGP Station 230, Lockport Compressor	Lockport	Niagara	1,643
2016	TGP Station 241 Lafayette	Lafayette	Onondaga	2,791
2016	TGP Station 245 West Winfield	West Winfield	Herkimer	2,673
2016	TGP Station 249 Carlisle	Carlisle	Schoharie	2,507
2016	TGP Station 254 Nassau	Nassau	Rensselaer	1,600
2016	The Brooklyn Union Gas Company	Brooklyn	Kings	229,246
			Total	**1,334,094**

2.4.3 EPA Oil and Gas Tool

The EPA's Oil and Gas Tool (EPA 2014) contains information used to develop a nonpoint source (i.e., originating from many diffuse sources) emissions inventory for upstream oil and natural gas activities across the 54 source categories listed in Table 5. The basic concept of the tool is to calculate the source category emissions using activity data, EFs, and basin factors (i.e., basin-level EFs). A conceptual flow is presented in Figure 11.

Figure 11. Conceptual Flowchart of EPA's Oil and Gas Tool



The Oil and Gas Tool is a Microsoft Access®-based tool used to generate county-level emission estimates of criteria and hazardous air pollutants (HAP). The Oil and Gas Tool was developed for state, local, and tribal agencies to help estimate criteria air pollutants (CAP) and HAP for submission to the EPA for use in the National Emissions Inventory (NEI). Though the Oil and Gas Tool was not specifically developed for GHGs, it does include EFs for CH_4 and other GHG sources. States are able to adjust EFs and data submitted to the NEI, which can also be reflected in GHG EFs. At present the EFs included for CH_4 in the Oil and Gas Tool reflect default factors developed by Environ for the Central States Air Resource Agencies (CenSARA) in 2012 (CenSARA 2012), and thus are not New York State-specific. The user is able to use pre-populated values or manually specify the geographic region, source categories, basin-level gas factors, EFs, and activity adjustments.

Like Subpart W, the Oil and Gas Tool provides a more detailed framework for BU, activity-based estimation of CH_4 emissions from oil and gas sources in the State. Using EFs from the Oil and Gas Tool and Subpart W, New York State can develop a detailed activity-based BU inventory of CH_4 emissions from oil and natural gas activities.

Default Oil and Gas Tool CH_4 EFs from natural gas operations in the State are shown in Table 6. The Oil and Gas Tool identifies EFs for every basin, county, and state in the U.S. For New York State, the CH_4 EFs for oil and natural gas are constant across basins, and in fact reflect default EFs for the tool derived from the CenSARA 2012 study. The Oil and Gas Tool lists EFs by activity, source category, and component, including emissions using different control devices/methods.

Table 5. List of Sources Included in EPA's Oil and Gas Tool

Activity	Source Category	Source Classification Code (SCC)	SCC Description
Exploration	Drill Rigs	2310000220	Oil and Gas Exploration Drill Rigs
Exploration	Hydraulic Fracturing	2310000660	Oil & Gas Expl & Prod/All Processes/Hydraulic Fracturing Engines
Exploration	Mud Degassing	2310023606	On-Shore Coal Bed Methane (CBM) Exploration/Mud Degassing
Exploration	Mud Degassing	2310111100	On-Shore Oil Exploration/Mud Degassing
Exploration	Mud Degassing	2310121100	On-Shore Gas Exploration/Mud Degassing
Exploration	Well Completions	2310023600	On-Shore CBM Exploration: CBM Well Completion: All Processes
Exploration	Well Completions	2310111700	On-Shore Oil Exploration: Oil Well Completion: All Processes
Exploration	Well Completions	2310121700	On-Shore Gas Exploration: Gas Well Completion: All Processes
Production	Artificial Lifts	2310000330	Oil & Gas Expl & Prod/All Processes/Artificial Lift
Production	Associated Gas	2310011000	On Shore Crude Oil Production All Processes
Production	Condensate Tanks	2310021010	On-Shore Gas Production/Storage Tanks: Condensate
Production	Condensate Tanks	2310023010	On-Shore CBM Production/Storage Tanks: Condensate
Production	Crude Oil Tanks	2310010200	Oil & Gas Expl & Prod/Crude Petroleum/Oil Well Tanks Flashing & Standing/Working/Breathing
Production	Dehydrators	2310021400	On-Shore Gas Production Dehydrators
Production	Dehydrators	2310023400	Coal Bed Methane NG Dehydrators
Production	Fugitives	2310011501	On-Shore Oil Production/Fugitives: Connectors
Production	Fugitives	2310011502	On-Shore Oil Production/Fugitives: Flanges
Production	Fugitives	2310011503	On-Shore Oil Production/Fugitives: Open Ended Lines
Production	Fugitives	2310011505	On-Shore Oil Production/Fugitives: Valves
Production	Fugitives	2310021501	On-Shore Gas Production/Fugitives: Connectors
Production	Fugitives	2310021502	On-Shore Gas Production/Fugitives: Flanges
Production	Fugitives	2310021503	On-Shore Gas Production/Fugitives: Open Ended Lines
Production	Fugitives	2310021505	On-Shore Gas Production/Fugitives: Valves
Production	Fugitives	2310021506	On-Shore Gas Production/Fugitives: Other

Table 5 continued

Activity	Source Category	Source Classification Code (SCC)	SCC Description
Production	Fugitives	2310023511	On-Shore CBM Production/Fugitives: Connectors
Production	Fugitives	2310023512	On-Shore CBM Production/Fugitives: Flanges
Production	Fugitives	2310023513	On-Shore CBM Production/Fugitives: Open Ended Lines
Production	Fugitives	2310023515	On-Shore CBM Production/Fugitives: Valves
Production	Fugitives	2310023516	On-Shore CBM Production/Fugitives: Other
Production	Gas-Actuated Pumps	2310023310	Coal Bed Methane NG Pneumatic Pumps
Production	Gas-Actuated Pumps	2310111401	On-Shore Oil Exploration/Oil Well Pneumatic Pumps
Production	Gas-Actuated Pumps	2310121401	On-Shore Gas Exploration: Gas Well Pneumatic Pumps
Production	Heaters	2310010100	On-Shore Oil Production/Heater Treater
Production	Heaters	2310021100	On-Shore Gas Production/Gas Well Heaters
Production	Heaters	2310023100	On-Shore CBM Production/CBM Well Heaters
Production	Lateral/Gathering Compressor Engines	2310021251	On-Shore Gas Production/Lateral Compressors 4 Cycle Lean Burn
Production	Lateral/Gathering Compressor Engines	2310021351	On-Shore Gas Production/Lateral Compressors 4 Cycle Rich Burn
Production	Lateral/Gathering Compressor Engines	2310023251	On-Shore CBM Production/Lateral Compressors 4 Cycle Lean Burn
Production	Lateral/Gathering Compressor Engines	2310023351	On-Shore CBM Production/Lateral Compressors 4 Cycle Rich Burn
Production	Liquids Unloading	2310021603	On-Shore Gas Production Gas Well Venting Blowdowns
Production	Liquids Unloading	2310023603	Coal Bed Methane NG Venting Blowdowns
Production	Loading Emissions	2310011201	On-Shore Oil Production/Tank Truck/Railcar Loading: Crude Oil
Production	Loading Emissions	2310021030	On-Shore Gas Production/Tank Truck/Railcar Loading: Condensate
Production	Loading Emissions	2310023030	On-Shore CBM Production/Tank Truck/Railcar Loading: Condensate
Production	Pneumatic Devices	2310010300	Oil Production Pneumatic Devices

Table 5 continued

Activity	Source Category	Source Classification Code (SCC)	SCC Description
Production	Pneumatic Devices	2310021300	On-Shore Gas Production Pneumatic Devices
Production	Pneumatic Devices	2310023300	On-Shore CBM Production Pneumatic Devices
Production	Produced Water	2310000550	Produced Water
Production	Wellhead Compressor Engines	2310021102	On-Shore Gas Production/Natural Gas Fired 2Cycle Lean Burn Compressor Engines 50 to 499 HP
Production	Wellhead Compressor Engines	2310021202	On-Shore Gas Production/Natural Gas Fired 4Cycle Lean Burn Compressor Engines 50 to 499 HP
Production	Wellhead Compressor Engines	2310021302	On-Shore Gas Production/Natural Gas Fired 4Cycle Rich Burn Compressor Engines 50 to 499 HP
Production	Wellhead Compressor Engines	2310023102	On-Shore CBM Production/CBM Fired 2Cycle Lean Burn Compressor Engines 50 to 499 HP
Production	Wellhead Compressor Engines	2310023202	On-Shore CBM Production/CBM Fired 4Cycle Lean Burn Compressor Engines 50 to 499 HP
Production	Wellhead Compressor Engines	2310023302	On-Shore CBM Production/CBM Fired 4 Cycle Rich Burn Compressor Engines 50 to 499 HP

Table 6. New York State CH_4 EFs from EPA Oil and Gas Tool

Source: CenSARA (2012)

Activity	Source Category	Component/Activity	EF	Unit	Control Status	Control Device
Oil and Gas Exploration and Production	Artificial Lifts	Artificial Lift	0.834624	g/hp-hr	0	Uncontrolled
	Crude Oil Tanks	Oil Well Tanks—Flashing & Standing/Working/Breathing	0.04	Pound (Lb)/million British thermal unit (MMBTU)	1	Flare
On-Shore Gas and CBM Production	Condensate Tanks	Storage Tanks: Condensate	0.04	Lb/MMBTU	1	Flare
	Dehydrators	Dehydrators	0.04	Lb/MMBTU	1	Flare
			2.3	Lb/Mcf-s	0	Flare
	Fugitives[a]	Connectors	-	kilogram (kg)/component	0	Uncontrolled
		Flanges	-	kg/component	0	Uncontrolled
		Open Ended Lines	-	kg/component	0	Uncontrolled
		Valves	-	kg/component	0	Uncontrolled
		Other	-	kg/component	0	Uncontrolled
	Heaters	Heater Treater	2.3	Lb/Mcf-s	0	Uncontrolled
	Lateral/Gathering Compressor Engines	Lateral Compressors 4 Cycle Lean Burn	4.536	gram (g)/horsepower hour (hp-hr)	0	Catalytic Oxidizer
		Lateral Compressors 4 Cycle Rich Burn	0.834624	g/hp-hr	0	Selective non-catalytic reduction (SNCR)
	Liquids Unloading	Gas Well Venting—Blowdowns	0.04	Lb/MMBTU	0	Uncontrolled
	Wellhead Compressor Engines	Natural Gas Fired 2 Cycle Lean Burn Compressor Engines 50 to 499 hp	5.261644	g/hp-hr	0	Catalytic Oxidizer
		Natural Gas Fired 4 Cycle Lean Burn Compressor Engines 50 to 499 hp	4.536	g/hp-hr	0	Catalytic Oxidizer
		Natural Gas Fired 4 Cycle Rich Burn Compressor Engines 50 to 499 hp	0.834624	g/hp-hr	0	SNCR

[a] No EFs are provided for fugitive emissions since the Oil and Gas Tool calculates fugitive emissions using pollutant ratios.

2.5 Integrating Best Practices into the New York State Methane Inventory

2.5.1 Best Practices

The current New York State approach for constructing the statewide CH_4 inventory has its limitations. Although the nature of the highly aggregated, sectoral, analysis is consistent with the U.S. national GHG Inventory and in some sense captures *all* source activities, in another sense it does not provide detailed information about those source activities in a meaningful and actionable way. An alternative approach would include a level of data refinement and spatial and temporal resolution that more accurately reflects State conditions, accounts for uncertainty, and has results that allow New York State to focus programs and policies on particular parts of the system where the greatest emission reductions may be realized. This section presents recommendations related to four best practices for inventory development and how these should be applied to the New York State case. These best practices are (1) use of appropriately scaled activity data, (2) inclusion of state-of-the-science EFs, (3) geospatial resolution of activities and emissions, and (4) application and reporting of uncertainty factors, including high-emitting sources.

2.5.2 Activity Data

As mentioned in section 3.2, the current New York State CH_4 inventory applies a highly aggregated, throughput-based approach. Section 3.3 outlines an activity-based approach aligned with EPA's SIT, GHGRP tool, and Oil and Gas Inventory Tool. Section 3.3 also demonstrates that activity data are available that would allow the State to conduct an activity-based inventory aligned with best practices.

> **Recommendation #1:** New York State should develop a more detailed set of activity data, including site-level and component-level data, for its CH_4 inventory in order to create an inventory with the detail needed to capture the impacts of CH_4 mitigation strategies targeted at the site- or component-level.

2.5.3 Emission Factors

Based on its current approach to constructing the CH_4 inventory, the State applies a *de facto* high-level, aggregate EF for the entire sector. This EF represents a national average and may not be appropriate for conditions in New York State. In reality, emission characteristics and average loss rates can vary significantly by regions and across the country (Alvarez et al. 2018) and also depend on well geography, age of the infrastructure, and statewide approaches to operations like venting and flaring.

Recommendation #2: New York State should estimate and apply EFs for upstream, midstream, and downstream oil and gas activities using best available data, validated by both BU and TD studies, and specific to geographic location in the State.

TD emission inventories employ remote-sensing techniques, including mobile vehicle, and aircraft- and satellite-mounted sensors to monitor atmospheric conditions. These atmospheric conditions, when coupled with atmospheric transport models, can be used to identify magnitudes and sources of emissions. TD emission inventories have the benefit of being decoupled from the activity, as a measure of the level of atmospheric concentration, and thus can be useful to validate BU, activity-driven inventories. One limitation of TD inventories is that they require sophisticated monitoring and atmospheric modeling systems, and thus are often limited to smaller study areas.

One approach common to TD inventories is aerial mass balance, which estimates the flow rate of a gas through a given parcel of air based on the dimensions of the parcel; atmospheric conditions, including wind; and the gas-mixing ratio. Once the flow rate is known and the air parcels in the region have been analyzed, it is possible to back-calculate the source of emissions and the mass of gas emitted. An example set of studies that used TD emission estimates is shown in Table 7.

Table 7. CH_4 Emission Rates (as a percent of production throughput) for Nine Survey Areas Derived from Aircraft-Based TD Studies

Calculated and reported in Alvarez et al. (2018).

TD Survey Area (Shale Basin)	Natural Gas Production ($Bcf \cdot day^{-1}$)	Estimated CH_4 Emissions from Oil and Natural Gas Production [megagram (Mg)$\cdot hr^{-1}$]	Estimated Emissions Rate (% of production)	Reference
Haynesville	7.7	73 ± 54	1.3	Peischl et al. 2015
Barnett	5.9	60 ± 11	1.4	Karion et al. 2015
Marcellus	5.8	18 ± 14	0.4	Barkley et al. 2017
San Juan	2.8	57 ± 54	3.0	Smith et al. 2017
Fayetteville	2.5	27 ± 8	1.4	Schwietzke et al. 2017
Bakken	1.9	27 ± 13	3.7	Peischl et al. 2015
Uinta	1.2	55 ± 31	6.6	Karion et al. 2013
Weld	1.0	19 ± 14	3.1	Pétron et al. 2014
West Arkoma	0.4	26 ± 30	9.1	Peischl et al. 2015
9-Basin Total	**29.0**	**360 ± 92**	**1.8% ± 0.5%**	

2.5.4 Geospatial Location

Geospatial data are publicly available for many of the inputs necessary for compiling activity-based oil and natural gas CH_4 inventories for New York State. Well locations and annual production data are available from DEC and processing and storage plant locations are available from EIA. Pipeline locations are not publicly available due to U.S. Homeland Security concerns, but small-scale (low geographic precision) pipeline locations are available from EIA or upon request from gis.ny.gov. Aggregate data on pipeline construction type are available, but do not include geospatial information. A map of available geospatial data is shown in Figure 7.

Geospatially resolved emission inventories are important for a number of reasons. First, estimating emissions geospatially allows policymakers and regulators to identify emission hotspots and address emissions in those hotspot areas. Geospatially resolved emission inventories also have important implications for air quality studies. While CH_4 is a global GHG, whose impacts are global regardless of emissions location, co-pollutants (not studied here) such as VOCs and other criteria pollutants have local impacts on human and environmental health. Geospatial inventories of these pollutants are a critical input to air quality modeling efforts to assess human and environmental health impacts, which leads us to our third recommendation:

> **Recommendation #3:** New York State should align available geospatial data with inventory data as much as possible to create a geospatial emissions inventory that allows greater consideration for identifying hot spots and air quality concerns as well as verification of emission inventories with empirical data.

2.5.5 Uncertainty Analysis and High-Emitting Sources

The issue of uncertainty is an important one for CH_4 inventories. As previously mentioned, EFs can vary significantly, and best practice suggests that inventories should account for some range of uncertainty in reporting. In addition, the issue of high-emitting sources, sometimes referred to as super-emitters, has received significant attention in the inventory literature (Zimmerle et al. 2015; Zavala-Araiza et al. 2015, 2017; Yacovitch et al. 2015; Lavoie et al. 2015; Lyon et al. 2016) and is discussed further in section 3.3.5. Depending on the definition used, high-emitting sources represent a small group of emission sources that contribute a disproportionately high amount of emissions across the supply chain due to abnormal process conditions, as opposed to emissions associated with non-functioning equipment (Allen 2016; Allen, Sullivan, et al. 2015). As such, emissions across a population may follow a skewed fat-tailed distribution, and therefore EFs based on mean emission rates may not capture the total volume of CH_4 emitted (ITRC 2018). An alternative and more technical term, "high-emitting sources," has been developed by the Interstate Technology and Regulatory Council (ITRC; ITRC 2018). There is very little research on how significant this problem is in New York State, thus leading to our fourth recommendation:

> **Recommendation #4:** New York State should conduct uncertainty analysis when calculating and reporting its CH_4 inventory. At a minimum, that uncertainty analysis should account for uncertainties in published EFs, but it could also include an assessment of high-emitting sources across the State. New York State should develop and apply models that help account for the existence of high-emitting sources either in cases where emission releases are known (e.g., reported leakage) or in cases where emission releases are not known (e.g., estimated leakage based on pipeline age or material).

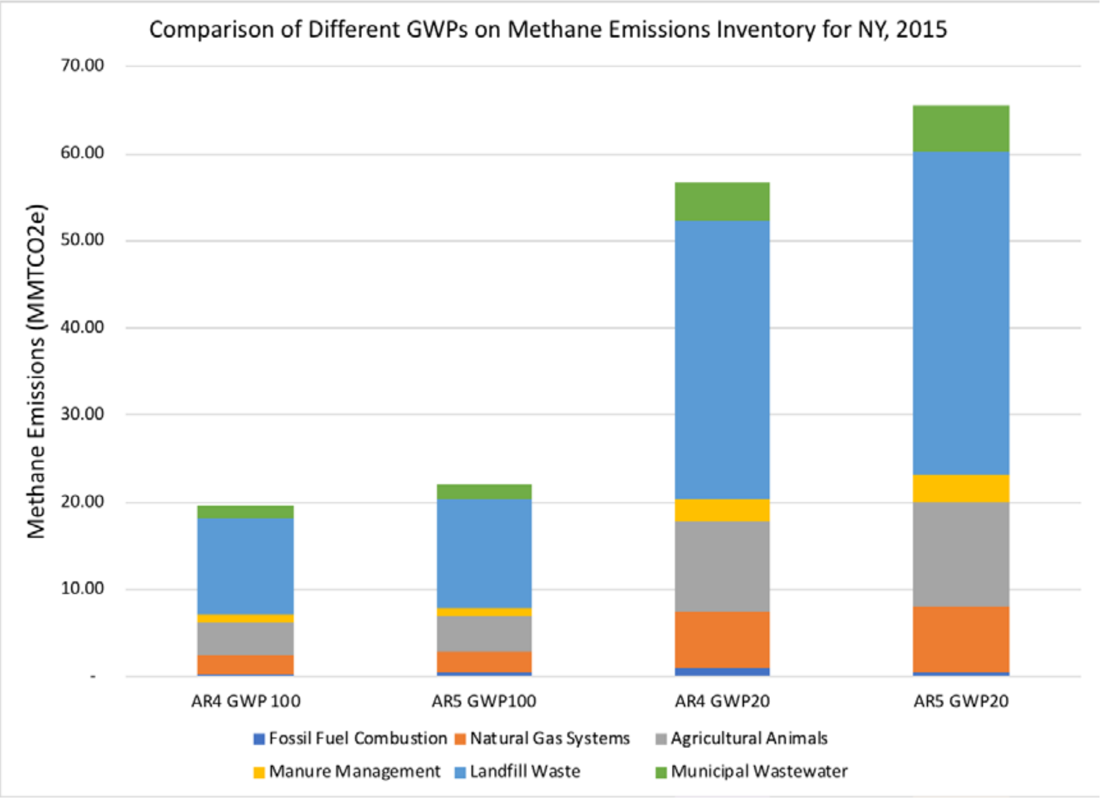
2.6 Selection of Global Warming Potential Factors

A final issue we raise in this assessment is the selection of an appropriate unit for inventory calculations. Over two decades ago, the IPCC recommended the GWP_{100} for converting CH_4 emissions to CO_2e for the purpose of governmental inventory reporting to the United Nations Framework Convention on Climate Change (UNFCCC). While this gives a long-range perspective, using GWP_{100} discounts important, near-term climate impacts (Alvarez et al. 2012). Some researchers are now suggesting the use of the GWP_{20} as an appropriate metric or at least reporting inventories using both GWP_{100} and GWP_{20} conversions (Balcombe et al. 2018; Alvarez et al. 2012; Ocko et al. 2017).

New York State currently uses the IPCC GWP_{100} from the AR4 of the IPCC (IPCC 2006) to be consistent with the U.S. National GHG Inventory, other national governmental inventories that follow UNFCCC protocols, and the SIT-based inventories reported by other states. The AR4 GWP_{100} for CH_4 is 25 and the GWP_{20} is 72, meaning that CH_4 is 25x more potent than CO_2 as a GHG over a 100-year time period and is 72x more potent over a 20-year time period. More recently, the IPCC significantly revised its GWP values in the 2013 Fifth Assessment Report [AR5 (Hartmann, Tank, and Rusticucci 2013)]. Under AR5, the GWP_{100} for CH_4 is 28 (a 12% increase) and the updated GWP_{20} is 84 (a 16.7% increase). The calculation of GWP with subsequent Assessment Reports is due in part to the changing concentration of GHGs in the atmosphere and updated modeling for their direct and indirect effects. Recent literature estimates indicate that the GWP for CH_4 may in fact be greater than reported in AR5 (Etminan et al. 2016). Using the updated AR5 GWP_{100} to adjust the 2017 New York State natural gas CH_4 emissions inventory (2.22 $MMTCO_2e$) results in a new estimate of 2.49 $MMTCO_2e$, a 12% increase.

The impact of the choice of GWP is illustrated in Figure 12. Here we show CH_4 emissions converted to $MMTCO_2e$ under four different GWP values (GWP_{100} from AR4 and AR5, and GWP_{20} from AR4 and AR5). The emissions of CH_4 in $MMTCO_2e$ increase by more than a factor of three when using the near-term, 20-year GWP. If the 20-year GWP were applied to the total inventory of all GHGs, the sources of short-lived GHGs like CH_4 would become a larger portion of emissions. Thus, the choice of a GWP can increase our understanding of the relative importance of CH_4 emissions.

Figure 12. Comparison of CH_4 Emissions ($MMTCO_2e$) in New York State under Different GWP Assumptions



2.7 Summary of Best Practices

In summary, characteristics of the New York State oil and natural gas industry differ from the national average. Therefore, using national estimates of the fraction of emissions attributed to each stage in the oil and natural gas system derives potentially spurious results for the State, and highlights the importance of performing a BU, activity-driven, component-level CH_4 emissions inventory for New York State. The development of such an inventory should focus on the (1) use of appropriately scaled activity data, (2) inclusion of state-of-the-science EFs, (3) geospatial resolution of activities and emissions, and (4) application and reporting of uncertainty factors, including high-emitting sources.

3 Methane Emissions Literature Review

3.1 Overview

New York State official CH_4 inventory (as reported in the State's annual GHG Inventory report; NYSERDA and DEC 2018) is generated through a simple scaling approach that may underestimate or overestimate emissions. This section provides the results of a literature review aimed at uncovering best practices for CH_4 inventory development and inputs to inform improvements in the State's inventory models in the future.

A literature review was conducted that included peer-reviewed articles, reports, and tools describing state-of-the-art CH_4 inventory development in the United States and internationally, with a focus on emissions in the oil and natural gas sector. While over 100 documents on this topic were carefully reviewed, specific attention was paid to three sources of information: (1) EPA's GHGRP Subpart W, (2) EPA's FLIGHT, and (3) the Environmental Defense Fund's (EDF) 16 Study Series. The European Union's (EU) most recent inventory report (European Environment Agency 2018) was also reviewed to explore differences between international and U.S.-centric inventory methodologies.

This review highlights the rapid advancement of state-of-the-art CH_4 inventory development. In just the last decade, new data now allow for more geographic-specific inventory development and greater certainty of emissions, ranging from routine leaks to episodic releases. The literature has also advanced on identifying the role of high-emitting sources, which have previously been ignored in conventional CH_4 inventories, but which can play an important part in a region's overall emission levels.

Section 3.2 presents key terminology so that readers may better understand subsequent sections. Section 3.3 discusses methodologies used to develop emission estimates for oil and natural gas systems. Section 3.4 presents the key findings from the review and highlights the importance of similar types of reviews for other major sources of CH_4, including agriculture, landfills, waste water management, and wetlands.

3.2 Key Terminology

3.2.1 Oil and Natural Gas Supply Chain

The U.S. oil and natural gas supply chain can be broken into nine main segments. For oil development, CH_4 emissions occur across the following four stages: (1) exploration, (2) production, (3) gathering and boosting, and (4) transmission. For natural gas development, CH_4 emissions occur across the following nine stages: (1) exploration, (2) production, (3) gathering and boosting, (4) processing, (5) transmission, (6) underground storage, (7) LNG import and export terminals, (8) LNG storage, and (9) distribution, as shown in Figure 13 (Howarth 2014; Harrison et al. 1997a). These stages are divided into three major groups: (1) upstream, (2) midstream, and (3) downstream stages.

3.2.1.1 Upstream Stages

- ***Exploration*** includes well drilling, testing, and completions. The predominant sources of emissions from exploration are well completions and testing.
- ***Production*** involves taking crude oil or raw natural gas from underground formations, whether using conventional drilling or unconventional drilling techniques. Sources of emissions during the oil production stage typically include leaks, pneumatic devises, storage tanks, and flaring of associated gases. Sources of emissions during the natural gas production stage depend on the technologies employed for gas extraction, but typically include leaks, pneumatic controllers, unloading liquids from wells, storage tanks, dehydrators, and compressors. Many wells co-produce oil and natural gas; therefore, the distinction between oil production and gas production is not always clear.
- ***Gathering and boosting*** stations receive natural gas from production sites/wells and via gathering pipelines, and then transfer the gas to transmission pipelines and/or processing facilities and distribution systems. Compression, dehydration, and sweetening (removal of foul-smelling sulfur containing compounds) occur in this segment. Sources of emissions in this segment include gathering stations, pneumatic controllers, natural gas engines, gathering pipelines, liquids unloading, and flaring.

3.2.1.2 Midstream Stages

- ***Natural gas processing*** includes the process of removing impurities and other hydrocarbons, including liquids, from raw natural gas, resulting in pipeline grade natural gas. Emissions from the processing stage originate from reciprocating and centrifugal compressors, blowdowns, venting, and leaks.

- The ***transmission and compression*** stage is the transfer of natural gas from gathering lines and processing plants to the city gate or to high-volume industrial users through main transmission lines. Compressor stations located along the pipelines maintain high pressure and move the gas throughout the system. Sources of emissions in this segment include compressor stations, venting from pneumatic controllers, uncombusted engine exhaust, unburned and pipeline venting.
- ***Underground storage*** involves injecting natural gas into underground formations during periods of low demand; and the natural gas is withdrawn, processed, and redistributed during periods of high demand. Compressors and dehydrators are the primary emission sources from the storage segment.
- ***LNG import/export terminal activities*** involve the receipt and delivery of LNG for storage and ultimately delivery.
- ***LNG storage*** involves the storage of LNG while it awaits final distribution.

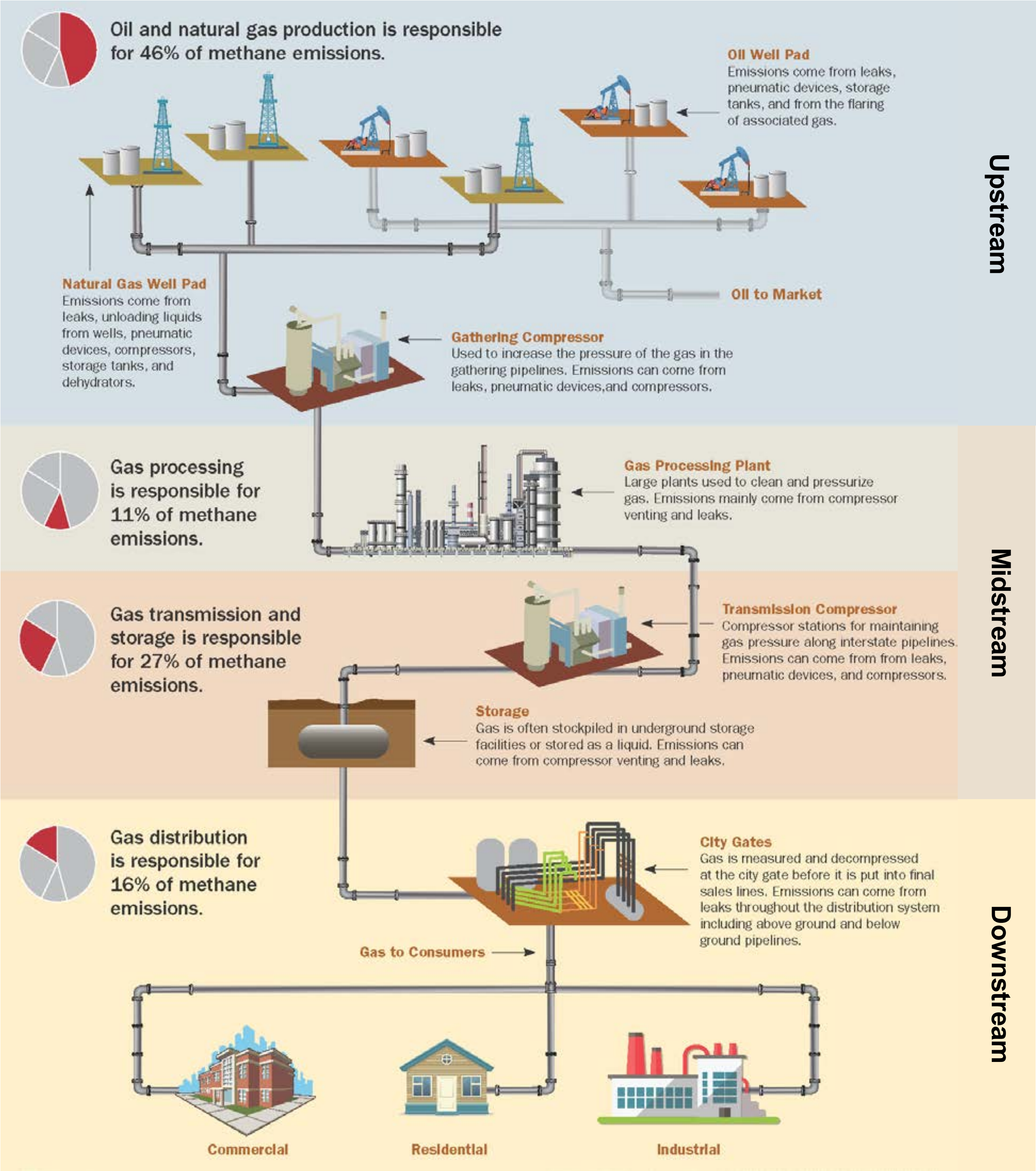
3.2.1.3 Downstream Stage

- The ***distribution*** stage represents the delivery of natural gas to end users through distribution mains and service pipelines. Distribution pipelines receive high-pressure gas from the transmission pipelines at city gate stations, where the pressure is reduced, and the gas is distributed through predominantly underground main and service pipelines to the customer's meter, where the downstream stage ends. Primary sources of emissions from the distribution segment are leaks from pipes and metering and regulating (M&R) stations. Fugitive emissions after the customer meter are not considered here since those emissions should be accounted for in the residential or commercial sector inventory.

Figure 13. Oil and Natural Gas System Depicting the Upstream, Midstream, and Downstream Grouping of Stages

Note: The fraction of emissions is based on the 2014 EPA U.S. GHG Inventory.

Source: McCabe et al. 2015



3.2.2 Emission Source Categories

Emissions from oil and natural gas production systems fall into three main categories: fugitive emissions, vented emissions, and combustion emissions (Kirchgessner 1997). Definitions of these categories are as follows:

- ***Fugitive emissions*** represent unintended emissions from equipment leaks (such as those from compressor stations, meters, pressure regulating stations, malfunctioning pneumatic controllers, and various parts of the production process) and pipeline leaks due to deteriorating pipelines or poor pipeline connectors.
- ***Vented emissions*** represent purposeful releases (i.e., by design) of CH_4 (e.g., through pneumatics, dehydrator vents, regular maintenance, and chemical injection pumps).
- ***Combustion emissions*** represent unburned CH_4 emitted during any fossil fuel combustion component of the production process (e.g., compressor exhaust emissions or flares).

These different types of emissions are discussed in the context of inventory development in the following sections.

3.2.3 Bottom-Up versus Top-Down Methodologies

CH_4 emissions from the oil and natural gas sector are typically quantified using either TD or BU methodologies. Definitions of these methodologies are as follows:

- ***TD*** studies calculate CH_4 emission levels using observational techniques, including airborne measurements, satellites, mobile measurement devices, and stationary sensors. These approaches estimate aggregate CH_4 emissions from all sources in a given region, and then attempt to apportion those emissions to different source categories. Allen (2014) notes that the challenges of estimating emissions using TD methods include separating anthropogenic emissions from natural emissions, and identifying legacy emission sources such as abandoned wells and nonoperational infrastructure. TD estimates are typically generated at the area-level.
- ***BU*** studies generate emission estimates by applying EFs to different activities in the oil and natural gas sector. The generation of EFs can be challenging and usually involve laboratory or in situ measurements of emissions that are then extrapolated and applied broadly to develop overall emission inventories. As Allen (2014, 2016) notes, one of the primary challenges with BU studies is obtaining a representative sample of a large, geographically dispersed, and diverse population of equipment and activities. Other uncertainties are due to inaccurate activity data, malfunctioning equipment, or poorly operated equipment (Allen 2016). Furthermore, emissions from various sources are not normally distributed, and so the use of an "average" EF may lead to both overestimation and underestimation (Littlefield et al. 2017). BU inventories are typically estimated at the component or site level.

BU estimates are particularly challenging when estimating emissions from high-emitting sources, as an accurate estimate requires either prior understanding of which sources are likely to be high-emitting sources; or obtaining a statistically representative sample, which is itself not easily determined without a large sample size. Lastly, because BU methods calculated at the component level only capture source emissions for known and well-defined sources, they typically underestimate actual emissions, which include emissions from unknown or ill-defined sources (Heath et al. 2015; Adam R Brandt, Heath, and Cooley 2016; A R Brandt et al. 2014; Miller et al. 2013; Alvarez et al. 2018).

- **Site-level** estimates use a similar methodology to TD estimates, often estimating emissions from atmospheric concentrations, but then apply those estimates in a BU approach. Site-level estimates are generated for each site (e.g., well head, compressor station) and are at a smaller geographic scale than TD estimates—and at a greater scale than component-level BU estimates.

In both BU and TD approaches, uncertainty exists and the literature suggests that CH_4 inventories at the national level are likely under representing actual emissions by 50% or more (Miller et al. 2013; A R Brandt et al. 2014). At a regional level, Miller et al. (2013) suggest that fossil fuel extraction and processing emissions could be three to seven times higher than reported. Zavala-Araiza et al. (2015a) also show that CH_4 emissions from oil and gas production are almost twice as large as reported by the EPA and represent approximately 1.5% of natural gas production. This 1.5% may also be on the low range; other authors have observed regional losses of 2–12% or more in the Natural Gas sector, implying CH_4 emissions nationally could be three times higher than the EPA reports (Pétron et al. 2012; A. Karion et al. 2013; Caulton et al. 2014). The ceiling for fugitive emissions can be considered as the delta between aggregated meter readings in the distribution segment and the input of gas into the system from production and gathering.

3.3 Review of Existing Methane Inventory Approaches for Oil and Natural Gas Systems

3.3.1 EPA's Greenhouse Gas Reporting Program Subpart W

EPA's GHGRP [codified at 40 Code of Federal Regulation (CFR) Part 98] requires large emitters of GHGs to report their emissions through a centralized database accessible by the public (EPA n.d.). Data collection began in 2011 and covers sources emitting over 25,000 MT of CO_2e per year, using the GWP_{100} from AR4 (IPCC 2006) for converting CH_4 and other GHGs to CO_2e. These facilities self-identify and report annually. The owners and operators of these facilities are tasked with calculating CO_2e emissions, filing their results with the EPA, and maintaining records.

Subpart W of the GHGRP is focused specifically on facilities operating in oil or gas sectors (EPA 2018a). This includes emission sources in the following segments of the oil and natural gas system. Subpart W facility definitions differ across segments and are defined in parentheses.

- Onshore Oil and Natural Gas Production (Company or Basin)
- Offshore Oil and Natural Gas Production (Company or Basin)
- Natural Gas Gathering and Boosting (Company or Basin)
- Natural Gas Processing (Site)
- Natural Gas Transmission Compression (Site)
- Natural Gas Transmission Pipeline (Site)
- Underground Natural Gas Storage (Site)
- LNG Import/Export (Site)
- LNG Storage (Site)
- Natural Gas Distribution (Company or State)

In 2016, 2,248 Subpart W facilities reported emissions totaling 282.9 MMTCO$_2$e, of which 186.7 MMTCO$_2$e was CO$_2$, 96.0 MMTCO$_2$e was CH$_4$, and 0.2 MMTCO$_2$e nitrous oxide (N$_2$O). Note that although the GHGRP data and the U.S. national GHG Inventory are not directly comparable, total emissions in the U.S. for all sectors in 2016 was 6,511 MMTCO$_2$e (EPA 2018a), so the Subpart W emitters contributed about 4.3% of total emissions nationally.

GHGRP facilities are required to report emissions greater than 25,000 MTCO$_2$e for specific source categories. Facilities report emissions data to the EPA through an electronic submission. A review of the spreadsheet tool used by the EPA for this purpose, herein called the "Subpart W Tool," was conducted. The Subpart W Tool is a BU approach that captures emissions of different components of the oil and natural gas system. The Subpart W forms are embedded in a Microsoft Excel spreadsheet and require facilities to provide input on equipment at an operational level. For example, Subpart W forms ask for input on the quantity of oil and natural gas produced, the quantity of oil and natural gas stored, the number and type of pneumatic devices and pumps, the number and types of dehydrators, the amount of well venting for liquids unloading, blowdown vent stacks, well completions, atmospheric storage units, flare stacks, and estimates of non-planned emission leaks.

The value of the Subpart W form for inventory development is its library of EFs, which provide specific values for a host of equipment and operations. For example, onshore production facilities that use natural gas pneumatic devices will find EFs (standard cubic feet/hour/device) for high-bleed pneumatic devices, intermittent-bleed pneumatic devices, and low-bleed pneumatic devices of 37.9, 13.5, and 1.39, respectively. This level of detail is useful for others constructing BU emission inventories.

3.3.2 EPA's Facility Level Information on GHG Tool

EPA's FLIGHT provides access to GHG data reported to the EPA through the previously mentioned Subpart W reporting system and other GHGRP subparts. Aside from providing data access in geospatial, graphical, and tabular formats, FLIGHT does not provide any additional advancements with respect to inventory methodology.[10]

Data included in FLIGHT are submitted to the EPA periodically under the GHGRP (typically in March following the reporting year), as reported by over 8,000 facilities, including Subpart W and non-Subpart W facilities. These data are submitted by large emitters (> 25,000 $MMTCO_2e.yr^{-1}$) and cover an estimated 85–90% of total GHG emissions in many sectors in the U.S., including power plants and landfills, but less than 50% of the oil and natural gas sector. GHGRP data are available at the national, state, local, sector, and facility levels (EPA 2018c).

Emission sources available in FLIGHT relevant to CH_4 inventory accounting include point sources, onshore oil and gas production, onshore oil and gas gathering and boosting, local distribution, and onshore gas transmission pipelines. Sectors available in FLIGHT are power plants, petroleum and natural gas systems, refineries, chemicals, other, minerals, waste, metals, and pulp and paper.

EPA's Envirofacts, which draws on data from EPA's GHGRP and provides an alternate path to accessing FLIGHT data, shows that CH_4 emissions from all sources in New York State in 2016 totaled 3,082,129 $MTCO_2e$ (using IPCC AR4 GWP_{100} values), of which 1,334,090 $MTCO_2e$ of CH_4 were emitted from the oil and natural gas sector, and 1,716,960 $MTCO_2e$ were emitted from waste facilities, primarily landfills (the agriculture sector was not included). Together, these two sectors account for 98.98% of non-agriculture-based CH_4 emissions reported in the State (43.28% and 55.70%, respectively).

3.3.3 EPA's Greenhouse Gas Emissions Inventory

EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2016 provides an overview of U.S. GHG emissions, including CH_4 emissions from oil and natural gas systems (EPA 2018a). The approach for calculating emissions for natural gas systems generally involves the application of EFs to activity data. For most sources, the approach uses technology-specific EFs or EFs that vary over time and consider changes to technologies and practices, which are used to calculate net emissions directly. For others, the approach uses what are considered "potential methane factors" and reduction data to calculate net emissions.

Key references for EFs for CH_4 emissions from the U.S. oil and natural gas sector include a 1996 study published by the Gas Research Institute (GRI) and the EPA (EPA/GRI 1996). The EPA/GRI study developed over 80 CH_4 EFs to characterize emissions from the various components within the operating stages of the U.S. natural gas system. The EPA/GRI study was based on a combination of process engineering studies, a collection of activity data, and measurements at representative gas facilities conducted in the early 1990s.

In the production segment, EPA's GHGRP data (EPA 2017) were used to develop EFs used for all years for well testing, gas well completions and workovers with and without hydraulic fracturing, pneumatic controllers and chemical injection pumps, condensate tanks, liquids unloading, and miscellaneous flaring. In the processing segment, for recent years of the times series, GHGRP data were used to develop EFs for fugitives, compressors, flares, dehydrators, and blowdowns/venting. In the transmission and storage segment, for recent years of the times series, GHGRP data were used to develop factors for pneumatic controllers. Other data sources used for CH_4 EFs include Marchese et al. (2015) for gathering stations, Zimmerle et al. (2015) for transmission and storage station fugitives and compressors, and Lamb et al. (2015) for recent years for distribution pipelines and meter/regulator stations. When changes are made to the EPA GHG Inventory methodology, the EPA adjusts inventories from prior years to be consistent with the updated methodology.

3.3.4 Environmental Defense Fund's 16 Study Series

The Environmental Defense Fund (EDF) has been a leader in undertaking investigations into CH_4 emissions in the oil and natural gas sector (EDF 2018). Through this work, EDF has drawn attention to factors such as leakage rates from aging equipment or poor operations, episodic emissions due to equipment failures, and high-emitting sources. EDF has also been a leading proponent of considering alternative GWP values when conducting GHG emission analyses, noting that the selection of an appropriate GWP depends on the types of environmental problems one is trying to address, and that the relatively arbitrary selection of a GWP_{100} may be inferior to a GWP_{20}, especially when considering the importance of short-term climate impacts (Alvarez et al. 2018).

With respect to supply chain analysis, EDF has been working since 2012 on a number of projects aimed at providing a peer-reviewed, scientific basis for assessing CH_4 emissions in natural gas supply systems. The research program is divided into 16 different areas, hence the “16 Study Series” moniker. This section of the report summarizes the results to date from EDF’s work. A summary of each of the 16 studies is shown in Table 8. These studies are useful in helping identify important issues, EFs, and areas of uncertainty for future inventory work for New York State.

Table 8. List of Studies Included in EDF's 16 Study Series as Discussed in EDF (2018)

Study Area/Title	Overview of Results	References
Production Studies		
Natural Gas Production Site Emissions	Conducted measurements of CH_4 emissions at natural gas production sites (conventional and hydraulically fractured wells). Found that CH_4 emissions over an entire completion flowback event ranged from less than 0.1 megagram (Mg) to more than 17 Mg, with a mean of 1.7 Mg [0.67-3.3 Mg with a 95% Confidence Interval (CI)]. Results show that wells with CH_4 capture and/or control devices captured 99% of the potential emissions, and that 3% of the wells account for 50% of estimated emissions during unloading.	Allen et al. 2013
	Identified that due to a possible malfunction, the Bacharach Hi Flow® Sampler (BHFS) may underestimate CH_4 emissions by as much as 40-80%. The authors constrained the potential underestimate and, given differences in flow rates and CH_4 content across different sites, they estimate that emissions from the Natural Gas Production sector may be 7–14% greater than initially thought, with total supply chain emissions being 2–5% greater.	Alvarez et al. 2016
Production Site Emissions Additional Data	Reviewed emissions from 377 gas actuated (pneumatic) controllers at natural gas production sites and a small number of oil production sites. Found that 19% of devices accounted for 95% of entire gas emission rates, with significant geographic variation. Gulf Coast CH_4 emission rates were the highest [10.61 standard cubic foot (scf)/hr] followed by mid-continent (4.87 scf/hr), Appalachian (1.65 scf/hr), and Rocky Mountain (0.67 scf/hr) emission rates. The highest-emitting devices were shown to be behaving in a manner inconsistent with their design specifications.	Allen, Pacsi, et al. 2015
	Investigated CH_4 emissions from wells during liquid unloading events. Liquid unloadings to clear wells of accumulated liquids to increase production may be necessary when a gas well also produces water. Wells with plunger lifts are triggered to unload far more frequently than wells without plunger lifts (thousands of times per year vs. less than 10 times per year). Though wells without plunger lifts emit more CH_4 per unloading event (0.4–0.7 Mg) than wells with plunger lifts (0.02–0.2 Mg), the frequency of unloading events means that wells with plunger lifts account for the majority of CH_4 emissions from liquid unloading. Twenty percent of wells sampled with plunger lifts account for 83% of emissions. With plunger lifts, 20% of wells account for 65–72% of annual emissions (manual and automatically triggered, respectively).	Allen, Sullivan, et al. 2015

Table 8. Continued

Study Area/Title	Overview of Results	References
Production Studies		
Production Data Analysis	Developed a multivariate linear regression to test the relationship of well age, gas production, and oil or condensate production to CH_4 emissions: $\log(\mathrm{CH_4}) = \beta_1 \log(\mathrm{gas}) + \beta_2 \log(\mathrm{oil}) + \beta_3\,\mathrm{age}$ Age was not significantly correlated with CH_4 production while gas production was significantly positively correlated [\beta_1 = 0.25 (p < 0.001)], and oil production was significantly negatively correlated [\beta_2 = -0.08 (p = 0.01)]. Emissions showed significant geographical variation by basin.	Brantley et al. 2014
Midstream Studies		
Gathering and Processing Study	Measurements at 114 gathering facilities and 16 processing plants showed CH_4 emissions ranging from 0.7 to 700 kg/hr^{-1}. Thirty percent of gathering facilities contributed 80% of total emissions, and normalized emissions are negatively correlated with facility throughput, though higher throughput is positively correlated with CH_4 emissions. Venting from liquids storage tanks occurred at ~ 20% of facilities, which showed four times the emission rates of similar facilities without substantial venting.	Mitchell et al. 2015
	Marchese et al. (2015) used the results from Mitchell et al. (2015), combined with state and national facility databases, to develop a Monte Carlo simulation to estimate CH_4 emissions from U.S. natural gas gathering and processing operations. Total annual CH_4 emissions of 2,421 (+245/-237) gigagrams (Gg) were estimated for all U.S. gathering and processing operations, representing a CH_4 loss rate of 0.47% (± 0.05%) when normalized by annual CH_4 production. Ninety percent of those emissions are attributed to normal operation of gathering facilities. CH_4 from gathering facilities are substantially higher than prior EPA estimates, and are equivalent to ~ 30% of total net CH_4 emissions from natural gas systems in the current GHG Inventory. Results showed substantial variation in losses by state, with the highest loss rates in Oklahoma (0.94%) and the lowest in Pennsylvania (0.19%). A facility-level EF for gathering stations (42.6 kg/hr/facility) and estimated number of U.S. gathering stations (4,459 facilities) from this study were incorporated into the EPA GHG Inventory in April 2016.	Marchese et al. 2015

Table 8 continued

Study Area/Title	Overview of Results	References
Midstream Studies		
Transmission and Storage Study	Data from 45 compressor stations in the Transmission and Storage sector showed highly skewed site-level CH_4 emissions, with 10% of sites contributing 50% of CH_4 emissions. The range in emissions observed is 1.7 ± 0.2 standard cubic foot per minute (SCFM) to 880 ± 120 SCFM, with the highest emissions generated by two high-emitting sites. Sites with reciprocating compressors showed typically greater emissions than sites with only centrifugal compressors.	Subramanian et al. 2015
	Evaluated CH_4 emissions from the Transmission and Storage sector. The largest emission sources were high-emitting sources, which showed site-level emission rates that were much higher than their aggregate component-level emission rates. In this instance, these high-emitting sources showed anomalous operations, such as leaking isolation valves, etc. Overall, on a per-station level, emissions from underground storage compressor stations were 847 $Mg \cdot station^{-1} \cdot yr^{-1}$ (+53%/-35%) and transmission stations were 670 $Mg \cdot station^{-1} \cdot yr^{-1}$ (+53%/-34%). Super-emitters contribute 39% of transmission fugitives and 36% of storage station fugitives. This highlighted the importance of observing high-emitting sources, and modeled super-emitters are better modeled as frequency of occurrence rather than based on equipment counts.	Zimmerle et al. 2015
Local Distribution Studies		
Multi-City Local Distribution Study	Direct measurements of 230 underground pipeline leaks and 229 metering/regulating facilities showed that emissions from leaks are generally lower (~ 2 times) than those described earlier in 1992, with a similar pattern in M&R facilities. Annual CH_4 emissions were calculated by multiplying the number of leaks in each category by the appropriate EF. Leaks in cast-iron and unprotected steel pipe account for 70% of eastern emissions and almost half of total U.S. emissions.	Lamb et al. 2015
Boston Study	Atmospheric study that showed overall emissions of 18.5 ± 3.7 g $CH_4 \cdot m^{-2} \cdot yr^{-1}$. Natural gas emissions rate is 2.7 ± 0.6% of consumed natural gas in Boston, which is ~ 2-3 times greater than prior estimates.	McKain et al. 2015
Indianapolis Study	Atmospheric study with observed emissions from distribution, metering, regulating, and pipeline leaks showed 48% of emissions were from biogenic sources, and 52% of emissions from natural gas usage. Mean observed leak rates from pipelines were 2.4 $g \cdot min^{-1}$ (range of 0.013 $g \cdot min^{-1}$ to 22.3 $g \cdot min^{-1}$).	Lamb et al. 2015
Methane Mapping	Mobile analysis using vehicle-based sensors showed cities with a greater prevalence of corrosion-prone distribution lines (~ 25 times larger). Eliminating 8% of leaks would reduce gas pipeline emissions by up to 30%, and the largest 20% of leaks account for half of all emissions.	Von Fischer et al. 2017

Table 8 continued

Study Area/Title	Overview of Results	References
Basin-Specific Studies		
Denver-Julesburg (D-J) Basin	Using ground-based and airborne measurements of the D-J Basin, study showed that non-oil and gas sources contribute around 7.1 ± 1.7 MT $CH_4 \cdot h^{-1}$ (May 29) and 6.3 ± 1.0 MT $CH_4 \cdot h^{-1}$ (May 31) or 24-27.5% of total measurement-based CH_4 emissions. Non-oil and gas sources include animals, animal waste, landfills, municipal wastewater plants, and industrial wastewater plants.	Pétron et al. 2014
Barnett Study	Extensive set of work that used air and ground measurements to develop CH_4 emission estimates for oil and gas wells in the Barnett Shale in Texas. Results indicated emissions were 50–90% higher than would have been predicted using EPA's GHG Inventory model.	Yacovitch et al. 2015 Rella et al. 2015 Nathan et al. 2015 Harriss et al. 2015 Lyon et al. 2015 Zavala-Araiza, Lyon, Alvarez, Palacios, et al. 2015 Smith et al. 2015 Johnson, Covington, and Clark 2015 Lavoie et al. 2015 Townsend-Small et al. 2015 Zavala-Araiza, Lyon, Alvarez, Davis, et al. 2015a Zavala-Araiza et al. 2017
Flyover Study: Barnett Shale	Involved aircraft measurements of hydrocarbons over the Barnett Shale in order to quantify regional CH_4 emissions.	Karion et al. 2015

Table 8 continued

Study Area/Title	Overview of Results	References
Other Studies		
Pump-to-Wheels	This research assessed CH_4 emissions from medium- and heavy-duty vehicles operating on natural gas. The research also included assessments of CH_4 emissions through liquefied and compressed natural gas refueling. CH_4 emissions from vehicle tailpipes (30%) and crank cases (39%) were the dominate emission sources, while refueling emissions were relatively low (12% of transport segment emissions).	Clark et al. 2017
Pilot Projects	EDF funded a number of pilot projects that helped informed the research threads included in this table Although no references are given for these pilot projects *per se*, the results of the projects are embedded in the work referenced throughout this table.	NA
Filling Gaps, Including Super-Emitters	This work aimed to identify high-emitting sources from a set of 8,000 well pads using aerial fly-overs and to estimate the contribution of CH_4 emissions by abandoned wells using a set of 138 abandoned oil and gas wells in 4 basins. These high-emitting sources represent sources that disproportionately contribute to emission inventories. Lyon et al. (2016) concluded that high-emitting sources are "widespread and unpredictable" but easily identifiable with appropriate monitoring systems. Townsend-Small et al. (2016) estimated that abandoned wells contribute less than 1% to regional CH_4 emissions in the study areas.	Lyon et al. 2016 Townsend-Small et al. 2016
Project Synthesis	A synthesis of the current state of knowledge around CH_4 emissions from natural gas production, with input from numerous stakeholders, was conducted; the conclusions indicate that actual emissions of CH_4 may be ~ 60% higher than currently reported in official U.S. inventories, and that 2.3% of the CH_4 in natural gas is emitted between extraction and delivery.	Littlefield et al. 2017 Alvarez et al. 2018

3.3.5 European Union's GHG Inventory

A review was performed on the inventory approaches implemented by the EU, as discussed in the Annual European Union Greenhouse Gas Inventory 1990–2016 and Inventory Report 2018 (EU Inventory) through the European Environment Agency 2018.[11] The EU Inventory applies methodologies outlined by the IPCC in 2006 and uses GWP information contained in AR4.[12] The EU Inventory is essentially an amalgamation of inventories for each of the 28 EU member nations plus Iceland. Each nation is allowed flexibility in its methodological approach, as long as it follows IPCC guidance. That guidance outlines three tiers of methodologies, representing increasing complexity and certainty. For example, Tier 1 methods are TD and apply average EU EFs (e.g., gCO_2e/MBTU natural gas) to national activity data (e.g., MBTU of natural gas consumed). Upon review of the EU Inventory and country-specific EFs, the data show that using EFs from the U.S. is more applicable to the New York State context. Tier 2 applies more nationally focused EFs and activity data, but still represents a TD approach, and Tier 3 represents significant BU analysis, where production and consumption systems are well-defined at the equipment level, and emissions are calculated through equations that depict activity at the micro-level, similar to the Subpart W analysis previously mentioned (IPCC 2006, Vol 2, Ch. 4). Tier 1, 2, and 3 approaches are described in more detail in the following passages.

The EU Inventory estimates gaseous emissions in four source categories in IPCC's Common Reporting Framework Source Category 1.B related to fossil fuel extraction, handling, and consumption. These are Coal Mining and Handling (1.B.1.a), Oil (1.B.2.a), Natural Gas (1.B.2.b), and Venting and Flaring (1.B.2.c). Source category 1.B.2(a and b) is the EU equivalent to the U.S. Oil and Natural Gas Production and Infrastructure sector. The EU GHG Inventory reports that 70.6% of emissions from Source Category 1.B are from fugitive CH_4 emissions, while 29.3% are fugitive CO_2 emissions.

The Tier 1 methodology involves the application of appropriate default EFs to a representative activity parameter, often natural gas throughput, to each segment or subcategory of the country's oil and natural gas industry. The set of equations applied here is a simple scaling of activity estimates by an EF, summed across industry segments. A major flaw of this approach is that emission intensities are fixed relative to activity levels and do not reflect changes in emissions that may result from efficiency improvements and infrastructure upgrades over time.

The Tier 2 methodology applies the same general approach as Tier 1 but applies country-specific EFs that were developed from studies and measurement programs specific to the country's infrastructure. Best practices suggest that Tier 2 EFs be updated periodically. Where reliable venting and flaring data are available, a country may use an alternative Tier 2 approach, which also factors in emissions due to venting and flaring through a set of defined equations (IPCC 2006). This alternative approach may be used to estimate emissions due to venting and flaring from oil production.

The Tier 3 methodology applies a rigorous BU assessment of primary emission sources at the facility level. This approach requires a high level of detail on facilities, wells, flare and vent processes, production, reported and measured releases (planned and unplanned), and country-specific EFs. These inventories require a significant level of effort and it is common among EU countries to periodically produce Tier 3 inventories, and then use these detailed studies to back-calculate the EFs, which can then be used in interim years' Tier 2 studies.

Data from the EU Inventory indicate that fugitive CH_4 emissions from natural gas (Source Category 1.B.2.b) account for 0.6% of total EU – 28 + ISL (28 EU countries, plus Iceland) GHG emissions, and account for 30% of all fugitive emissions. Fugitive sources include exploration, production, processing, transmission, and storage and distribution of natural gas. Fugitive CH_4 emissions from oil (Source Category 1.B.2.a) account for 0.1% of total EU – 28 + ISL GHG emissions and 4% of all fugitive emissions. Fugitive emissions from oil are associated with exploration, production, transmission, upgrading and refining of crude oil, and distribution of crude oil products.

Data for Source Category 1.B.2.b were calculated at the EU country level using a range of methodologies, from Tier 1 to Tier 3 methods, as prescribed by the IPCC in 2006 (IPCC 2006). Data for Source Category 1.B.2.a were calculated at the EU country level using Tier 1 and Tier 2 methods. The decision trees provided by the IPCC for determining which methodology to apply for each source category are shown in Figure 14 and Figure 15. The decision trees are provided here because they may offer useful guidance as the State considers different approaches to inventory development.

Figure 14. Decision Tree for Determining Natural Gas System Fugitive CH_4 Emissions Estimation Methodology

Source: Figure 4.2.1 from IPCC (2006)

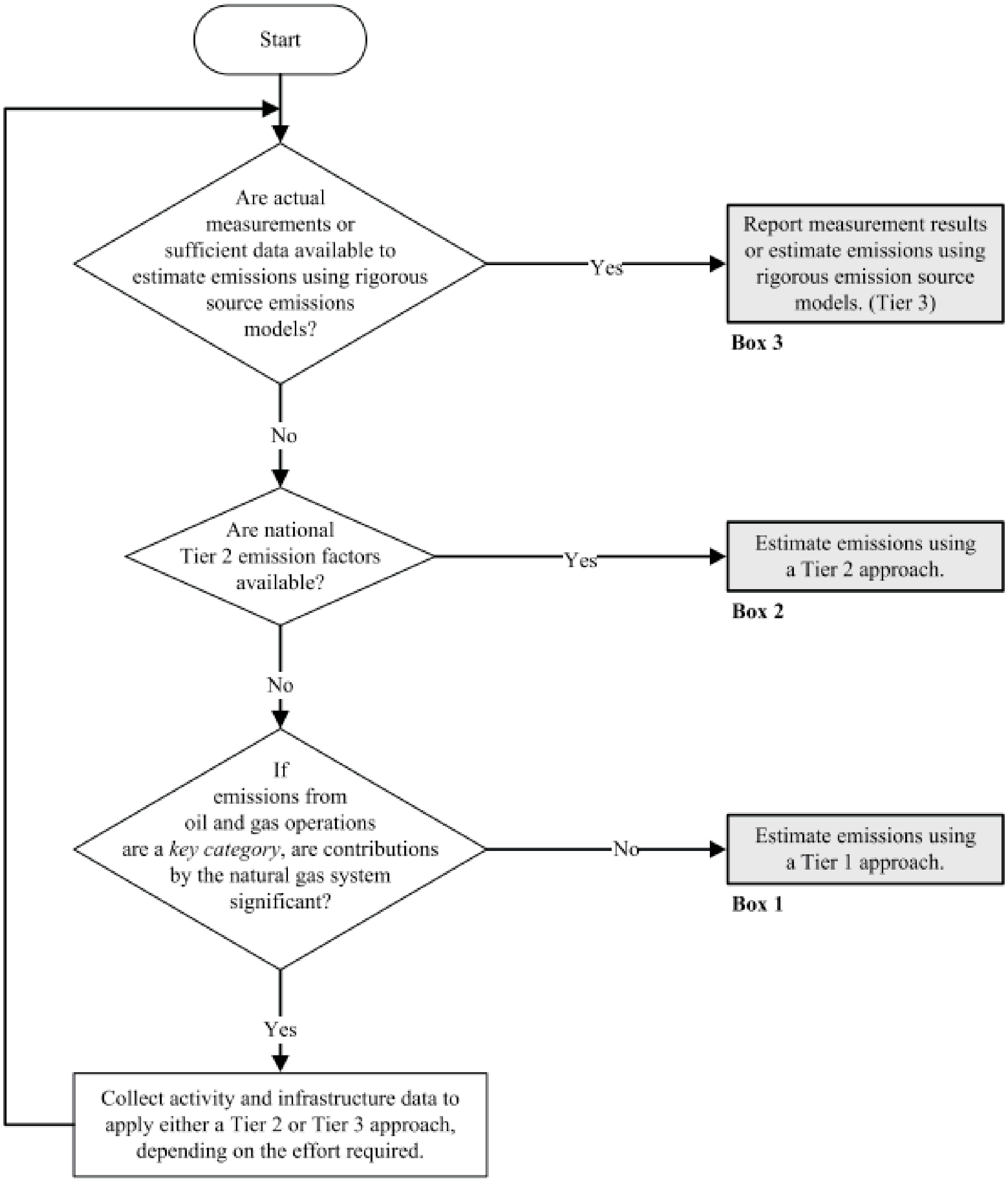
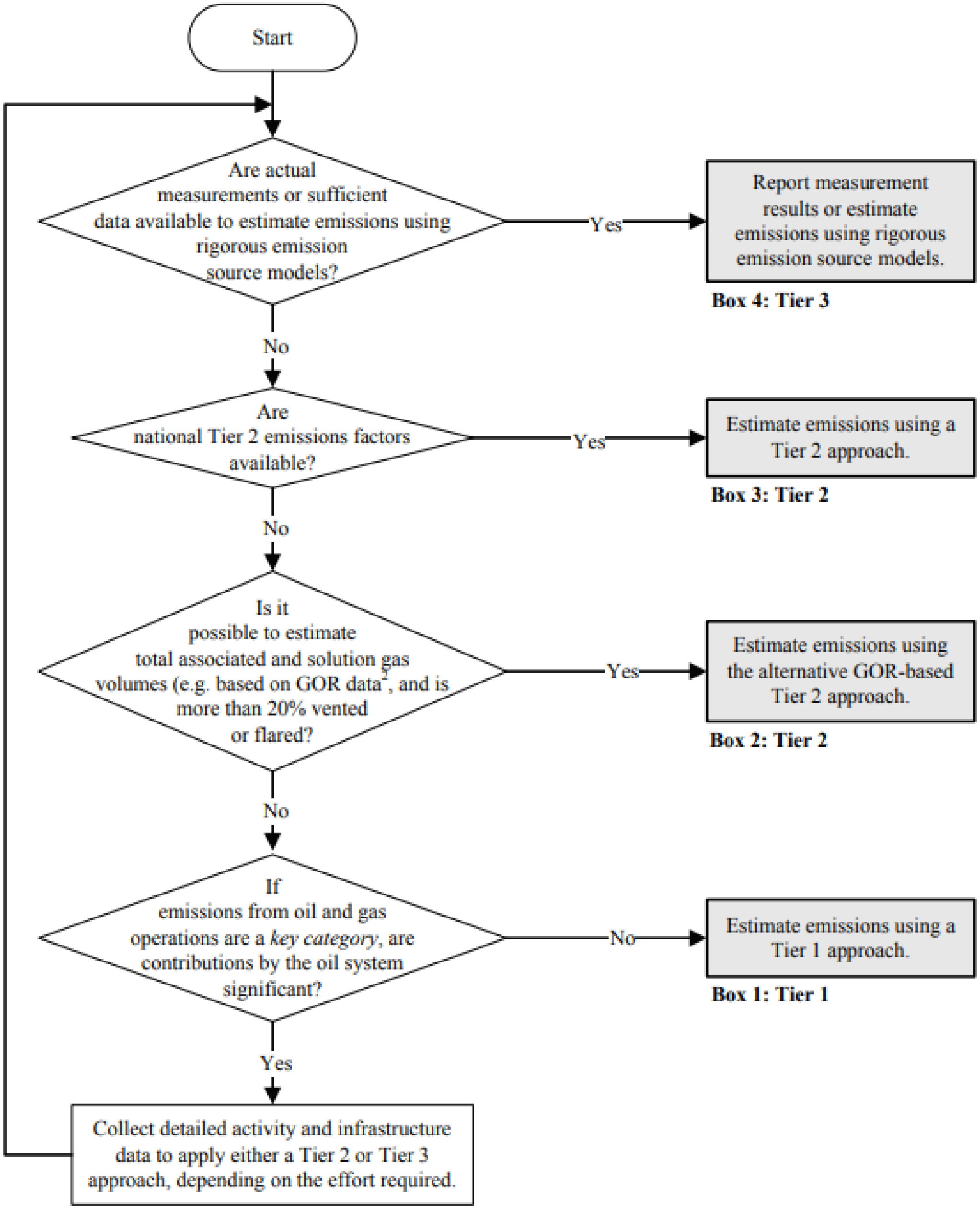


Figure 15. Decision Tree for Determining Oil System Fugitive CH_4 Emissions Estimation Methodology

Source: Figure 4.2.2 from IPCC (2006)



3.3.6 Emission Factors, Spatial Variability, and High-Emitting Sources

3.3.6.1 Emission Factors

One of the most important inputs for CH_4 inventories is the identification of appropriate EFs for BU analyses. These EFs are applied to different activities to calculate emission inventories at either (1) a national, regional, or state basis, or Tier 2 analyses, or (2) a process and system level, or Tier 3 analyses.

In its simplest form, an example of a Tier 2 type of calculation is shown in the following equation, where $E_{s,i}$ is the emissions of type i for period s, NG_s is the natural gas consumption (or throughput) in period s in SCF, and EF_i is the EF for emissions of type i in mass·SCF^{-1}.

Equation 2 $\boldsymbol{E_{s,i} = NG_s \cdot EF_i}$

Tier 2 approaches allow reporting facilities or organizations to easily prepare inventories in cases where limited data exist. EFs for Tier 2 analyses are generally estimated by sampling or testing a set of devices, processes, and facilities; generating EFs at a component level; and then synthesizing those EFs so that they can be applied more widely. Although simple to use, the drawback is that EFs for Tier 2 analyses are averages based on sample testing and may not reflect the actual emissions of the particular facility or region under study.

Tier 3 analyses are more site-specific and estimate emissions at a facility level by incorporating data at an operational level. An example of a type of Tier 3 analysis is shown in the following equation, which is used by facilities to estimate emissions from three types of pneumatic devices using EPA's Subpart W inventory tool mentioned previously.

Equation 3 $\boldsymbol{E_{s,i} = \sum_{t=1}^{3} N_t \cdot EF_t \cdot GHG_i \cdot T_t}$

where:

- $E_{s,i}$ is emissions of type i for year period s
- N_t is the number of devices of type t
- EF_t is the EF for device of type t measured in SCF·hr^{-1}·device^{-1}
- GHG_i is the concentration of GHG of type i in natural gas as a percent
- T_t is the average number of hours during the period the devices were operating

Although Tier 3 analyses use more specific facility and operational data (i.e., activity data) when calculating emissions, the EFs used may not reflect actual EFs for the facility. Thus, in both Tier 2 and Tier 3 analyses, the selection of an appropriate EF is critically important, as emissions are directly and proportionally related to these values.

What has emerged in the literature is an evolution of EFs over time, informed by ongoing research, testing, and demonstration projects. As an example of that variability, data from Howarth (2014) that summarize CH_4 emissions as a percentage of natural gas throughput by process stage (upstream/downstream) and type of natural gas extraction (conventional/unconventional) are reproduced in Table 9.

Table 9. Information on EFs (as a percentage loss) for Upstream, Downstream, and Total Based on Data in Howarth (2014)

Source	Upstream Conventional (%)	Upstream Unconventional (%)	Downstream (%)	Total (%)
Kirchgessner 1997; Harrison et al. 1997b	0.54		0.88	1.42 ± 0.47
Hayhoe et al. 2002	1.4		2.5	3.9
Jaramillo, Griffin, and Matthews 2007	0.2		0.9	1.1
Howarth, Santoro, and Ingraffea 2011	1.4	3.3	2.5	3.9-5.8
EPA 2011	1.6	3.0	0.9	2.5-3.9
Venkatesh et al. 2011	1.8	--	0.4	2.2
Jiang et al. 2011	--	2.0	0.4	2.4
Stephenson, Valle, and Riera-Palou 2011	0.4	0.6	0.07	0.47-0.67
Hultman et al. 2011	1.3	2.8	0.9	2.2-3.7
Burnham et al. 2012	2.0	1.3	0.6	1.9-2.6
Cathles et al. 2012	0.9	0.9	0.7	1.6

More recent work by Alvarez et al. (2018) and Littlefield et al. (2017) synthesize a set of source-specific and site-specific analyses to derive EFs for certain parts of the natural gas supply chain. Littlefield et al. (2017) synthesize component-based data from other studies on well completion, pumps, and equipment leaks (Allen et al. 2013), pneumatic controllers (Allen, Pacsi, et al. 2015), liquids unloading (Allen, Sullivan, et al. 2015), general production (Zavala-Araiza, Lyon, Alvarez, Davis, et al. 2015a), gathering and processing (Marchese et al. 2015), transmission and storage (Zimmerle et al. 2015), and local distribution systems (Lamb et al. 2015). Alvarez et al. (2018) provide the most comprehensive assessment to date of CH_4 emissions from the natural gas supply chain, demonstrating that site-based analyses show CH_4 emission levels that are 1.2 to 2 times higher than EPA's estimates. The EFs derived in this literature provide additional inputs for BU inventory development for New York State.

3.3.6.2 Spatial Variability

CH_4 missions from natural gas production and distribution are also affected by location. This can be seen most obviously in Table 7, which is derived from Alvarez et al. (2018) and shows estimated CH_4 emissions from oil and natural gas production across nine different production basins. Emissions, as a percentage of total production, vary considerably from 0.4% (northeast Pennsylvania) to 9.1% (west Arkoma).

Allen (2016) explains variability due to the different characteristics of the reservoir, the production systems used to extract oil or natural gas, and the air quality regulations that are in place for the region, to name a few. This variability is also reflected in BU analyses that evaluate emissions from equipment and devices, and that can vary by an order of magnitude across different regions (Daniel Zavala-Araiza, Allen, et al. 2015).

In addition to production variability, other sources of variability by region occur throughout the natural gas supply chain. For example, some regions of the county have old distribution systems that may exhibit much higher leakage rates than what national average values would imply (Brandt et al. 2016). For this reason, BU analyses need to be cognizant of regional variability and address that variability in inventory development.

3.3.6.3 Comparison across Historical Methane Loss Rates

Kirchgessner (1997) provides a review of past papers that provide a window into historical assumed loss rates, which is useful for considering hindcasting of emissions using updated methodology. Assumed loss rates, generally measured as unaccounted for gas in the 1970s varied between 1–3% and 6–10%, which was considered an exceptionally high leakage rate. Through the 1980s the assumed CH_4 loss rates were generally 2–4%, with additional considerations for vented and flared CH_4. Considering total natural gas marketed production of 18,712 billion standard cubic feet (Bscf) and estimated CH_4 emissions of 314 Bscf in 1992, Kirchgessner's (1997) estimate of CH_4 loss in 1992 was 1.678% of total production. Given the variation seen in these historical loss rates, it is difficult to determine any trend toward increasing or decreasing CH_4 loss rates from the oil and natural gas sector over the 1968–1992 time period.

3.3.6.4 High-Emitting Sources

An area that has received recent attention in the inventory literature is related to high-emitting sources, sometimes referred to in the literature as "super-emitters".[13] High-emitting sources represent a small group of emission sources that contribute a disproportionately high amount of emissions across the supply chain (Allen 2016). However, high-emitting source status may vary over time and may be better thought of as a statistical status across the entire set of sites and components. That is, if a set of hundreds of sites were observed instantaneously, a fraction of them may be high-emitting sources. If that same set of sites were observed on another occasion, one might expect to see similar rates of high-emitting sources, but not necessarily correlated to the same prior high-emitting sources.

These high-emitting sources may be planned and episodic (e.g., during certain high-emitting liquid unloadings), where planned activity emissions can be "equivalent to a thousand or more wells in routine operation" (Allen, Sullivan, et al. 2015); or can occur due to unplanned events such as equipment malfunction (Allen 2016; Conley et al. 2016).

To illustrate the potential impact of high-emitting sources, consider an example provided by Allen (2016) regarding the venting of CH_4 during liquid unloadings. EPA has reported that ~ 50,000 wells in the U.S. conduct this type of venting, amounting to 259 $Gg \cdot yr^{-1}$ of CH_4 emissions (EPA 2018a). It is believed that 3–5% of these wells account for ~ 50% of these emissions. Similar effects are observed for pneumatic controllers (where 20% of the controllers are thought to emit 95% of emissions) and other equipment and processes in the natural gas supply chain (Allen, Pacsi, et al. 2015). Table 10 summarizes other studies on high-emitting sources.

Table 10. Example Cases of High-Emitting Sources from the Literature, Demonstrating the Disproportionate Level of Emissions Coming from a Small Subset of the Natural Gas Production Supply Chain

Source: Ona Papageorgiou, DEC, personal communication, October 2018

Citation	Segment	Sample Size	Result
Robertson et al. 2017	Oil & Gas Producing Wells	160 wellpads	51/16/30 wellpads in Upper Green River/DJ/Uinta, respectively. 20% of the wellpads contributed ~72-83% of emissions. 53 wellpads in Fayetteville; 20% of the wellpads contributed ~54% of emissions.
Brandt, Heath, and Cooley 2016	All	15,000 previous measurements	Aggregated 15,000 measurements from 18 prior studies, finding that 5% of leaks contribute over 50% of total leakage volume.
Zavala-Araiza et al. 2017	Gas Producing Wells	17,000 wellpads	Highest emitting 1% and 10% of sites accounted for roughly 44% and 80%, respectively, of total CH_4 production emissions from ~17,000 production sites.
Frankenberg et al. 2016	Gas Producing Wells, Gas Processing Plants, Gas Gathering Lines, Gas Transmission Pipelines	250 point sources	10% of emitters accounted for ~ 50% of observed point source emissions, roughly ~ 25% of total basin emissions.
Lyon et al. 2016	Oil and Gas Producing Wells	8,000 well pads	Of 8,000 well pads, 4% of sites had high-emitting sources (detection threshold was 1-3 g/s).
Schade and Roest 2016	Gas Producing Wells		Eagle Ford Region “routine” ethane 4-5 x background; “upsets” ethane ~ 100 x background.
Hendrick et al. 2016	Distribution Mains	100 natural gas leaks from cast-iron distribution main	7% of leaks contributed 50% of emissions measured.
Omara, Sullivan, Li, Subramian, et al. 2016	Gas Producing Wells	35 well pads	Of 13 unconventional routinely operating well pads, 23% of sites accounted for ~ 85% of emissions; of 17 conventional well pads, 17% of sites accounted for ~ 50% of emissions.
Zavala-Araiza, Lyon, Alvarez, Davis, et al. 2015a	Gas Producing Wells, Gas Processing Plants, Gas Transmission Compressor Stations	413 sites	2% of facilities are responsible for 50% of the emissions, and 10% of facilities are responsible for 90% of the emissions.

Table 10 continued

Citation	Segment	Sample Size	Result
Zimmerle et al. 2015	Gas Transmission Compressor Stations, Gas Underground Storage	New measurements from 677 facilities, activity data from 922 facilities	Authors note that "equipment-level emissions data are highly skewed."
Lamb et al. 2015	Distribution Mains/Services, Regulators & Meters	257 pipe leakage measurements, 693 metering and regulator measurements	3 large leaks accounted for 50% of total measured emissions from pipeline leaks.
Rella et al. 2015	Oil and Gas Producing Wells	182 well pads	~ 6% of sites accounted for 50% of emissions, and 22% of sites accounted for 80% of emissions.
Yacovitch et al. 2015	Oil and Gas Producing Wells, Gas Gathering & Boosting Compressor Stations, Gas Transmission Compressor Stations, Gas Processing Plants	188 emissions measurements	7.5% of emitters contributed to 60% of emissions.
Marchese et al. 2015	Gas Gathering & Boosting Compressor Stations	114 compressor stations (CSs)	25 CSs vented > 1% of gas processed, 4 CSs vented > 10% of gas processed.
Mitchell et al. 2015	Gas Gathering & Boosting Compressors, Gas Processing Plants	114 gathering facilities, 16 processing plants	Of 114 CSs, 30% of sites were responsible for ~ 80% of emissions; of 16 gas processing plants, 45% of sites were responsible for ~ 80% of emissions.
Subramanian et al. 2015	Gas Transmission Compressor Stations	47 compressor stations	Of 45 CSs, 10% of sites accounted for ~ 50% of emissions.
Kang et al. 2014	Abandoned Wells	19 abandoned wells	Of 19 abandoned wells, 3 had flow rates 3x larger than the median flow rate.
Allen, Pacsi, et al. 2015	Gas Producing Wells	377 pneumatic controllers	20% of devices accounted for 96% of emissions.
Allen, Sullivan, et al. 2015	Gas Producing Wells	107 wells with liquids unloading	Without plunger lift, 20% of wells accounted for 83% of emissions; with plunger lift and manual, 20% of wells accounted for 65% of emissions; with plunger lift and automatic, 20% of wells accounted for 72% of emissions.

3.4 Conclusion

This comprehensive literature review has identified five major issues that need to be considered in order to improve the CH_4 emissions inventory for the oil and natural gas sector.

- First, the literature stresses the importance of an activity-based, component-level analysis. These methodologies meet the highest standards laid out by the IPCC and EPA.
- Second, this review has shown the importance of identifying appropriate EFs for the systems that are in place in the geographic region. EFs can vary significantly by region due to differences in gas pressure and gas composition, as well as equipment type, material, and age. Thus, using region-specific EFs provide the most accurate results.
- Third, geospatial allocation of emissions is important for planners and regulators to identify hotspots and to link emission inventories with chemical fate and transport and health models.
- Fourth, the literature demonstrates significant uncertainty in estimating emissions, stressing the need to incorporate uncertainty analysis into the emissions inventory methodology.
- Fifth, there is a clear and pressing need to consider high-emitting sources, their causes, and the role that they play in overall emission inventories.

The fact that the literature presents a large variability in inventory calculations further argues for the need to customize emission inventories for the State's geography and infrastructure. In addition, the information learned from this literature review can be used to inform similar reviews for other major sources of CH_4, including agriculture, landfills, waste water management, and wetlands.

4 Methane Emissions Inventory Development

4.1 Summary

This section contains a detailed accounting of the emissions inventory development methodology, informed by the assessment and literature review. Sources included in the inventory are listed in Table 11. For each source section, the section contains the following subsections: (1) a source category description, (2) a discussion of EFs, (3) a discussion on activity data, (4) geospatial data and any allocation methodologies, (5) sample calculations, (6) limitations and uncertainties, and (7) potential areas of improvement.

In addition, the general equation for emissions estimation is:

Equation 4 $E = A \times EF$

where:

- E = emissions
- A = activity
- EF = emissions factor

EFs in the published literature typically are averages of available data of acceptable quality and are assumed to represent long-term averages for similar facilities. However, variations among facilities, such as operational conditions and emission controls, can significantly affect emissions. Whenever possible, the development of local, source-specific EFs is highly desirable.

Table 11. Sources of CH_4 Emissions Included in the Improved New York State Inventory

Section	Category	Segment	Source
1	Upstream	Onshore Exploration	Drill Rigs
2	Upstream	Onshore Exploration	Fugitive Drilling Emissions
3	Upstream	Onshore Exploration	Oil Well: Mud Degassing
	Upstream	Onshore Exploration	Gas Well: Mud Degassing
4	Upstream	Onshore Exploration	Oil Well: Completions
	Upstream	Onshore Exploration	Gas Well: Completions
5	Upstream	Onshore Production	Oil Well: Conventional Production
	Upstream	Onshore Production	Gas Well: Conventional Production
	Upstream	Onshore Production	Oil Well: Unconventional Production

Table 11 continued

Section	Category	Segment	Source
	Upstream	Onshore Production	Gas Well: Unconventional Production
6	Upstream	Onshore Production	Oil: Abandoned Wells
	Upstream	Onshore Production	Gas: Abandoned Wells
7	Midstream	Gathering and Boosting	Oil: Gathering and Processing
	Midstream	Gathering and Boosting	Gas: Gathering and Processing
8	Midstream	Gathering and Boosting	Gathering Pipeline
9	Midstream	Crude Oil Transmission	Oil: Truck Loading
	Midstream	Natural Gas Transmission and Compression	Gas: Truck Loading
10	Midstream	Natural Gas Processing	Gas Processing Plant
11	Midstream	Natural Gas Transmission and Compression	Transmission Pipeline
12	Midstream	Natural Gas Transmission and Compression	Gas Transmission Compressor Stations
13	Midstream	Underground Natural Gas Storage	Gas Storage Compressor Stations
	Midstream	Underground Natural Gas Storage	Storage Reservoir Fugitives
14	Midstream	LNG Storage	LNG Storage Compressor Stations
15	Midstream	LNG Import/Export	LNG Terminal
16	Downstream	Natural Gas Distribution	Cast-Iron Distribution Pipeline: Main
	Downstream	Natural Gas Distribution	Cast-Iron Distribution Pipeline: Services
	Downstream	Natural Gas Distribution	Unprotected Steel Distribution Pipeline: Main
	Downstream	Natural Gas Distribution	Unprotected Steel Distribution Pipeline: Services
	Downstream	Natural Gas Distribution	Protected Steel Distribution Pipeline: Main
	Downstream	Natural Gas Distribution	Protected Steel Distribution Pipeline: Services
	Downstream	Natural Gas Distribution	Plastic Distribution Pipeline: Main
	Downstream	Natural Gas Distribution	Plastic Distribution Pipeline: Services
	Downstream	Natural Gas Distribution	Copper Distribution Pipeline: Main
	Downstream	Natural Gas Distribution	Copper Distribution Pipeline: Services
17	Downstream	Natural Gas Distribution	Meters

4.2 Emissions Factor Confidence

EFs used in this inventory are derived from a comprehensive search of the literature and selected based on expert judgment and best available data. In most cases, EFs are transferred from studies performed at sites outside of New York State, which have varying methodologies and are not all peer-reviewed. In addition, some of the EFs applied in this inventory are derived from empirical studies or engineering estimates performed well in the past and may not reflect current conditions in New York State. As such, it is important to describe the certainty of the EF in being applied to the State. In order to address EF certainty, this section outlines the four metrics used to evaluate the EF applied: geography, recency, study methodology, and publication status. Each metric is presented equally and independently with no judgments as to weighting of the four categories.

4.2.1 Geography

Geography is an important consideration when evaluating EFs. Selecting EFs that most closely reflect local conditions will result in the most robust estimates, as they are likely to share similar local environmental conditions and regulations, which can influence average EFs. As discussed in sections 2.5.3 and 3.3.5.2, site-level EFs show significant geographic variation varying from 0.4% of production in the Marcellus Basin, to 9.1% of production in the West Arkoma Basin, highlighting the need to select EFs that are as geographically local as possible.

New York State	**Marcellus/Appalachian Basin**	**Rest of the Country**

4.2.2 Recency

Many of the EFs employed in the EPA Oil and Gas Tool and SIT are derived from older studies, with some values originating from studies first published in 1977. The oil and natural gas sector has changed a good deal since that time, transitioning toward plastic pipelines with lower leak rates, and centrifugal compressors with greater throughput than reciprocating, and lower leak rates, among other changes to the sector. As such, it is important to use EFs that most closely reflect the current state of the industry when evaluating the inventory.

Study Age ≤ 5 Years	**5 > Study Age ≤ 15 Years**	**15 < Study Age**

4.2.3 Study Methodology

The EFs in this inventory are derived using a variety of methodologies. At their simplest, EF estimates are derived from engineering estimates, which take assumptions about equipment throughputs and leak rates to estimate EFs, in the absence of empirical observations. More sophisticated methodologies apply component- or site-level sampling methods to empirically observe emission rates. Empirical observations of EFs represent best available practices, as they reflect real-world operations and uncertainties that may not be captured by engineering estimates.

Empirical Observation	**Engineering Estimate**

4.2.4 Publication Status

EFs in this inventory are derived from two primary sources: grey and peer-reviewed literature. Grey literature estimates are typically from government publications and reports, which are prepared by experts and in many cases provide a wealth of information on clearly documented EFs, but do not undergo a formal external peer review. The second source of EFs is the peer-reviewed literature. These EFs are subject to peer-review prior to publication, indicating that they have been thoroughly vetted, are derived using robust scientific methodologies, and represent the best available data.

Peer-Reviewed	**Grey Literature**

4.2.5 Summary Table

Table A-1 summarizes the EF confidence assessment by CH_4 emissions source for EFs used in developing the improved New York State inventory.

Table 12. EF Confidence Assessment for EFs Used in the Improved New York State Inventory

Emissions Source	EF Low	EF Mid	EF High	EF Unit	Geography	Recency	Methodology	Status	Source
Drill Rigs	0.003	0.004	0.006	g/hp-hr	🟨	🟨	🟨	🟨	EPA NONROAD 2008 Model
Fugitive Drilling Emissions	-	0.0521	-	MTCH_4 well^{-1}	🟥	🟥	🟨	🟨	EPA 2018b, Annex 3.6-2
Oil Well: Mud Degassing	0.2605	0.324	0.38	MTCH_4 drillingday^{-1}	🟥	🟥	🟨	🟨	EPA Oil and Gas Tool
Gas Well: Mud Degassing	0.2605	0.324	0.38	MTCH_4 drillingday^{-1}	🟥	🟥	🟨	🟨	EPA Oil and Gas Tool
Oil Well: Completions	0.67	1.7	3.3	MTCH_4 completion^{-1}	🟨	🟦	🟦	🟦	Allen et al. (2013)
Gas Well: Completions	0.67	1.7	3.3	MTCH_4 completion^{-1}	🟨	🟦	🟦	🟦	Allen et al. (2013)
Oil Well: Conventional Production	9.4	25.4	60.7	% of throughput	🟨	🟦	🟦	🟦	≤ 10 MSCFD (top) > 10 MSCFD (bottom) Omara et al (2016)
	4.1	7.2	13.7						
Gas Well: Conventional Production	9.4	25.4	60.7	% of throughput	🟨	🟦	🟦	🟦	≤ 10 MSCFD (top) > 10 MSCFD (bottom) Omara et al (2016)
	4.1	7.2	13.7						
Oil Well: Unconventional Production	0.1	0.15	0.26	% of throughput	🟨	🟦	🟦	🟦	≤ 10,000 MSCFD (top) > 10,000 MSCFD (bottom) Omara et al (2016)
	0.018	0.03	0.178						
Gas Well: Unconventional Production	0.1	0.15	0.26	% of throughput	🟨	🟦	🟦	🟦	≤ 10,000 MSCFD (top) > 10,000 MSCFD (bottom) Omara et al (2016)
	0.018	0.03	0.178						

Table 12 continued

Emissions Source	EF			EF Unit	Geography	Recency	Methodology	Status	Source
	Low	Mid	High						
Oil: Abandoned Wells	0	0.09855	0.1971	MTCH$_4$ well^{-1} yr^{-1}	🟨	🟦	🟦	🟦	Kang et al. (2014)
Gas: Abandoned Wells	0	0.0878	0.196	MTCH$_4$ well^{-1} yr^{-1}	🟥	🟦	🟦	🟦	Townsend-Small et al. (2016)
Oil: Gathering and Processing	303.1	373.2	460.8	% of throughput	🟨	🟦	🟦	🟦	Marchese et al. (2015)
Gas: Gathering and Processing	303.1	373.2	460.8	MTCH$_4$ facility^{-1}-yr^{-1}	🟨	🟦	🟦	🟦	Marchese et al. (2015)
Gathering Pipeline	0.036	0.4	0.044	MTCH$_4$ mile^{-1} yr^{-1}	🟥	🟥	🟨	🟨	EPA SIT Natural Gas and Oil Module
Oil: Truck Loading	0	33.7	-	mg CH$_4$ L^{-1} crude oil	🟥	🟥	🟨	🟨	AP-42: Compilation of Air Emission Factors
Gas: Truck Loading	-	-	-	-	-	-	-	-	-
Gas Processing Plant	832.2	919.8	1,016.2	MTCH$_4$ plant^{-1} yr^{-1}	🟨	🟦	🟦	🟦	Marchese et al. (2015)
Transmission Pipeline	0.394	0.62	1.01	MTCH$_4$ mile^{-1} yr^{-1}	🟥	🟥	🟨	🟨	EPA SIT Natural Gas and Oil Module
Gas Transmission Compressor Stations	442.2	670	1,018.4	MTCH$_4$ station^{-1} yr^{-1}	🟨	🟦	🟦	🟦	Zimmerle et al. (2015)

Table 12 continued

Emissions Source	EF			EF Unit	Geography	Recency	Methodology	Status	Source
	Low	Mid	High						
Gas Storage Compressor Stations	550.6	847	1,295.1	MTCH$_4$ station^{-1} yr^{-1}	🟨	🟦	🟦	🟦	Zimmerle et al. (2015)
Storage Reservoir Fugitives	-	-	-	-	-	-	-	-	-
LNG Storage Compressor Stations	920	1,077.48	1,234.9	MTCH$_4$ facility^{-1} yr^{-1}	🟨	🟨	🟨	🟨	EPA 2016 GHG Inventory, Dr. A. Marchese
LNG Terminal	Not Applicable to New York State								
Cast-Iron Distribution Pipeline: Main	-	1.1573	4.5974	MTCH$_4$ mile^{-1} yr^{-1}	🟨	🟦	🟦	🟦	Lamb et al. 2015; EPA 2018b
Cast-Iron Distribution Pipeline: Services	-	1.1573	4.5974	MTCH$_4$ mile^{-1} yr^{-1}	🟨	🟦	🟦	🟦	Lamb et al. 2015; EPA 2018b
Unprotected Steel Distribution Pipeline: Main	-	0.8613	2.1223	MTCH$_4$ mile^{-1} yr^{-1}	🟨	🟦	🟦	🟦	Lamb et al. 2015; EPA 2018b
Unprotected Steel Distribution Pipeline: Services	-	0.0145	0.0328	MTCH$_4$ mile^{-1} yr^{-1}	🟨	🟦	🟦	🟦	Lamb et al. 2015; EPA 2018b

Table 12 continued

Emissions Source	EF			EF Unit	Geography	Recency	Methodology	Status	Source
	Low	Mid	High						
Protected Steel Distribution Pipeline: Main	-	0.0967	0.0967	MTCH$_4$ mile^{-1} yr^{-1}	🟨	🟦	🟦	🟦	Lamb et al. 2015; EPA 2018b
Protected Steel Distribution Pipeline: Services	-	0.0013	0.0034	MTCH$_4$ mile^{-1} yr^{-1}	🟨	🟦	🟦	🟦	Lamb et al. 2015; EPA 2018b
Plastic Distribution Pipeline: Main	-	0.0288	0.1909	MTCH$_4$ mile^{-1} yr^{-1}	🟨	🟦	🟦	🟦	Lamb et al. 2015; EPA 2018b
Plastic Distribution Pipeline: Services	-	0.0003	0.0003	MTCH$_4$ mile^{-1} yr^{-1}	🟨	🟦	🟦	🟦	Lamb et al. 2015; EPA 2018b
Copper Distribution Pipeline: Main	-	-	-	-	-	-	-	-	-
Copper Distribution Pipeline: Services	-	0.0049	0.0049	MTCH$_4$ mile^{-1} yr^{-1}	🟨	🟦	🟦	🟦	Lamb et al. 2015; EPA 2018b
Meters: Residential	-	0.0015	-	MTCH$_4$ meter^{-1} yr^{-1}	🟥	🟨	🟦	🟨	EPA 2018b, Annex 3.6-2
Meters: Commercial	-	0.0097	-	MTCH$_4$ meter^{-1} yr^{-1}	🟥	🟨	🟦	🟨	EPA 2018b, Annex 3.6-2

4.3 Activity Data Summary

Presented in Table 13 are activity data descriptions and data sources by emissions source, along with flags for whether activity data were based on assumptions, whether an allocation method was applied to obtain county-level activity, and whether data cleansings were performed to remove suspected outliers.

Table 13. Activity Data Summary for Activity Data Used in the Improved New York State Inventory

Emissions Source	Activity Data Description	Activity Data Based on Assumption	Allocation Method Applied	Data Cleansing Performed	Source
Drill Rigs	Drilling days	X		X	ESOGIS 2018
Fugitive Drilling Emissions	Count of well completions				ESOGIS 2018
Oil Well: Mud Degassing	Drilling days for oil wells	X		X	ESOGIS 2018
Gas Well: Mud Degassing	Drilling days for gas wells	X		X	ESOGIS 2018
Oil Well: Completions	Count of oil well completions				ESOGIS 2018
Gas Well: Completions	Count of gas well completions				ESOGIS 2018
Oil Well: Conventional Production	Mcf of associated gas production				ESOGIS 2018
Gas Well: Conventional Production	Mcf of gas production				ESOGIS 2018
Oil Well: Unconventional Production	Mcf of associated gas production	No activity in New York State			
Gas Well: Unconventional Production	Mcf of gas production	No activity in New York State			
Gas: Abandoned Wells	Count of abandoned gas wells				ESOGIS 2018
Oil: Abandoned Wells	Count of abandoned oil wells	X			ESOGIS 2018

Table 13 continued

Emissions Source	Activity Data Description	Activity Data Based on Assumption	Allocation Method Applied	Data Cleansing Performed	Source
Oil: Gathering and Processing	Mcf of associated gas production				ESOGIS 2018
Gas: Gathering and Processing	Mcf of natural gas production				ESOGIS 2018
Gathering Pipeline	Miles of pipeline	X	X		PHMSA 2018
Oil: Truck Loading	Bbls of crude oil loaded into trucks		X	X	ESOGIS 2018, EIA 2019a
Gas: Truck Loading	Mcf of gas loaded into trucks	No activity in New York State			
Gas Processing Plant	Count of gas processing plants	No activity in New York State			
Transmission Pipeline	Miles of pipeline		X	X	PHMSA 2018
Gas Transmission Compressor Stations	Count of gas transmission compressor stations	X			PHMSA 2018, DEC permitting database
Gas Storage Compressor Stations	Count of gas storage compressor stations				DEC permitting database, EIA 2019b
Storage Reservoir Fugitives	TBD—no data available				
LNG Storage Compressor Stations	Count of LNG Storage Compressor Stations				DEC database
LNG Terminal	Count of terminals	No activity in New York State			
Cast-Iron Distribution Pipeline: Main	Miles of pipeline		X	X	PHMSA 2018

Table 13 continued

Emissions Source	Activity Data Description	Activity Data Based on Assumption	Allocation Method Applied	Data Cleansing Performed	Source
Cast-Iron Distribution Pipeline: Services	Miles of pipeline		X	X	PHMSA 2018
Unprotected Steel Distribution Pipeline: Main	Miles of pipeline		X		PHMSA 2018
Unprotected Steel Distribution Pipeline: Services	Miles of pipeline		X	X	PHMSA 2018
Protected Steel Distribution Pipeline: Main	Miles of pipeline		X	X	PHMSA 2018
Protected Steel Distribution Pipeline: Services	Miles of pipeline		X	X	PHMSA 2018
Plastic Distribution Pipeline: Main	Miles of pipeline		X		PHMSA 2018
Plastic Distribution Pipeline: Services	Miles of pipeline		X		PHMSA 2018
Copper Distribution Pipeline: Main	Miles of pipeline	No activity in New York State			
Copper Distribution Pipeline: Services	Miles of pipeline		X	X	PHMSA 2018
Meters: Residential	Count of services		X		PHMSA 2018
Meters: Commercial	Count of services		X		PHMSA 2018

4.4 Upstream Stages

4.4.1 Drill Rigs

4.4.1.1 Source Category Description

Drill rigs are machines used to drill holes in the Earth's crust for oil wells and natural gas extraction wells, among other types of wells. They can be massive or small to medium-sized structures. Factors influencing the size and type of rig are whether or not directional drilling is being performed, the size of the operation, the anticipated length and intensity of the operation, and the depth and range of the well. The small to medium-sized rigs are also called mobile rigs as they are mounted on trucks or trailers and can be easily transferred from one location to another. There are two primary rig types: mechanical and diesel-electric. Some of the major components of drill rigs are mud tanks, mud pumps, a derrick, a rotary table, a drill string, draw works, and primary and auxiliary power equipment. CH_4 emissions from drill rigs occur from on-site power generation and are correlated to cumulative feet drilled.

4.4.1.2 Emission Factors

<table>
<tr><th>Drill Rig Engine Power (hp)</th><td colspan="4">300 to 600</td><td colspan="4">600 to 750</td><td colspan="4">750 to 3000</td></tr>
<tr><th>Default EF (g/hp-hr)</th><td colspan="4">0.004</td><td colspan="4">0.003</td><td colspan="4">0.006</td></tr>
<tr><th>EF Source</th><td colspan="12">EPA NONROAD2008 Model</td></tr>
<tr><th>EF Confidence</th><td colspan="3">Geography
Marcellus/
Appalachian Basin</td><td colspan="3">Recency
5-15 Years</td><td colspan="3">Methodology
Engineering Estimate</td><td colspan="3">Status
Grey Literature</td></tr>
<tr><th>EF Source Description</th><td colspan="12">This is the default EF from the EPA Oil and Gas Tool, which in turn is based on data from the CenSARA (2012) study. The CenSARA study domain covers basins in Texas, Louisiana, Oklahoma, Arkansas, Nebraska, Kansas, and Missouri. The CenSARA study estimated emissions from drill rigs based on an engineering calculation factoring in hp; EF; load; hours of operation; and the number of draw works, mud pumps, and generator engines. The EF is described as the average EF from the EPA NONROAD2008 model. Drill rig EFs derived from EPA's NONROAD2008 model have been widely applied to state-level emission inventories and represent a comprehensive source of drill rig emission estimates.</td></tr>
</table>

4.4.1.3 Activity Data

In calculating activity data for drilling rigs, the approach does not distinguish between oil- and gas-directed rigs because once a well is completed it may produce both oil and gas. The activity data, calculated as drilling days, were derived from the Empire State Organized Geologic Information System (ESOGIS). This database contains information on all wells in New York State, including county location, well type, spud date, and completion date. The number of drilling days per well was calculated as the completion date minus the spud date for all well types, including “gas development,” “gas wildcat,” “gas extension,” “dry wildcat,” “dry hole,” “monitoring storage,” “storage,” “oil development,” “oil extension,” “oil wildcat,” and “enhanced oil recovery-injection.” To correct for outliers, if the calculated drilling days exceeded 50 for a given well, the drilling days for that well were set to 22. The average drilling time of 22 days is based on an assessment of peer-reviewed literature, such as Roy et al. (2014), and engineering judgment based on the specific characteristics of New York State geological formations. Once well-level drilling days were calculated for each well, the drilling days were summed to the county level.

Since the EFs (discussed in section 4.4.1.2) are based on horsepower hour (hp-hr), information on the average engine size of 402 hp was pulled from EPA’s Oil and Gas Tool. The average in the tool is based on the CenSARA study (2012) for diesel-vertical drill rig engines. The hp-hr was calculated by multiplying the number of drilling days by 24 hours per day times the average engine horsepower.

The CH_4 emissions were converted from grams to MTs using a conversion factor of $1e^{-6}$. The MTs of CH_4 were converted to $MTCO_2e$ by applying the $GWP_{AR4,100}$ factor of 25.

4.4.1.4 Geospatial Data and Allocation Methodology

No allocation methodology was necessary since the ESOGIS database contains information at the well level for all analysis years.

4.4.1.5 Sample Calculations

Equation 5 CH_4 **emissions (**$MTCO_2e$**) = DD x 24 hr/day x hp x EF x CF x** $GWP_{AR4,100}$

where:

- DD = drilling days
- hp = average horsepower of drill rig engine = 402
- EF = CH_4 EF (g/hp-hr) = 0.004
- CF = conversion factor from g to MTs = $1e^{-6}$
- $GWP_{AR4,100}$ = GWP = 25

For example, there were 3,974 days of drilling in Cattaraugus County in 2010, resulting in 3.83 $MTCO_2e$:

Drill rig CH_4 **(**$MTCO_2e$**) = 3,974 x 24 hr/day x 402 x 0.004 x** $1e^{-6}$ **x 25**
Drill rig CH_4 **(**$MTCO_2e$**) = 3.83** $MTCO_2e$

4.4.1.6 Limitations and Uncertainties

The CenSARA study applies EFs derived for EPA's NONROAD2008 model, which in turn updates the NONROAD2005 model, including no substantive changes for drill rigs. As a result, these EFs are derived from data that are over a decade old. Although the CenSARA study and NONROAD models are not New York State-specific, dill rig engine EFs are unlikely to vary across states. Drill rig engine hp is likely to show the greatest regional variation.

4.4.1.7 Potential Areas of Improvement

This inventory applies an average drill rig engine power of 402 hp, derived from the EPA Oil and Gas Tool and based on the CenSARA study. This value could be updated to better reflect New York State given better information on the sizes, loads, and primary engine types. In addition, as noted, these EFs, used widely in the EPA Oil and Gas Tool, are over a decade old and may need updating.

4.4.2 Fugitive Drilling Emissions

4.4.2.1 Source Category Description

The first step in completing a well is to case the hole. Casing ensures that the well will not close after removal of drilling fluids and protects the well stream from outside incumbents like water or sand. The next step in well completion involves cementing the well, which includes pumping cement slurry into the well to displace existing drilling fluids and filling in the space between the casing and the actual sides of the drilled well. At the reservoir level, there are two types of completion methods used on wells: open- or cased-hole completions. An open-hole completion refers to a well that is drilled to the top of the hydrocarbon reservoir. The well is then cased at this level and left open at the bottom. Cased-hole completions require casing to be run in to the reservoir. In order to achieve production, the casing and cement are perforated to allow the hydrocarbons to enter the well stream.

4.4.2.2 Emission Factors

Source Category	Fugitive drilling emissions			
Default EF ($MTCH_4$ $well^{-1}$)	0.0521			
Source	EPA 2018b, Annex 3.6-2			
EF Confidence	Geography Rest of the Country	Recency 15+ years	Methodology Engineering Estimate	Status Grey Literature
EF Source Description	This EF is provided by EPA's 2018 Greenhouse Gas Emission Inventory (EPA 2018a), and is in turn derived from the 1992 Radian/API report, "Global Emissions of Methane from Petroleum Sources." API Report No. DR140.			

4.4.2.3 Activity Data

In calculating activity data for drilling rigs, the approach does not distinguish between oil- and gas-directed rigs because once a well is completed it may produce both oil and gas. The activity data, calculated as the count of well completions, were derived from the ESOGIS. This database contains information on all wells in New York State, including county location, well type, and completion date. The number of well completions is based on the reported well completion date for well types including "gas development," "gas wildcat," "gas extension," "dry wildcat," "dry hole," "monitoring storage," "storage," "oil development," "oil extension," "oil wildcat," and "enhanced oil recovery-injection." The number of well completions were summed by year of completion to the county level.

4.4.2.4 Geospatial Data and Allocation Methodology

No allocation methodology was necessary since the ESOGIS database contains information at the well level for all analysis years.

4.4.2.5 Sample Calculations

Equation 6 CH_4 **emissions** ($MTCO_2e$) **= well completions x EF x CF x** $GWP_{AR4, 100}$

where:

- Well completions = count of well completions
- EF = CH_4 EF ($MTCH_4$ $well^{-1}$) = 0.0521
- $GWP_{AR4, 100}$ = GWP = 25

For example, there were 151 well completions in Cattaraugus County in 2010, resulting in 3.83 $MTCO_2e$:

Fugitive drilling CH_4 ($MTCO_2e$) = 151 x 0.0521 x 25
Fugitive drilling CH_4 ($MTCO_2e$) = 196.7 $MTCO_2e$

4.4.2.6 Limitations and Uncertainties

The EF for fugitive emissions from well drilling is taken from an older study, which may not reflect current best practices for CH_4 capture during drilling. In addition, the study might not reflect likely borehole conditions for New York State, which may be subject to different pressures and porosity than those conditions in the study.

4.4.2.7 Potential Areas of Improvement

This estimate may be improved by updating the EF based on empirical study of fugitives during drilling operations in the Northeast or Appalachian Basin and would be best tailored to New York State if the drilling observations were taken in the State.

4.4.3 Mud Degassing

4.4.3.1 Source Category Description

Drilling mud is the liquid added to the wellbore to facilitate the drilling process by suspending cuttings, controlling pressure, stabilizing exposed rock, providing buoyancy and cooling, and lubricating the drill bit. Drilling fluids can be water-, oil-, or synthetic-based. Drilling fluids are used as a suspension tool to keep cuttings from refilling the borehole and to control pressure in a well by providing hydrostatic pressure to offset the pressure of the hydrocarbons and the rock formations. Weighing agents are added to the drilling fluids to increase their density and, therefore, their pressure on the well walls. Another important function of drilling fluid is rock stabilization. Special additives are used to ensure that the drilling fluid is not absorbed by the rock formation in the well and that the pores of the rock formation are not clogged. The deeper the well, the more drill pipe is needed to drill the well. This amount of drill pipe gets heavy, and the drilling fluid adds buoyancy, which reduces stress. Additionally, drilling fluid helps to reduce heat by minimizing friction with the rock formation. The lubrication and cooling prolong the life of the drill bit.

Mud degassing refers to the removal of air or gases such as CH_4, hydrogen sulfide (H_2S), and CO_2 in the drilling mud once it is outside of the wellbore. The major source of CH_4 is the release of entrained natural gas from the drilling mud.

4.4.3.2 Emission Factors

<table>
<tr><th>Source Category</th><td colspan="4">Mud Degassing: Gas and Oil wells</td></tr>
<tr><th>Default EF (MTCH$_4$ drillingday^{-1})</th><td colspan="4">0.2605</td></tr>
<tr><th>Source</th><td colspan="4">EPA Oil and Gas Tool</td></tr>
<tr><th>EF Confidence</th><td>Geography
Rest of the Country</td><td>Recency
15 + Years</td><td>Methodology
Engineering Estimate</td><td>Status
Grey Literature</td></tr>
<tr><th>Source Description</th><td colspan="4">This is the default EF from the EPA Oil and Gas Tool, which is in turn based on data from the CenSARA (2012) study. The CenSARA study domain covers basins in Texas, Louisiana, Oklahoma, Arkansas, Nebraska, Kansas, and Missouri. The CenSARA study derives default EFs from the Bureau of Ocean Energy Management's (BOEM's) inventory of emissions in the Gulf of Mexico (Wilson et al., 2007), which is in turn based on the 1977 EPA report, Atmospheric Emissions from Offshore Oil and Gas Development and Production, which states that BOEM were unable to find sources of the data, but estimates total gaseous hydrocarbon emissions to be 0.4 Mg.d^{-1} based on engineering calculations, factoring in bore depth and diameter, porosity, and pressure. This EF, though derived from older engineering estimates, has been widely applied to national and state-level emission inventories, and communication with experts indicates that no more recent estimates are available.</td></tr>
</table>

4.4.3.3 Activity Data

The activity data, calculated as drilling days, were derived from ESOGIS. This database contains information on all wells in New York State, including county location, well type, spud date, and completion date. The number of drilling days per well was calculated as the completion date minus the spud date. For the estimate of oil well drilling days, the well types included were “oil development,” “oil extension,” “oil wildcat,” and “enhanced oil recovery-injection.” For the estimate of natural gas well drilling days, the well types included were “gas development,” “gas extension,” “gas wildcat,” “dry wildcat,” “dry hole,” “monitoring storage,” and “storage.” To correct for outliers, if the calculated drilling days exceeded 50 for a given well, the drilling days for that well were set to 22. The average drilling time of 22 days is based on an assessment of peer-reviewed literature, such as Roy et al. (2014), and engineering judgment is based on the observed drilling days in the New York State well data. Once well-level drilling days were calculated for each well, the drilling days were summed to the county level.

CH$_4$ emissions were calculated as the total drilling days times the EF discussed in section 4.4.3.2. The MTs of CH$_4$ were converted to MTCO$_2$e by applying the GWP$_{\text{AR4, 100}}$ factor of 25.

4.4.3.4 Geospatial Data and Allocation Methodology

No allocation methodology was necessary since the ESOGIS database has information at the well level for all analysis years.

4.4.3.5 Sample Calculations

Equation 7 **CH_4 emissions ($MTCO_2e$) = DD x EF x $GWP_{AR4,100}$**

where:

- DD = drilling days
- EF = CH_4 EF ($MTCH_4$ $drillingday^{-1}$) = 0.2605
- $GWP_{AR4,100}$ = GWP = 25

For example, there were 230 days of natural gas well drilling in Cattaraugus County in 2010, resulting in 1,498 $MTCO_2e$:

Mud degassing CH_4 ($MTCO_2e$) = 230 x 0.2605 x 25
Mud degassing CH_4 ($MTCO_2e$) = 1,498 $MTCO_2e$

4.4.3.6 Limitations and Uncertainties

The EF for mud degassing is based on a best guess, specific to offshore oil and gas development, from 1977 data. The limitations and uncertainty of applying this estimate involve appropriateness for application to onshore formations, bore diameters and depths in use in New York State, as well as porosity and reservoir pressures. Uncertainty in these calculations is a function of the CH_4 fraction of total hydrocarbon emissions from mud degassing, which is modeled as 65% on the lower bound, 81% for the central estimate, and 95% for the upper bound.

4.4.3.7 Potential Areas of Improvement

The mud degassing EF may be improved by tailoring the estimate of total gaseous hydrocarbon emissions to New York State-specific bore depths and diameters, as well as reservoir porosity, pressures, and CH_4 fraction of total gaseous hydrocarbons.

4.4.3.8 Well Completion Source Category Description

Well completion is the process of making an oil or natural gas well ready for production. After casing and cementing during well drilling, the completion phase starts with perforation through the production formation, followed by any treatment such as acidizing or fracturing. The last step in completing a well is to install a wellhead at the surface of the well. Often called a production tree or Christmas tree, the wellhead device includes casingheads and a tubing head combined to provide surface control of well subsurface conditions. The main source of CH_4 emissions from the completion phase occurs during the flowback period following fracturing.

4.4.3.9 Emission Factors

Source Category	Well Completions: Gas and Oil Wells			
Default EF ($MTCH_4$ completion^{-1})	1.7			
Source	Allen et al. 2013			
EF Confidence	Geography Marcellus/ Appalachian Basin	Recency ≤ 5 Years	Methodology Empirical Observation	Status Peer-Reviewed
Source Description	Allen et al. (2013) analyzed well completion flowback events at 190 onshore natural gas sites in the United States. Measured values over the completion event varied from 0.01 Mg CH_4 to 17 MgCH_4, with a mean of 1.7 MgCH_4 emitted per event (95% CI 0.67-3.3 MgCH_4 per well completion). Emissions were estimated over 27 events using direct measurements at the flowback tank as well as tracer-ratio measurements to produce site-level EFs. This study is peer-reviewed, widely cited, and presents empirical data from observations of Appalachian well completions.			

4.4.3.10 Activity Data

The activity data, calculated as number of wells, were derived from ESOGIS. This database contains information on all wells in New York State, including county location, well type, and completion date. To estimate the number of wells, the count of wells by county and year was based on type. For oil wells, the well types included were "oil development," "oil wildcat," "oil extension," and "enhanced oil recovery," and for gas wells, the well types included were "gas development," "gas wildcat," "gas extension," "gas wildcat," "dry hole," "monitoring storage," and "storage."

CH_4 emissions were calculated as the well count times the EF discussed in section 4.4.4.2. MTs of CH_4 were converted to $MTCO_2e$ by applying the $GWP_{AR4,100}$ factor of 25.

4.4.3.11 Geospatial Data and Allocation Methodology

No allocation methodology was necessary since the ESOGIS database has information at the well level for all analysis years.

4.4.3.12 Sample Calculations

Equation 8 **CH_4 emissions ($MTCO_2e$) = well count x EF x $GWP_{AR4,100}$**

where:

- well count = number of wells
- EF = CH_4 EF ($MTCH_4$ completion^{-1}) = 1.7
- $GWP_{AR4,100}$ = GWP = 25

For example, there were seven natural gas well completions in Cattaraugus County in 2010, resulting in 298 $MTCO_2e$:

$$\textbf{Natural gas well completion } CH_4\ (MTCO_2e) = 7 \times 1.7 \times 25$$
$$\textbf{Natural gas well completion } CH_4\ (MTCO_2e) = 298\ MTCO_2e$$

4.4.3.13 Limitations and Uncertainties

The primary source of uncertainty in this EF results from a limited sample size. The mean value is estimated based on measurements from five completion flowbacks in the Appalachian region, seven in the Gulf region, five in the mid-continent, and 10 in the Rocky Mountain region. Well completion flowback duration was also shown to affect the magnitude of emissions per well completion.

4.4.3.14 Potential Areas of Improvement

The central estimate for emissions per well completion flowback event is derived from a rigorous peer-reviewed study of well completions around the country. Hourly rates of CH_4 emissions varied widely, indicating the importance of estimating uncertainty using 95% confidence intervals (CI). In addition, this estimate may be improved by estimating emissions at New York State wells during completion, as a large portion of the wells observed were hydraulically fractured.

4.4.4 Conventional Production

4.4.4.1 Source Category Description

The production of conventional oil and gas applies to oil and gas extracted by the natural pressure of the wells after the drilling operations. Unconventional resources require pumping or compression operations to liberate resources from formations where the borehole pressure is too low. After the depletion of maturing fields, the natural pressure of the wells may be too low to produce significant quantities of oil and gas. Different techniques may be used to boost production, mainly water and gas injection or depletion compression, but these oil and gas fields will still be conventional resources. Beyond the use of classical methods of enhanced oil recovery or artificial lift, the oil and gas production is classified as unconventional. There is no unconventional oil and gas production in New York State.

4.4.4.2 Emission Factors

Source Category	Oil Well: Conventional Production	Oil Well: Unconventional Production	Gas Well: Conventional Production	Gas Well: Unconventional Production
Default EF (% of production)	≤ 10 MSCFD: 9.4% > 10 MSCFD: 4.1%	≤ 10,000 MSCFD: 0.1% > 10,000 MSCFD: 0.018%	≤ 10 MSCFD: 9.4% > 10 MSCFD: 4.1%	≤ 10,000 MSCFD: 0.1% > 10,000 MSCFD: 0.018%
Source	Omara, Sullivan, Li, Subramanian, et al. 2016			
EF Confidence	Geography Marcellus/ Appalachian Basin	Recency ≤ 5 years	Methodology Empirical Observation	Status Peer-Reviewed
Source Description	Omara et al., 2016 measured facility-level emissions, comparing conventional and unconventional natural gas sites in West Virginia and Pennsylvania. The range of emissions estimates over the 18 conventional and 13 unconventional sites varied widely, with unconventional sites generally producing much more natural gas, but having lower emission rates relative to production. The 25th percentile and 75th percentile represent the upper and lower bounds for uncertainty analysis. The lower bound EFs are presented in this table and used in the New York State inventory.			

4.4.4.3 Activity Data

The activity data, calculated as volume of associated gas production from oil wells and the natural gas production from natural gas wells, were derived from ESOGIS. This database contains information on all wells in New York State, including county location, well type, and the volume of natural gas produced by year. To estimate the quantity of natural gas produced, the volume produced by county and year was based on well type and well status. For oil wells, the well type included “oil development,” “oil extension,” and “enhanced oil recovery-injection,” and the well status included “active,” “drilled deeper,” “drilling completed,” “plugged back,” and “plugged back multilateral.” For natural gas wells, the well type included “gas development,” “gas extension,” and “gas wildcat,” and the well status included “active,” “drilled deeper,” “drilling completed,” “plugged back,” and “plugged back multilateral.” Once wells were identified in the ESOGIS database as producing associate gas or natural gas, the wells were binned into low-producing (≤ 10 MSCFD for gas wells and ≤ 10,000 MSCFD for oil wells) and high-producing wells (>10 MSCFD for gas wells and >10,000 MSCFD for oil wells).

CH_4 emissions were calculated for each category of well production as the volume of natural gas production converted from volume to mass using the ideal gas law times the EFs discussed in section 4.4.5.2. MTs of CH_4 were converted to $MTCO_2e$ by applying the $GWP_{AR4,\,100}$ factor of 25.

4.4.4.4 Geospatial Data and Allocation Methodology

No allocation methodology was necessary since the ESOGIS database has information at the well level for all analysis years.

4.4.4.5 Sample Calculations

Equation 9 CH_4 emissions ($MTCO_2e$) = production x CF x EF x $GWP_{AR4, 100}$

where:

- production = volume of natural gas produced (Mcf)
- CF = conversion from Mcf to MTs = [(CH_4 molecular weight / ideal gas law conversion factor)/2,000] x 1,000 cf/Mcf x 0.907185 MTs/short ton
- CF = (1000 x 16.043/379.3)/2000 x 0.907185 = 0.019185 MTs/Mcf
- EF = CH_4 EF (fraction of production) = 0.094 for low producing natural gas wells
- $GWP_{AR4, 100}$ = GWP = 25

For example, there were 499,629 Mcf of natural gas produced from low producing natural gas wells in Cattaraugus County in 2010, resulting in 22,526 $MTCO_2e$ as shown:

Low producing conventional gas well CH_4 ($MTCO_2e$) = 499,629 x 0.019185 x 0.094 x 25
Low producing conventional gas well CH_4 ($MTCO_2e$) = 22,526 $MTCO_2e$

4.4.4.6 Limitations and Uncertainties

Omara et al. (2016) show significant differences in emissions between conventional emissions and emissions from high-volume hydraulic fracturing in shale gas formations. Furthermore, these estimates indicate that natural gas production is an important component of emission estimation. The sample size for conventional and unconventional wells is small, and thus uncertainty around the central estimates would be improved by increasing the sample.

4.4.4.7 Potential Areas of Improvement

These EFs are derived from a broad population but are not New York State-specific. As such, while these estimates may encompass the State EFs, further study of New York State wells would be necessary to determine State-specific estimates of production emissions.

4.4.5 Abandoned Wells

4.4.5.1 Source Category Description

When a well is finished producing, it is typically abandoned. Abandoned wells may be either plugged or orphaned—and thereby not plugged. Plugging and abandoning the well can take various forms. Each state has specific requirements that govern well abandonment. In New York State, regulations require that certain wells are plugged once operations cease. Plugs are strategically placed to prevent migration of residual oil and gas to other zones, aquifers, or to the surface. Sometimes, when CO_2 has been used for enhanced secondary or tertiary recovery, part of the abandonment procedure involves blowing down the well to release any existing pressure. If this is done, large amounts of gas could be released into the atmosphere. After abandonment, some wells can continue to emit CH_4.

4.4.5.2 Emission Factors

Source Category	Oil: Abandoned Wells			
Default EF **($MTCH_4$ well^{-1} yr^{-1})**	0.09855			
Source	Kang et al. 2014			
EF Confidence	Geography Marcellus/ Appalachian Basin	Recency ≤ 5 Years	Methodology Empirical Observation	Status Peer-Reviewed
Source Description	Kang et al. (2014) measured CH_4 emissions from abandoned oil and gas wells in Pennsylvania. Mean emissions were 0.27 kg well-1 day-1 or 0.09855 $MTCH_4$ well-1 yr-1. A static flux chamber methodology was used to measure gaseous emissions from abandoned wellheads and surrounding soil-plant systems, as well as for controls containing no wellhead. This widely cited, peer-reviewed study provides recent EF estimates, derived using empirical observations from abandoned oil and gas wells in two Pennsylvania counties that border New York State.			

Emission Factors continued

Source Category	Gas: Abandoned Wells			
Default EF ($MTCH_4$ $well^{-1}$ yr^{-1})	0.0878			
Source	Townsend-Small et al. 2016			
EF Confidence	Geography Rest of the Country	Recency ≤ 5 Years	Methodology Empirical Observation	Status Peer-Reviewed
Source Description	Townsend-Small et al. (2016) measured CH_4 emissions from 138 abandoned oil and gas wells in Wyoming, Colorado, Utah, and Ohio. Of the plugged wells, 6.5% had measurable emissions. Mean emissions for all wells (plugged and unplugged) were 10.02 g well-1 hr-1, which translates to 0.0878 $MTCH_4$ well-1 yr-1. Emissions from pressurized and leaking wellhead components were measured using a high-flow sampler, while emissions from underground and smaller leaks were measured using the static flux chamber method. This study provides recent, peer-reviewed, empirically observed CH_4 emission rates from a population of 138 abandoned oil and gas wells.			

4.4.5.3 Activity Data

Activity data, calculated as the number of abandoned wells, were derived from ESOGIS. This database contains information on all wells in New York State, including county location, well type, and well status. To estimate the number of abandoned wells, the count of wells by county and year was based on well type and well status. For oil wells, the well type included “oil development,” “oil extension,” “oil wildcat,” and “enhanced oil recovery-injection,” and the well status included “Inactive,” “Not Reported on AWR,” “Shut-In,” “Temporarily Abandoned,” and “Unknown.” For natural gas wells, the well type included “Dry Hole,” “Dry Wildcat,” “Gas Development,” “Gas Extension,” “Gas Wildcat,” “monitoring storage,” and “storage,” and the well status included “Inactive,” “Not Reported on AWR,” “Shut-In,” “Temporarily Abandoned,” and “Unknown.”

To correct for missing data in the ESOGIS database, the number of abandoned oil wells for years 1990 to 1999 were set equal to the number of abandoned oil wells in year 2000.

CH_4 emissions were calculated as the well count times the EFs discussed in section 4.4.6.2. The MTs of CH_4 were converted to $MTCO_2e$ by applying the $GWP_{AR4,\,100}$ factor of 25.

4.4.5.4 Geospatial Data and Allocation Methodology

No allocation methodology was necessary since the ESOGIS database has information at the well level for all analysis years.

4.4.5.5 Sample Calculations

Equation 10 CH_4 **emissions** ($MTCO_2e$) **= well count x EF x** $GWP_{AR4,\,100}$

where:

- well count = number of wells
- EF = CH_4 EF ($MTCH_4$ abandoned $well^{-1}$ yr^{-1})
- $GWP_{AR4,\,100}$ = GWP = 25

For example, there were 59 abandoned natural gas wells in Cattaraugus County in 2010, resulting in 129.5 $MTCO_2e$ as shown:

Abandoned natural gas well CH_4 ($MTCO_2e$) **= 59 x 0.0878 x 25**
Abandoned natural gas well CH_4 ($MTCO_2e$) **= 129.5** $MTCO_2e$

4.4.5.6 Limitations and Uncertainties

Both Kang et al. (2014) and Townsend-Small et al. (2016) sampled a relatively small number of oil and gas wells. Given available information, Kang et al. (2014) were unable to distinguish between oil and gas wells, nor did they find a significant difference between plugged and abandoned or orphaned wellheads. Townsend-Small et al. (2016) additionally stress the importance of accounting for regional differences in CH_4 emissions from abandoned and plugged well sites.

4.4.5.7 Potential Areas of Improvement

Following advice presented in the studies from which these EFs were derived, the EFs should be better tailored to oil or natural gas wells, which were poorly identified in the literature, and in New York State are shown to not be distinctive from one another in many instances. In addition, due to differences between New York State and Pennsylvania drilling practices, the EF estimates given here may be improved by employing New York State-specific sampling and measurements.

In addition, abandoned wells, as defined, should not include shut-in or temporarily abandoned because these status types are applied to idle producing wells. They are included as abandoned wells in this inventory since data on EFs for idle producing wells did not exist in the research literature. The inclusion of the idle wells in the abandoned well source category is relatively insignificant to overall oil and natural gas sector emissions, accounting for less than 0.002% of total emissions.

4.5 Midstream Stages

4.5.1 Gathering Compressor Stations

4.5.1.1 Source Category Description

Gathering and processing encompasses all operations between the well site delivery meter and the receipt meter to the transmission segment or local distribution. Systems include gathering pipelines, gathering facilities, and processing plants; equipment includes gathering pipelines, separators, compressors, acid gas removal units, dehydrators, pneumatic devices/pumps, storage vessels, engines, boilers, heaters, and flares. Gathering compressor stations collect oil or natural gas from multiple wells, compress it and discharge it to another location (i.e., another gathering facility, transmission line, or processing plant). Gathering compressor stations often include inlet separators to remove water and/or hydrocarbon condensate, dehydration systems to remove gaseous H_2O, and amine treatment systems. Processing plants often include the same operations but also include systems to remove ethane and/or LNG.

4.5.1.2 Emission Factors

Source Category	Natural Gas Gathering Compressor Stations			
Default EF (% of production)	0.4			
Source	Marchese et al. 2015			
EF Confidence	Geography Marcellus/ Appalachian Basin	Recency ≤ 5 Years	Methodology Empirical Observation	Status Peer-Reviewed
Source Description	Marchese et al (2015) studied CH_4 emissions at 114 gathering facilities in the United States using downwind tracer flux methodology. Emission rates varied widely, from 2 to 600 kg h^{-1}, corresponding to normalized emission rates of 0.4% of throughput, or 42.6 kg CH_4 facility^{-1} hr^{-1}. This peer-reviewed study includes emissions estimates from sites in states adjacent to New York State, providing empirically observed regional emissions estimates from gathering and processing facilities, and is validated by results from Mitchell et al. (2015), who found CH_4 emissions of 0.2% of throughput in Pennsylvania gathering facilities.			

4.5.1.3 Activity Data

Throughput was assumed to be equal to production. As such, activity data, calculated as volume of associated gas production from oil wells and the natural gas production from natural gas wells, were derived from ESOGIS. This database contains information on all wells in New York State, including county location, well type, and the volume of natural gas produced by year. To estimate the quantity of natural gas produced, the volume produced by county and year was based on well type and well status. For oil wells, the well type included "oil development," "oil extension," and "enhanced oil recovery-injection," and the well status included "active," "drilled deeper," "drilling completed," "plugged back," and "plugged back multilateral." For natural gas wells, the well type included " gas development," "gas extension," and "gas wildcat," and the well status included "active," "drilled deeper," "drilling completed," "plugged back," and "plugged back multilateral."

CH_4 emissions were calculated as the volume of natural gas production converted from volume to mass using the ideal gas law times the EFs discussed in section 4.5.1.2. The MTs of CH_4 were converted to $MTCO_2e$ by applying the $GWP_{AR4,100}$ factor of 25.

4.5.1.4 Geospatial Data and Allocation Methodology

No allocation methodology was necessary since the ESOGIS database has information at the well level for all analysis years.

4.5.1.5 Sample Calculations

Equation 11 CH_4 emissions ($MTCO_2e$) = production x CF x EF x $GWP_{AR4,100}$

where:

- production = volume of natural gas produced (Mcf)
- CF = conversion from Mcf to MTs = [(CH_4 molecular weight / ideal gas law conversion factor)/2,000] x 1,000 cf/Mcf x 0.907185 MTs/short ton
- CF = (1000 x 16.043/379.3)/2000 x 0.907185 = 0.019185 MTs/Mcf
- EF = CH_4 EF (fraction of production) = 0.004
- $GWP_{AR4,100}$ = GWP = 25

For example, there were 1,382,968 Mcf of natural gas produced from gas wells in Cattaraugus County in 2010, resulting in 2,653 $MTCO_2e$ as shown:

Gathering and processing station CH_4 ($MTCO_2e$) = 1,382,968 x 0.019185 x 0.004 x 25
Gathering and processing station CH_4 ($MTCO_2e$) = 2,653 $MTCO_2e$

4.5.1.6 Limitations and Uncertainties

The results of this study showed a “fat tail” distribution, with a large number of low-emitting sites, and a comparatively small number of high-emitting sites. Furthermore, these estimates are estimated at the site level, corresponding to specific component counts, which may not reflect typical site-level components in New York State. As such, it is important to perform sensitivity analysis around this estimate.

4.5.1.7 Potential Areas of Improvement

These estimates may be improved by better understanding the frequency of high-emitting sites in the State, which complicate the application of a single normalized emissions rate to the general population.

4.5.2 Gathering Pipeline

4.5.2.1 Source Category Description

Gathering pipelines transport gases and liquids from the source of production (well pad) to storage tanks or to the processing facility, refinery, or transmission line. Gathering pipelines are commonly fed by flowlines, each connected to individual wells in the ground. In a gathering pipeline, raw gas is usually carried at pressures from 0–900 pounds per square inch (psi). Compared to other pipelines, lengths in this category are relatively short—approximately 200 meters long.

4.5.2.2 Emission Factors

<table>
<tr><td>Source Category</td><td colspan="4">Gathering Pipeline</td></tr>
<tr><td>Default EF ($MTCH_4$ mile^{-1} yr^{-1})</td><td colspan="4">0.4</td></tr>
<tr><td>Source</td><td colspan="4">EPA SIT Natural Gas and Oil Module</td></tr>
<tr><td>EF Confidence</td><td>Geography
Rest of the Country</td><td>Recency
5-15 Years</td><td>Methodology
Engineering Estimate</td><td>Status
Grey Literature</td></tr>
<tr><td>Source Description</td><td colspan="4">This is the default SIT gathering pipeline EF. The SIT documentation indicates that the GRI (1996) study is the source for this EF. EPA/GRI (1996) estimates leak rates from distribution mains from data in the Cooperative Leak Measurement Program and assumes identical leak rates for gathering lines. These EFs are well-aligned with the most recent EPA GHG Inventory (EPA 2018a), which uses a value of 395.5 kg mile^{-1} year^{-1} (Annex Table 3.6-2). In the peer-reviewed literature, Zimmerle et al (2017) find emissions of 402 kg $CH_4 \text{hr}^{-1}$ from a total of 4,684 km of gathering pipeline in the Fayetteville shale play. This translates to a rate of 402 kg $CH_4.\text{hr}^{-1}$ over 2,910.5 miles, or 1.210 $MTCH_4$ mile^{-1} yr^{-1}, indicating that the SIT and EPA estimated EFs applied here are conservatively low.</td></tr>
</table>

4.5.2.3 Activity Data

The activity data for gathering pipelines is miles of pipeline. State-level data on the gathering pipeline mileage was pulled from the Pipeline and Hazardous Materials Safety Administration (PHMSA) Pipeline Mileage and Facilities database. Based on guidance from DEC, the miles of gathering pipelines from PHMSA were scaled up to account for the fact that only 7.5% of gathering pipeline miles are being reported under PHMSA.

CH_4 emissions were calculated as the miles of pipeline times the EF discussed in section 4.5.2.2. The MTs of CH_4 were converted to $MTCO_2e$ by applying the $GWP_{AR4,\,100}$ factor of 25.

4.5.2.4 Geospatial Data and Allocation Methodology

The adjusted State-level miles of gathering pipeline were allocated to county level using the annual ratio of the volume of natural gas produced in the county to the volume of natural gas produced in New York State. The production data were derived from ESOGIS. This database contains information on all wells in the State, including county location, well type, and the volume of natural gas produced by year. To estimate the quantity of natural gas produced, the volume produced by county and year was based on well type and well status. For associated gas from oil wells, the well type included “oil development,” “oil extension,” and “enhanced oil recovery-injection,” and the well status included “active,” “drilled deeper,” “drilling completed,” “plugged back,” and “plugged back multilateral.” For natural gas production from natural gas wells, the well type included “gas development,” “gas extension,” and “gas wildcat,” and the well status included “active,” “drilled deeper,” “drilling completed,” “plugged back,” and “plugged back multilateral.”

4.5.2.5 Sample Calculations

Equation 12 **CH_4 emissions ($MTCO_2e$) = pipeline miles x SF x AF x EF x $GWP_{AR4,\,100}$**

where:

- pipeline miles = state-level miles of gathering pipeline
- SF = scaling factor to account for unreported miles of pipeline = 13.33
- AF = allocation factor based on ratio of county-level natural gas production in 2017 to state-level natural gas production in 2017
- EF = CH_4 EF ($MTCH_4$ $mile^{-1}$ yr^{-1}) = 0.4
- $GWP_{AR4,\,100}$ = GWP = 25

For example, according to the PHMSA data, there were 347 miles of gathering pipeline in New York State in 2010. In addition, there was 1,696,754 Mcf of natural gas production in Cattaraugus County in 2010 and 30,206,007 Mcf of natural gas production in the State. Applying the scaling and allocation factors, there were 259.9 miles of gathering pipeline in Cattaraugus County in 2010 resulting in 2,599 $MTCO_2e$ as shown:

Gathering pipeline CH_4 ($MTCO_2e$) = 347 x 13.33 x 1,696,754/30,206,007 x 0.4 x 25
Gathering pipeline CH_4 ($MTCO_2e$) = 2,599 $MTCO_2e$

4.5.2.6 Limitations and Uncertainties

These per-mile emission rates are based on an older study, with embedded leak frequencies that reflect conditions at the time but may not reflect the current condition of gathering lines in New York State. The value applied here is aligned with the 2018 EPA GHG Inventory EF, but in peer-reviewed literature EFs (Zimmerle et al. 2017) are ~ 3x higher, indicating that this estimate may lead to a lower estimate of gathering pipeline emissions.

4.5.2.7 Potential Areas of Improvement

PHMSA pipeline statistics may be applicable to derive New York State-specific estimates of emissions. Reported lost and unaccounted for (LAUF) gas, provided in PHMSA data may be used to generate state-level emission estimates, but county-specific gathering line mileage and throughput are necessary for attribution at the county level.

4.5.3 Truck Loading

4.5.3.1 Source Category Description

Gas condensate production, when transferred from storage into tank trucks, can generate significant volumes of CH_4 vapor due to pressure, temperature changes, and evaporation. Historically, this CH_4 was vented to the atmosphere to prevent the internal tank pressure from rising. Since a loading cycle may occur every three to five days or approximately 100 loading transfers per year, emissions can be significant. Many operations are now using closed loop systems where a vapor recovery line is connected to the tank, a vapor recovery unit, or flare stack. These closed loop systems essentially eliminate CH_4 emissions.

Truck loading of crude oil may release CH_4 as discussed in section 4.5.3.2. In addition, it is assumed that natural gas is transported by pipeline, and therefore, there is no truck loading for natural gas in New York State.

4.5.3.2 Emission Factors

Source Category	Truck Loading			
Default EF ($mgCH_4\ L^{-1}$ crude oil)	0 or 33.70			
Source	AP-42: Compilation of Air Emission Factors			
EF Confidence	Geography Rest of the Country	Recency 15+ Years	Methodology Engineering Estimate	Status Grey Literature
Source Description	AP-42: Compilation of Air Emission Factors, available at https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emissions-factors in Chapter 5, Table 5.2-5 indicates between 240 and 580 mg organic emissions lost per L of crude oil transferred into tank trucks. Assuming, as described in the source, ~ 15% of the total organic emissions is CH_4/ethane combined, then using the conservative lower bound gives emissions of 36 mg/L transferred. Data from Mitchell et al. (2015) indicate that CH_4 comprises 93.6% of natural gas produced in New York wells, so we alternatively use 36 x 0.936 = 33.70 mg/L as the CH_4 EF during loading. The available data on emissions from tank loading are sparse, therefore we use AP-42 air EFs, which are ultimately derived from two industry studies performed in 1977 by Chevron, USA, but are consistent with the EPA recommended methodology.			

4.5.3.3 Activity Data

The activity data for 2003–2017, calculated as bbl of crude oil production, were derived from ESOGIS. This database contains information on all wells in New York State, including county location, well type, and volume of oil produced. To estimate the quantity of oil produced, the volume produced by county and year was summed for all well types. Since the ESOGIS database contained incomplete oil well production data for 1990–2002, annual oil production values for these years were obtained from EIA's Crude Oil Production report (EIA, 2019a).

Natural gas is transported by pipelines.

4.5.3.4 Geospatial Data and Allocation Methodology

For 2003–2017, no allocation methodology was necessary since the ESOGIS database has information at the well level for all analysis years. However, information on the location of loading areas would help refine the location of the emissions. For 1990–2002, State-level oil production was allocated to the county level using the ratio of county-level production to State-level production in 2003 from the ESOGIS database.

4.5.3.5 Sample Calculations

Equation 13 CH_4 emissions ($MTCO_2e$) = gas condensate loaded x CF_1 x EF x CF_2 x $GWP_{AR4, 100}$

where:

- gas condensate loaded = volume of gas condensate loaded onto trucks
- CF_1 = conversion factor for barrels to liters = 158.987 liters/bbl
- EF = CH_4 EF ($mgCH_4$ L^{-1} crude oil) = 0
- CF_1 = conversion from mg to MT = $1e^{-9}$
- $GWP_{AR4, 100}$ = GWP = 25

For example, there were 22,265 bbl of oil produced in Allegany County in 2017, resulting in 0 $MTCO_2e$ from truck loading as shown:

Truck loading of crude oil CH_4 ($MTCO_2e$) = 22,265 x 158.987 x 0 x $1e^{-9}$ x 25
Truck loading of crude oil CH_4 ($MTCO_2e$) = 0 $MTCO_2e$

4.5.3.6 Limitations and Uncertainties

Based on the boiling points of CH_4 and ethane, it is likely that much of the CH_4/ethane present in crude will be released when the crude is exposed to atmospheric temperature and pressure conditions during storage. Therefore, there are two bounding conditions.

- Assume that any CH_4 present in crude oil stored at oil production sites and transferred via truck will evaporate while stored in atmospheric tanks, and therefore emissions are included/embedded in site-level EFs.
- Assume that none of the CH_4 evaporates prior to truck tank loading, and therefore the 33.7 mg/L EF applies during loading.

A review of some of the oil well sites indicates that many of the wells have tanks associated with them. From the satellite views, it's difficult to assess whether these are oil storage tanks or other tanks such as water or separators. For this inventory, it is assumed that all CH_4 evaporates while stored in atmospheric tanks.

4.5.3.7 Potential Areas of Improvement

Estimates of emissions from truck loading may be improved by a better understanding of quantities of oil transferred from wellheads to processing sites by truck in New York State as well as confirmation that all CH_4 has evaporated prior to truck loading. At present, the lack of good activity data requires the use of bounding conditions where either all or none of the CH_4 has evaporated prior to loading.

4.5.4 Gas Processing Plants

4.5.4.1 Source Category Description

Raw natural gas comes from three types of wells: oil, gas, and condensate wells. Natural gas that comes from oil wells is known as associated gas. This gas can exist separate from oil in the formation (free gas) or dissolved in the crude oil (dissolved gas). Natural gas from gas and condensate wells, in which there is little or no crude oil, is known as non-associated gas. Gas wells typically produce raw natural gas, while condensate wells produce free natural gas along with a semi-liquid hydrocarbon condensate. Natural gas, once separated from crude oil (if present), commonly exists in mixtures with other hydrocarbons, principally ethane, propane, butane, and pentanes. In addition, raw natural gas contains water vapor, H_2S, CO_2, helium, nitrogen, and other compounds. Natural gas processing plants purify raw natural gas by removing these contaminants using processes such as glycol dehydration to remove water and the amine process to sweeten the natural gas by removing sulfur.

4.5.4.2 Emission Factors

Source Category	Gas Processing Plant			
Default EF ($MTCH_4$ $plant^{-1}$ yr^{-1})	919.8			
Source	Marchese et al. 2015			
EF Confidence	Geography Marcellus/ Appalachian Basin	Recency ≤ 5 Years	Methodology Empirical Observation	Status Peer-Reviewed
Source Description	This EF is derived from tracer flux measurements of 16 processing plants in 13 U.S. states. The data used in this study are the same as those used in Mitchell et al. (2015). This study combines rigorous sampling methods with robust statistical modeling and finds an estimated facility-level EF of 105 kg $plant^{-1}$ hr^{-1}, or 919.8 $MTCH_4$ $plant^{-1}$ yr^{-1}. This estimate is a downward revision of the EPA SIT default value 1,249.95 $MTCH_4$ $plant^{-1}$ yr^{-1}` based on recent, rigorous, empirical observation and statistical modeling.			

4.5.4.3 Activity Data

According to the EIA and confirmed by DEC, there are no gas processing plants in New York State.

4.5.4.4 Geospatial Data and Allocation Methodology

N/A

4.5.4.5 Sample Calculations

Equation 14 **CH_4 emissions ($MTCO_2e$) = gas processing plants x EF x $GWP_{AR4, 100}$**

where:

- gas processing plants = number of gas processing plants
- EF = CH_4 EF ($MTCH_4$ $plant^{-1}$ yr^{-1}) = 1,249.95
- $GWP_{AR4, 100}$ = GWP = 25

For example, there were no natural gas processing plants in Cattaraugus County in 2010, resulting in 0 $MTCO_2e$ as shown:

Natural gas processing plant CH_4 ($MTCO_2e$) = 0 x 1,249.95 x 25
Natural gas processing plant CH_4 ($MTCO_2e$) = 0 $MTCO_2e$

4.5.4.6 Limitations and Uncertainties

This EF is based on data collected across 13 states and is not specific to New York State. In addition, Marchese et al. (2015) identify uncertainty bounds of +11/-10 kg $plant^{-1}$ hr^{-1} around the central estimate.

4.5.4.7 Potential Areas of Improvement

Due to the described uncertainty in the EF, it is useful to perform sensitivity analysis around the central estimate.

4.5.5 Gas Transmission Pipelines

4.5.5.1 Source Category Description

Transmission pipelines are used to transport natural gas for long distances across states. They are used to move the product from the production regions to distribution centers. Transmission pipelines operate at high pressures, ranging from 200–1,200 psi, with each transmission line using compressor stations to maintain gas pressure.

4.5.5.2 Emission Factors

Source Category	Transmission Pipeline			
Default EF (MTCH$_4$ mile^{-1} yr^{-1})	0.62			
Source	EPA SIT Natural Gas and Oil Module			
EF Confidence	🟥 Geography Rest of the Country	🟥 Recency 15+ Years	🟨 Methodology Engineering Estimate	🟨 Status Grey Literature
Source Description	This is the default SIT gathering pipeline EF. The SIT documentation indicates that the study is the source for this EF. EPA/GRI (1996) estimates leak rates from distribution mains from data in the Cooperative Leak Measurement Program. The EF used here is approximately half of the value used in the most recent EPA GHG Inventory (EPA 2018a), which uses an EF of 1,122.7 kg mile^{-1} year^{-1} (Annex table 3.6-2), reportedly also derived from the EPA/GRI 1996 study. The updates in the most recent EPA GHG Inventory are not clearly documented, so the EPA/GRI (1996) estimate, which documents the methodology, is used.			

4.5.5.3 Activity Data

The activity data for transmission pipelines is miles of pipeline. State-level data on the transmission pipeline mileage was pulled from the PHMSA Pipeline Mileage and Facilities database. Due to suspected anomalies in the PHMSA pipeline data, corrections were applied per guidance from DEC. Data reported in the PHMSA database for years 2002–2017 were used to develop a trendline to estimate emissions from 1990–2001. In addition, PHMSA data for year 2002 were applied to years 2003–2005, PHMSA data for year 2008 were applied to years 2009–2012 and PHMSA data for year 2013 were applied to years 2014 to 2017.

CH_4 emissions were calculated as the miles of pipeline times the EFs discussed in section 4.5.4.9. The MTs of CH_4 were converted to $MTCO_2e$ by applying the $GWP_{AR4,\,100}$ factor of 25.

4.5.5.4 Geospatial Data and Allocation Methodology

An estimate of transmission pipeline miles per county were calculated by summing reported line segments from PHMSA's public viewer.[14] The state-level miles reported in the PHMSA database were allocated to the county level by using the 2017 ratio of the estimated miles of transmission pipeline in the county to estimated miles of transmission pipeline in New York State, calculated by summing transmission line segments from the map.

4.5.5.5 Sample Calculations

Equation 15 **CH_4 emissions ($MTCO_2e$) = pipeline miles x AF x EF x $GWP_{AR4,\,100}$**

where:

- pipeline miles = state-level miles of transmission pipeline
- AF = allocation factor based on ratio of county-level miles of pipeline in 2017 to state-level miles of pipeline in 2017
- EF = CH_4 EF ($MTCH_4$ $mile^{-1}$ yr^{-1}) = 0.62
- $GWP_{AR4,\,100}$ = GWP = 25

For example, there were 4,582 miles of transmission pipeline in New York State in 2017. The data on miles from summing line segments from the PHMSA map indicated there were 124.28 miles of transmission pipeline in Albany County in 2017 and 3,940 miles of transmission pipeline. Applying the allocation factor, there were 144.57 miles of transmission pipeline in Albany County in 2017, resulting in 2,241 $MTCO_2e$ as shown:

Transmission pipeline CH_4 ($MTCO_2e$) = 4,582 x 124.28/3,940 x 0.62 x 25
Transmission pipeline CH_4 ($MTCO_2e$) = 2,241 $MTCO_2e$

4.5.5.6 Limitations and Uncertainties

These per-mile emission rates are based on an older study, with embedded leak frequencies that reflect conditions at the time but may not reflect the current condition of gas transmission pipelines in New York State. In addition, the 2018 EPA GHG Inventory (EPA 2018a) indicates that transmission pipeline emissions may be as high as 1,122.7 kg $mile^{-1}$ $year^{-1}$ (Annex table 3.6-2), or 81% higher than the SIT default value.

4.5.5.7 Potential Areas of Improvement

PHMSA pipeline statistics may be applicable to derive New York State-specific estimates of emissions. Reported LAUF gas, provided in PHMSA data, may be used to generate State-level emissions estimates, but county-specific transmission line mileage and throughput are necessary for attribution at the county level.

4.5.6 Gas Transmission Compressor Stations

4.5.6.1 Source Category Description

Transmission compressor stations are facilities roughly located every 70 miles along a natural gas pipeline to boost the pressure that is lost by the friction of the natural gas moving through the pipeline (Greenblatt 2015). Natural gas enters a compressor station through station yard piping. Scrubbers and filters remove any liquids, solids, or other particulate matter and then gas is directed to individual compressors. Most compressor stations have an aerial cooler system to cool the gas stream before leaving the compressor facility.

4.5.7 Emission Factors

Source Category	Gas Transmission Compressor Stations			
Default EF (MTCH$_4$ station^{-1} yr^{-1})	670			
Source	Zimmerle et al. 2015			
EF Confidence	Geography Marcellus/ Appalachian Basin	Recency ≤ 5 Years	Methodology Empirical Observation	Status Peer-Reviewed
Source Description	Zimmerle et al. (2015) studied 922 transmission and storage compressors, applying probabilistic emissions, activity models, and statistical methods to model emissions, which were then validated using field measurements. The mean emissions rate for transmission stations was 670 MT station^{-1} year^{-1} (+52%/-34%), which is 32% lower than the default SIT value. The estimate applied here is derived from a peer-reviewed study of 823 transmission compressor stations employing empirical observations and statistical modeling techniques.			

4.5.7.1 Activity Data

The number of natural gas transmission compressors stations were calculated by dividing the number of miles of transmission pipeline by the approximate pipeline distance per compressor station of 70 miles. The resultant number of transmission compressor stations was cross-checked with data provided by DEC from their permitting database, which provides compressors stations by county. The type of compressor station was determined by reviewing permits and publicly available information on the compressor stations. While the number of compressor stations in the permitting database is lower than the calculated number, the calculated number likely includes compressor stations with electric compressors that would not require permits (and, therefore, would not be included in the permitting database).

4.5.7.2 Geospatial Data and Allocation Methodology

No allocation methodology was necessary since the DEC database on permits and EIA data set have information at the county level for all analysis years.

4.5.7.3 Sample Calculations

Equation 16 CH_4 emissions ($MTCO_2e$) = compressor stations x EF x $GWP_{AR4,\,100}$

where:

- compressor stations = number of natural gas transmission compressor stations
- EF = CH_4 EF ($MTCH_4$ $station^{-1}$ yr^{-1}) = 670
- $GWP_{AR4,\,100}$ = GWP = 25

For example, there were two natural gas transmission compressor stations in Cattaraugus County in 2017, resulting in 33,500 $MTCO_2e$ as shown:

Natural gas transmission compressor station CH_4 ($MTCO_2e$) = 2 x 670 x 25
Natural gas transmission compressor station CH_4 ($MTCO_2e$) = 33,500 $MTCO_2e$

4.5.7.4 Limitations and Uncertainties

Subramanian et al. (2015) also performed detailed, peer-reviewed, top-down (TD) and bottom-up (BU) analyses of emissions from compressor stations, finding values 30.8% lower than Zimmerle et al. (2015). As identified in many other areas, super-emitting sites comprised a small fraction of the total number of sites, but a large fraction of the total emissions, resulting in wide uncertainty bands. Additionally, this study shows differences between reciprocating and centrifugal compressor stations.

4.5.7.5 Potential Areas of Improvement

Given the likelihood that differences in compressor engine emissions would not show a large variation, the most pressing need in this area is for the analysis of potentially high-emitting sources.

4.5.8 Gas Storage Compressor Stations

4.5.8.1 Source Category Description

Natural gas can be stored underground in depleted oil or gas reservoirs, salt formation caverns, and mined underground caverns. Whether used to meet typical demand, or as a strategic reserve during a low-priced market or unanticipated supply shortage, gas storage and withdrawal play an important role in maintaining a stable natural gas market. For example, gas can be injected into storage facilities during the summer months and withdrawn during winter months to meet increased customer demand. Storage compressor stations provide the necessary boost to move natural gas between the storage field and the distribution system. The compressor units operate during injection to move natural gas into the storage field as well as during withdrawal from storage to move natural gas to the distribution system.

4.5.8.2 Emission Factors

Source Category	Natural Gas Storage Compressor Station			
Default EF ($MTCH_4$ $station^{-1}$ yr^{-1})	847			
Source	Zimmerle et al. 2015			
EF Confidence	Geography Marcellus/ Appalachian Basin	Recency ≤ 5 Years	Methodology Empirical Observation	Status Peer-Reviewed
Source Description	Zimmerle et al. (2015) studied 922 transmission and storage compressors, applying probabilistic emissions, activity models, and statistical methods to model emissions, which were then validated using field measurements. The mean emissions rate for transmission stations was 847 MT $station^{-1}$ $year^{-1}$ (+53%/-35%), which is 12.2% lower than the default SIT value. The estimate applied here is derived from a peer-reviewed study of 99 storage compressor stations employing empirical observations and statistical modeling techniques. This estimate is supported by published data from Subramanian et al (2015), who studied CH_4 emissions at 45 compressor stations across 16 states using 2 methodologies: a BU measurement of individual emission sources showed a strong correlation with a TD measurement using tracer flux techniques to measure CH_4 gas concentrations in downwind plumes. Subramanian et al (2015) found mean emissions of 585.81 $MTCH_4$ $station^{-1}$ yr^{-1}, 30.8% lower than Zimmerle et al. (2015). Super-emitting stations were significantly higher emitters than normal stations, with the highest emitting 10% of stations accounting for 50% of emissions. The lowest emitting 50% of stations accounted for 10% of emissions. Both Zimmerle et al. and Subramanian et al. are peer-reviewed and robust studies. This inventory uses the Zimmerle et al. estimate for storage compressor stations as it has a larger sample size. However, the literature indicates that understanding compressor types, as well as the distribution of emissions, are critical to robustly estimating emissions from compressor stations.			

4.5.8.3 Activity Data

The number of natural gas storage compressors stations were provided by DEC from their permitting database, which provides compressor stations by county and supplemented with data from EIA collected on the EIA-191 survey (EIA, 2019b). The type of compressor station was determined by reviewing permits and publicly available information on the compressor stations.

4.5.8.4 Geospatial Data and Allocation Methodology

No allocation methodology was necessary since the DEC database on permits and EIA data set have information at the county level for all analysis years.

4.5.8.5 Sample Calculations

Equation 17 $\mathbf{CH_4}$ **emissions** ($\mathbf{MTCO_2e}$) **= compressor stations x EF x** $\mathbf{GWP_{AR4,\,100}}$

where:

- compressor stations = number of natural gas storage compressor stations
- EF = CH_4 EF ($MTCH_4$ station^{-1} yr^{-1}) = 847
- $GWP_{AR4,\,100}$ = GWP = 25

For example, there were three natural gas storage compressor stations in Cattaraugus County in 2017, resulting in 63,525 $MTCO_2e$ as shown:

Natural gas storage compressor station $\mathbf{CH_4}$ ($\mathbf{MTCO_2e}$) **= 3 x 847 x 25**
Natural gas storage compressor station $\mathbf{CH_4}$ ($\mathbf{MTCO_2e}$) **= 63,525** $\mathbf{MTCO_2e}$

4.5.8.6 Limitations and Uncertainties

Subramanian et al. (2015) also performed detailed, peer-reviewed, TD and BU analyses of emissions from compressor stations, finding values 30.8% lower than Zimmerle et al. (2015). As identified in many other areas, super-emitting sites comprised a small fraction of the total number of sites but a large fraction of the total emissions, resulting in wide uncertainty bands. Additionally, this study shows differences between reciprocating and centrifugal compressor stations.

4.5.8.7 Potential Areas of Improvement

As noted, reciprocating and centrifugal compressors show different average emission rates. When normalized by horsepower, however, centrifugal compressors show much lower emissions; therefore, emissions per unit throughput are lower for centrifugal compressors. In addition, the issue of high-emitting sources also applies to compressors, with inconclusive evidence for high-emitting sources being more likely in standby or operational modes. This again highlights the importance of improving the understanding of high-emitting source rates and distributions.

4.5.9 Storage Reservoir Fugitives

4.5.9.1 Source Category Description

As described in section 4.5.7, natural gas is stored in underground formations for use at a later date. Underground storage formations are typically depleted oil and gas reservoirs, salt caverns, or mined underground caverns. Fugitive emissions from these storage formations may occur but are not well characterized. This inventory does not include emissions from underground storage facilities due to a lack of available EFs. Inclusion of storage reservoir fugitive emissions is recommended for future study.

4.5.10 LNG Storage Compressor Stations

4.5.10.1 Source Category Description

LNG storage compressor stations take natural gas from the pipeline system during periods of lower demand, liquefy and store the gas, and then vaporize it during periods of high demand. The process of liquefying natural gas shrinks the gas volume by a factor of approximately 600. The LNG process allows for an economic way to store natural gas for vaporization and distribution at a later date when demand increases. The LNG storage tanks at these stations can be above ground or in ground and could store LNG at very low temperatures in order to maintain the gas in a liquid form. The storage tanks are insulated in order to limit evaporation. A small amount of heat is still able to penetrate the tanks and evaporation can occur, resulting in boil-off gas. This gas is captured and fed back into the LNG flow using compressor and re-condensing systems, preventing the occurrence of venting natural gas. However, during maintenance periods, boil-off gas must be burnt off by the flare stack.

4.5.10.2 Emission Factors

Source Category	LNG Storage Compressor Station			
Default EF ($MTCH_4$ facility^{-1} yr^{-1})	1,077.48			
Source	2016 GHG Inventory			
EF Confidence	Geography Marcellus/ Appalachian Basin	Recency 5-15 years	Methodology Engineering Estimate	Status Grey Literature
Source Description	The EF is estimated as the annual product of 123 kg facility^{-1} hr^{-1}, which is the rolled-up per-station EF, using assumed inputs from the EPA GHG Inventory, per guidance from Dr. Anthony Marchese, as follows: 3.85 reciprocating compressors per station (round up to 4). 0.91 centrifugal compressor per station (round up to 1). Engine hp-hr per station (assuming 4 engines per station) = 8.6 MMhp-hr. Station level fugitive EF = 21,507 standard cubic feet per day (scfd)/station. Reciprocating compressor EF (assuming 4 compressors/station) = 84,464 scfd/station. Centrifugal compressor EF (assuming 1 centrifugal compressor/station) = 30,573 scfd/station. Engine CH_4 exhaust per station = 5,640 scfd/station (assuming 4 engines per station). Gas turbine exhaust = 51 scfd/station (assuming 1 gas turbine per station). Station venting = 11,942 scfd/station. This results in an EF of 154,177 scfd/facility, 123 kg hr^{-1} facility^{-1}, or 1,077.48 $MTCH_4$ facility^{-1} yr^{-1}. This estimate is derived from expert review, including EPA guidance and local component count estimates.			

4.5.10.3 Activity Data

There are currently three large LNG storage facilities in New York State (Astoria, Greenpoint, and Holtsville) and all have been operational since 1990. The location of the facilities was provided by DEC.

4.5.10.4 Geospatial Data and Allocation Methodology

No allocation methodology was necessary since the DEC provided the county-level locations of the three facilities.

4.5.10.5 Sample Calculations

Equation 18 CH_4 **emissions** ($MTCO_2e$) **= compressor stations x EF x** $GWP_{AR4,\,100}$

where:

- compressor stations = number of LNG storage compressor stations
- EF = CH_4 EF ($MTCH_4$ station^{-1} yr^{-1}) = 1,077.48
- $GWP_{AR4,\,100}$ = GWP = 25

For example, there was one LNG storage compressor station in Kings County in 2017 resulting, in 26,937 MTCO$_2$e as shown:

LNG storage compressor station CH$_4$ (MTCO$_2$e) = 1 x 1,077.48 x 25
LNG storage compressor station CH$_4$ (MTCO$_2$e) = 26,937 MTCO$_2$e

4.5.10.6 Limitations and Uncertainties

This EF is estimated based on rolling up standard assumptions for LNG storage compressor station components. As such, several assumptions were made, including compressor types and counts, engine horsepower and counts, and venting assumptions. These assumptions have not been validated by empirical observations. Uncertainty bounds are estimated by assuming one (plus or minus) reciprocating compressor per station.

4.5.10.7 Potential Areas of Improvement

As noted in section 4.5.9.6, several assumptions were made in estimating the EF for LNG storage compressor stations. This estimate may be improved by validating the assumptions used against LNG storage compressor station components in New York State.

4.5.11 LNG Terminal

4.5.11.1 Source Category Description

An LNG terminal is a facility for re-gasifying the LNG that was transported from production zones. LNG terminals function to berth LNG tankers and unload or reload cargo, store LNG in cryogenic tanks, re-gas LNG, and/or send gas out into the transmission grid. There are no LNG terminals in New York State.

4.6 Downstream Stages

4.6.1 Distribution Pipelines

4.6.1.1 Source Category Description

Distribution pipelines are a system comprised of mains and service lines that are used by distribution companies to deliver natural gas to homes and businesses. Mains are the step between high-pressure transmission lines and low-pressure service lines. Materials used for these pipes include steel, cast iron, plastic, and copper. Pressures can vary considerably but can be as high as 200 psi. Service pipelines connect to a meter and deliver natural gas to individual customers. Materials used for service pipes include plastic, steel, cast iron, or copper. Pressure of the gas in these pipes is low at around 6 psi.

4.6.1.2 Emission Factors

<table>
<tr><th colspan="2">Source Category</th><th>Cast Iron</th><th>Unprotected Steel</th><th>Protected Steel</th><th>Plastic</th><th>Copper</th></tr>
<tr><td rowspan="2">Default EF ($MTCH_4$ mile^{-1} yr^{-1})</td><td>Main</td><td>1.1573</td><td>0.8613</td><td>0.0967</td><td>0.0288</td><td>-</td></tr>
<tr><td>Services</td><td>1.1573</td><td>0.0145</td><td>0.0013</td><td>0.0003</td><td>0.0049</td></tr>
<tr><td>Source</td><td colspan="6">Lamb et al. 2015; EPA 2018a</td></tr>
<tr><td>EF Confidence</td><td colspan="2">Geography Marcellus/ Appalachian Basin</td><td>Recency ≤ 5 Years</td><td>Methodology Empirical Observation</td><td colspan="2">Status Peer-Reviewed</td></tr>
<tr><td>Source Description</td><td colspan="6">The EFs used for distribution mains and services are derived from the 2018 EPA GHG Inventory (EPA 2018a, Annex 3.6-2), which are in turn built on a study by Lamb et al. (2015), which uses empirical and statistical modeling methods to estimate leak rates, factoring in soil oxidation of leaks. As described elsewhere in the literature, consideration of high-emitting sources leads to a skewed distribution of leak rates, with a few sources accounting for the majority of emissions.</td></tr>
</table>

Note: The EF for cast iron services is assumed to be equal to the EF for cast-iron mains.

4.6.1.3 Activity Data

Activity data for main and service distribution pipelines are miles of pipeline by pipeline material type. Operator-level data on the pipeline mileage by type was pulled from the PHMSA Pipeline Mileage and Facilities database. To correct for potential outliers in the PHMSA data, likely due to incomplete reporting, the following data adjustments were made:

- **Cast-Iron Mains**: 1991 is the average of 1990 and 1992 PHMSA data.
- **Cast-Iron Services**: 1990 to 2003 are based on a trendline from 2004 to 2017 PHMSA data.
- **Unprotected Steel Services**: 1991, 1998 and 2009 are the average of PHMSA data in adjacent years.
- **Protected Steel Mains**: 1994 to 1996 are based on a linear trend using 1993 and 1997 PHMSA data.
- **Protected Steel Services**: 1998 and 2009 are the average of PHMSA data in adjacent years.
- **Copper Services**: 1991 to 1992 are based on a linear trend using 1990 and 1993 PHMSA data; 1998, 2001 and 2010 are the average of PHMSA data in adjacent years.

CH_4 emissions were calculated as the miles of pipeline, by pipeline type, times the EFs discussed in section 4.6.1.2. The MTs of CH_4 were converted to $MTCO_2e$ by applying the $GWP_{AR4,\,100}$ factor of 25.

4.6.1.4 Geospatial Data and Allocation Methodology

The operator-level miles of distribution pipelines reported in the PHMSA database were allocated to the county-level based on the number of services. The methodology for estimating the number of services is discussed in section 4.6.2.4.

4.6.1.5 Sample Calculations

$$\mathbf{CH_4\ emissions\ (MTCO_2e) = pipeline\ miles_{type} \times AF \times EF \times GWP_{AR4,\,100}}$$

where:

- pipeline $\text{miles}_{\text{type}}$ = state-level miles of distribution pipeline by pipeline material type
- AF = allocation factor based on the ratio of the number of county natural gas services (residential and commercial) to the number of state natural gas services (residential and commercial)
- EF = CH_4 EF ($MTCH_4$ mile^{-1} yr^{-1})
- $GWP_{AR4,\,100}$ = GWP = 25

For example, according to the PHMSA data, there were 4,404 miles of unprotected steel distribution service pipeline in New York State in 2017. From the allocation method, the total number of natural gas services in Albany County in 2017 was 109,358, and the total number natural gas services in New York State in 2017 was 4,559,150. Applying the allocation factor, there were 105.64 miles of unprotected steel distribution service pipeline in Albany County in 2017, resulting in 38.3 $MTCO_2e$ as shown:

$$\mathbf{Unprotected\ steel\ distribution\ pipeline\ CH_4\ (MTCO_2e) = 4{,}404 \times 109{,}358/4{,}559{,}150 \times 0.0145 \times 25}$$
$$\mathbf{Unprotected\ steel\ distribution\ pipeline\ CH_4\ (MTCO_2e) = 38.3\ MTCO_2e}$$

4.6.1.6 Limitations and Uncertainties

These per-mile emission rates are based on a peer-reviewed study, with embedded leak frequencies that reflect nationwide leak rates, but may not reflect the current condition of gas mains in New York State. Uncertainty estimates are based on the upper bound per-mile EF provided in EPA's 2016 inventory of greenhouse gases in the United States (Annex 3.6, table 3.6-2).

The PHMSA present data that show 170 leaks in New York State from 22 gas distribution operators, resulting in LAUF gas between 0% and 4%, with a mean of 1.14% from all reported distribution pipelines in 2017. The current EF used is independent of reported or observed leaks and instead applies a national average rate.

4.6.1.7 Potential Areas of Improvement

PHMSA pipeline statistics may be applicable to derive New York State-specific estimates of emissions. Reported LAUF gas, provided in PHMSA data, may be used to generate state-level emissions estimates but cannot be disaggregated by pipeline type, and county-specific mains mileages and throughput are necessary for attribution at the county level.

4.6.2 Service Meters

4.6.2.1 Source Category Description

A gas meter is a specialized flow meter that measures the volume of gas transferred from an operator to a consumer. Gas meters can be for residential, commercial, or industrial use. In some cases, such as residential use, when the gas reaches a customer's meter, it passes through another pressure regulator to reduce its pressure to under 0.25 psi.

4.6.2.2 Emission Factors

Source Category	**Residential Meters**		**Commercial / Industrial Meters**	
Default EF ($MTCH_4$ meter^{-1} yr^{-1})	0.0015		0.0097	
Source	EPA 2018a, Annex 3.6-2			
EF Confidence	Geography Rest of the Country	Recency 5-15 Years	Methodology Empirical Observation	Status Grey Literature
Source Description	This inventory applies the residential and commercial/industrial EFs derived by EPA in the 2018 inventory (EPA 2018a), based on data from the Gas Technical Institute (GTI 2009) and Clearstone Engineering (Clearstone 2011). These studies performed sampling at meter locations in the United States and Canada and represent the best available data. The emissions estimates in the 2018 EPA GHG Inventory are 52% lower than the default value in the EPA SIT.			

4.6.2.3 Activity Data

The activity data for service meters is the number of service meters. State-level data on the distribution meter counts was pulled from the PHMSA Pipeline Mileage and Facilities database, U.S. Census Bureau reported household utility gas counts, and EIA reported residential, commercial, and industrial customer counts.

CH_4 emissions were calculated as the number of distribution meters times the EF discussed in section 4.6.2.2. The MTs of CH_4 were converted to $MTCO_2e$ by applying the $GWP_{AR4,\,100}$ factor of 25.

4.6.2.4 Geospatial Data and Allocation Methodology

Residential meters were allocated to the county level using U.S. Census counts of utility gas as the primary home heating fuel. These data were available from 2006–2017 at the census-tract level. The meter counts were then geospatially allocated by census tract to the county and gas utility service areas, based on the most recently available geospatial distribution of service areas.[15] Finally, due to an undercounting of homes with utility gas in the one-year census data, census counts were scaled by the total residential meter count reported by EIA.[16] Census data were not readily available for years 1990–2006, so the distribution of meters by census block in 2006 was used as the baseline, and the same methodology was applied to scale the total residential meter count using EIA reported data for those years. The number of homes with utility gas as the primary heat source was reported in the U.S. Census Bureau's American Community Survey.[17]

Commercial meters were allocated based on the count of businesses by zip code, available from the Census County Business Patterns data set[18] geospatially allocated to county and gas service territories. The count of eligible businesses (i.e., those within gas utility service areas) were then scaled by the total count of commercial and industrial customers as reported by EIA.[19]

4.6.2.5 Sample Calculations

Equation 19 CH_4 emissions ($MTCO_2e$) = service meters x AF_1 x AF_2 x EF x $GWP_{AR4,\ 100}$

where:

- service meters = state-level number of service meters
- AF_1 = ratio of meter type (residential or commercial) to total meters
- AF_2 = allocation factor based on ratio of county-level number of meters (residential or commercial) to the state total number of meters (residential or commercial)
- EF = CH_4 EF ($MTCH_4$ $meter^{-1}$ yr^{-1})
- $GWP_{AR4,\ 100}$ = GWP = 25

For example, according to the PHMSA data, there were 3,241,702 service meters in New York State in 2017. The ratio of residential to total meters estimated from the allocation methodology is 4,150,738/4,559,150. Based on the allocation methodology, the number of homes in Albany County with utility gas as the primary heat source in 2017 was 101,851 and the total number of homes in New York State with utility gas as the primary heat source in 2017 was 4,150,738. Applying the allocation factors to the PHMSA data, there were 72,419 residential service meters in Albany County in 2017, resulting in 2,716 $MTCO_2e$ as shown:

Distribution meter CH_4 ($MTCO_2e$) = 3,241,702 x 4,150,738/4,559,150 x 101,851/4,150,738 x 0.0015 x 25

Distribution meter CH_4 ($MTCO_2e$) = 2,716 $MTCO_2e$

4.6.2.6 Limitations and Uncertainties

Emissions from services and meters are estimated using values from the EPA 2018 GHG emissions inventory (Annex 3.6, Table 3.6-2), which builds on estimates from the Gas Research Institute (GRI) 1996 study, which in turn is based on a 1992 report from Indaco Air Quality Services titled Methane Emissions from Natural Gas Customer Meters: Screening and Enclosure Studies, which estimates emissions from residential meters, not including service lines, to be 138.5 ± 23.1 scf meter-yr^{-1}. These estimates are updated using data from GTI (GTI 2009) and Clearstone Engineering (Clearstone 2011) to produce the estimates used in the EPA 2018 GHG Inventory. Given that these meter data are derived from a set of older studies, not local to New York State, it is possible that these estimates do not accurately reflect current conditions and leak rates from meters in the State.

4.6.2.7 Potential Areas of Improvement

This estimate may be improved by employing more up-to-date estimates of leak rates from residential meters. The EPA/GRI (1996) study indicated that there may be differences in regional leak rates from residential meters, so using New York State or northeast-specific measurements, where available, would be most applicable.

5 Results

This section presents an analysis of the detailed, activity driven, CH_4 emissions inventory for the oil and natural gas sector in New York State, developed through the information provided in sections 2 and 3 and using the methodology in section 4. Following best practices described by IPCC guidelines and the EPA, this analysis identifies and describes CH_4 emissions by source category and provides a geospatially resolved breakdown of emissions by county. In addition, the overall trends in CH_4 emissions captured by the inventory for 1990–2017 are presented.

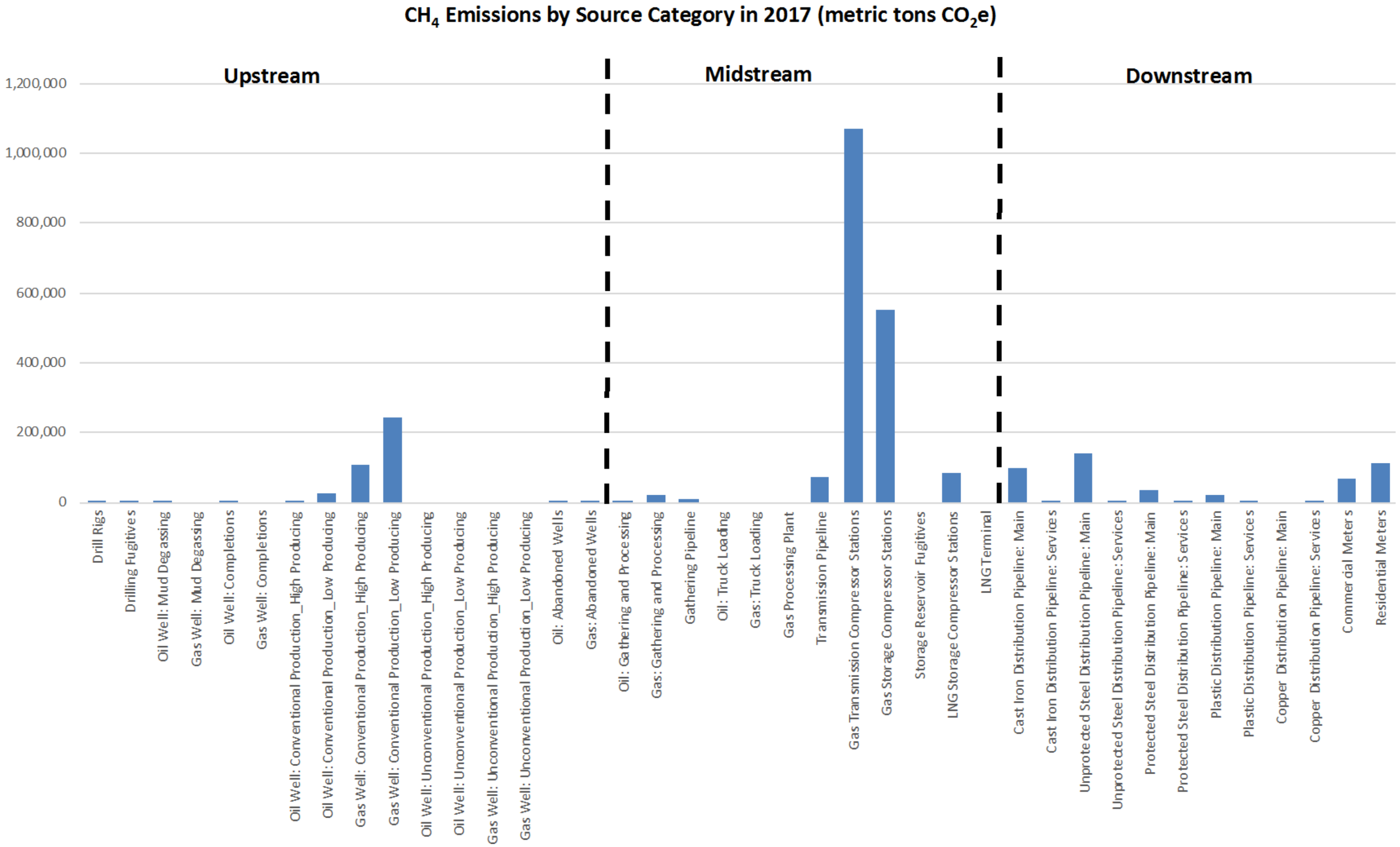
5.1 Total Emissions

CH_4 emissions from oil and natural gas activity in New York State in 2017 totaled 106,561 $MTCH_4$, equivalent to 2,664,182 $MTCO_2e$ (values given in AR4 GWP_{100} unless otherwise noted). Using 2015 as the most recent common year, this study estimates CH_4 emissions to be 20% higher than the previous estimate of CH_4 emissions from the oil and natural gas sector in the 2015 New York State GHG inventory (2.22 $MMTCO_2e$).

5.2 Emissions in Year 2017 by Upstream, Midstream, and Downstream Stages

Figure 16 shows CH_4 emissions by source category broken out by upstream, midstream, and downstream source categories using AR4 GWP_{100} units. Downstream emissions totaled 0.477 $MMTCO_2e$ in 2017, accounting for 17.9% of total emissions. These data are also shown in Table 14. Unprotected steel mains are the largest single-source category, followed by residential meters, and cast-iron distribution mains. Midstream emissions totaled 1.807 $MMTCO_2e$ in 2017, accounting for 67.8% of emissions, with compressors (storage and transmission) comprising the largest source categories in the inventory. In fact, storage and transmission compressor stations are the two largest single-source categories identified in New York State. Upstream sources, dominated by conventional gas wells, emitted 0.380 $MMTCO_2e$, accounting for 14.2% of total CH_4 emissions. These results reflect the fact that the State is largely a consumer of natural gas. As such, the midstream and downstream source categories are expected to drive the majority of CH_4 emissions.

Figure 16. CH_4 Emissions by Source Category and Grouped by Upstream, Midstream, and Downstream Stages in New York State in 2017 (AR4 GWP_{100})



5.3 Emissions by Source Category in Year 2017

As shown in Figure 16, the 64 natural gas transmission compressor stations are the largest single source category in New York State, accounting for 1,072 MMTCO$_2$e or 40.2% of total CH$_4$ emissions, followed by the 26 gas storage compressor stations, accounting for 550.55 MMTCO$_2$e or 20.7% of total CH$_4$ emissions. Taken together, the top five emitting source categories in this inventory (gas transmission compressor stations, gas storage compressor stations, conventional low-producing gas wells, unprotected steel distribution mains, and residential meters) account for 79.3% of total CH$_4$ emissions, highlighting the importance of compressor stations, gas wells, unprotected steel mains, and customer meters to the New York State CH$_4$ inventory. Considering gas pipelines, emissions from gathering pipelines account for 0.41% of total emissions, transmission pipelines account for 2.67%, distribution mains for 11%, and distribution service lines for 0.15%.

In addition, this inventory estimates zero CH$_4$ emissions in 2017 from a number of source categories. These categories largely relate to oil and gas exploration and well completion activities, which as shown in Figure 2, were inactive in 2017. Additional source categories identified as having zero emissions include (1) truck loading, which is assumed to be zero as evaporative emissions of CH$_4$ from oil while stored in atmospheric tanks are incorporated into site-level EFs, (2) gas processing, since there are no processing plants in the State, and (3) LNG terminals, since there are also no LNG terminals in the State. The prior inventory approach, scaling the national inventory to New York State, implicitly and erroneously included these categories as emitting.

Table 14. CH_4 Emissions by Source Category in New York State from 1990–1999

Category	Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Upstream	Drill Rigs	3	4	3	3	2	1	2	2	1	2
	Drilling Fugitives	195	236	182	160	117	87	147	85	78	95
	Oil Well: Mud Degassing	3,797	6,799	12,569	3,426	5,835	4,702	10,329	6,337	1,368	3,725
	Gas Well: Mud Degassing	17,480	13,194	10,576	13,494	7,835	4,318	5,536	4,363	7,945	7,541
	Oil Well: Completions	1,445	2,168	2,890	1,063	1,445	1,403	2,975	1,360	340	1,020
	Gas Well: Completions	4,888	5,398	3,018	4,038	2,210	1,275	1,700	1,403	1,785	1,275
	Oil Well: Conventional Production_High Producing	1,687	1,756	1,855	1,025	743	1,196	917	590	550	639
	Oil Well: Conventional Production_Low Producing	965	1,034	859	1,154	1,545	1,432	1,270	1,309	1,247	1,331
	Gas Well: Conventional Production_High Producing	291,844	269,426	270,180	245,759	202,333	178,736	157,332	141,392	135,284	123,976
	Gas Well: Conventional Production_Low Producing	204,084	231,142	242,921	249,187	257,553	252,829	260,050	246,873	250,765	254,593
	Oil Well: Unconventional Production_High Producing	0	0	0	0	0	0	0	0	0	0
	Oil Well: Unconventional Production_Low Producing	0	0	0	0	0	0	0	0	0	0
	Gas Well: Unconventional Production_High Producing	0	0	0	0	0	0	0	0	0	0
	Gas Well: Unconventional Production_Low Producing	0	0	0	0	0	0	0	0	0	0
	Oil: Abandoned Wells	3,903	3,903	3,903	3,903	3,903	3,903	3,903	3,903	3,903	3,903
	Gas: Abandoned Wells	911	928	1,005	1,038	1,086	1,082	1,106	1,106	1,055	1,119
Midstream	Oil: Gathering and Processing	206	215	218	149	138	178	144	113	107	119
	Gas: Gathering and Processing	37,157	36,121	36,696	34,580	30,699	28,196	26,415	24,300	23,869	22,929
	Gathering Pipeline	33,600	26,267	18,667	26,133	67,733	68,933	106,267	84,067	61,867	60,133

Table 14 continued

Midstream	Oil: Truck Loading	0	0	0	0	0	0	0	0	0	0
	Gas: Truck Loading	0	0	0	0	0	0	0	0	0	0
	Gas Processing Plant	0	0	0	0	0	0	0	0	0	0
	Transmission Pipeline	63,947	64,222	64,498	64,774	65,049	65,325	65,601	65,876	66,152	66,428
	Gas Transmission Compressor Stations	988,250	988,250	988,250	988,250	988,250	988,250	988,250	988,250	988,250	988,250
	Gas Storage Compressor Stations	359,975	359,975	359,975	359,975	359,975	444,675	465,850	487,025	487,025	487,025
	Storage Reservoir Fugitives	0	0	0	0	0	0	0	0	0	0
	LNG Storage Compressor Stations	80,811	80,811	80,811	80,811	80,811	80,811	80,811	80,811	80,811	80,811
	LNG Terminal	0	0	0	0	0	0	0	0	0	0
Downstream	Cast-Iron Distribution Pipeline: Main	196,220	195,164	194,108	190,781	188,032	185,197	182,853	180,568	177,356	171,338
	Cast-Iron Distribution Pipeline: Services	4,181	4,181	4,139	3,911	3,896	3,862	3,861	4,218	4,239	4,212
	Unprotected Steel Distribution Pipeline: Main	266,809	230,807	263,752	255,225	268,166	234,812	243,576	249,885	241,702	236,319
	Unprotected Steel Distribution Pipeline: Services	3,255	3,131	3,006	2,854	2,929	2,840	2,672	2,678	2,723	2,769
	Protected Steel Distribution Pipeline: Main	32,774	33,265	34,000	34,607	34,530	34,453	34,376	34,299	33,695	33,780
	Protected Steel Distribution Pipeline: Services	206	205	214	216	194	199	192	190	188	185
	Plastic Distribution Pipeline: Main	4,919	5,122	6,085	6,661	7,108	7,491	7,878	8,286	9,239	9,580
	Plastic Distribution Pipeline: Services	63	66	78	85	91	96	101	106	118	123
	Copper Distribution Pipeline: Main	0	0	0	0	0	0	0	0	0	0
	Copper Distribution Pipeline: Services	258	255	253	250	248	245	244	244	243	242
	Commercial Meters	46,085	40,502	46,692	47,676	49,314	49,499	48,900	50,106	53,812	54,532
	Residential Meters	91,744	82,193	95,091	96,182	99,044	97,804	98,538	100,492	101,162	101,444

Table 15. CH_4 Emissions by Source Category in New York State from 2000–2009

Category	Source	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Upstream	Drill Rigs	2	3	2	2	3	5	9	11	11	5
	Drilling Fugitives	111	156	121	94	189	277	552	659	599	310
	Oil Well: Mud Degassing	2,677	3,764	3,067	4,800	9,085	13,807	26,408	28,505	27,633	13,930
	Gas Well: Mud Degassing	9,580	14,210	8,818	6,096	12,784	18,170	35,428	48,342	45,125	20,996
	Oil Well: Completions	638	1,105	765	1,190	2,380	4,038	7,650	8,075	6,970	4,038
	Gas Well: Completions	2,083	3,528	2,253	1,275	2,848	4,590	10,030	13,048	11,943	5,780
	Oil Well: Conventional Production_High Producing	625	361	443	249	533	489	1,485	1,383	2,337	943
	Oil Well: Conventional Production_Low Producing	2,013	6,874	6,549	7,557	7,756	13,609	25,643	28,177	25,655	23,669
	Gas Well: Conventional Production_High Producing	138,735	291,074	389,173	416,998	614,641	805,018	760,769	739,533	653,945	573,314
	Gas Well: Conventional Production_Low Producing	254,289	258,560	258,685	264,273	263,225	259,619	263,310	270,347	266,989	267,982
	Oil Well: Unconventional Production_High Producing	0	0	0	0	0	0	0	0	0	0
	Oil Well: Unconventional Production_Low Producing	0	0	0	0	0	0	0	0	0	0
	Gas Well: Unconventional Production_High Producing	0	0	0	0	0	0	0	0	0	0
	Gas Well: Unconventional Production_Low Producing	0	0	0	0	0	0	0	0	0	0
	Oil: Abandoned Wells	3,903	3,999	3,358	3,846	3,986	4,016	3,735	3,922	4,028	4,028
	Gas: Abandoned Wells	1,328	1,255	1,240	1,240	1,253	1,189	1,288	1,402	1,479	1,477
Midstream	Oil: Gathering and Processing	147	328	322	346	382	627	1,236	1,334	1,320	1,099
	Gas: Gathering and Processing	24,356	39,400	48,976	51,928	71,166	89,586	85,426	83,654	75,161	67,337
	Gathering Pipeline	60,000	43,733	51,333	52,133	51,067	50,933	50,213	68,200	71,147	73,173

Table 15 continued

	Oil: Truck Loading	0	0	0	0	0	0	0	0	0	0
	Gas: Truck Loading	0	0	0	0	0	0	0	0	0	0
	Gas Processing Plant	0	0	0	0	0	0	0	0	0	0
	Transmission Pipeline	66,703	66,979	67,782	67,782	67,782	67,782	68,092	68,092	70,510	70,510
	Gas Transmission Compressor Stations	988,250	988,250	1,005,000	1,005,000	1,005,000	1,005,000	1,005,000	1,005,000	1,072,000	1,072,000
	Gas Storage Compressor Stations	487,025	508,200	508,200	529,375	529,375	529,375	529,375	529,375	529,375	550,550
	Storage Reservoir Fugitives	0	0	0	0	0	0	0	0	0	0
	LNG Storage Compressor Stations	80,811	80,811	80,811	80,811	80,811	80,811	80,811	80,811	80,811	80,811
	LNG Terminal	0	0	0	0	0	0	0	0	0	0
Downstream	Cast-Iron Distribution Pipeline: Main	164,163	161,328	158,058	154,934	151,925	148,713	147,209	144,749	141,682	138,008
	Cast-Iron Distribution Pipeline: Services	4,208	4,176	4,108	4,104	4,104	4,387	4,396	4,264	4,236	3,923
	Unprotected Steel Distribution Pipeline: Main	230,269	228,180	219,373	212,224	206,367	202,429	200,711	196,172	198,325	186,764
	Unprotected Steel Distribution Pipeline: Services	2,868	2,690	2,772	2,726	2,653	2,605	2,551	2,476	2,433	2,312
	Protected Steel Distribution Pipeline: Main	34,038	34,217	34,703	35,013	35,039	34,726	35,081	35,090	35,003	34,543
	Protected Steel Distribution Pipeline: Services	173	169	146	145	139	138	138	134	134	126
	Plastic Distribution Pipeline: Main	10,232	10,721	11,222	11,759	12,213	12,631	12,922	13,214	13,692	14,209
	Plastic Distribution Pipeline: Services	131	137	144	150	156	159	163	166	169	173
	Copper Distribution Pipeline: Main	0	0	0	0	0	0	0	0	0	0
	Copper Distribution Pipeline: Services	241	240	238	236	238	235	232	229	226	222
	Commercial Meters	57,965	55,968	57,281	60,391	57,981	59,128	62,022	62,199	67,442	59,782
	Residential Meters	105,569	101,724	104,336	105,205	106,610	106,727	107,146	107,590	107,264	108,158

Table 16. CH_4 Emissions by Source Category in New York State from 2010–2017

Category	Source	2010	2011	2012	2013	2014	2015	2016	2017
Upstream	Drill Rigs	8	6	4	3	4	1	1	0
	Drilling Fugitives	436	302	204	178	210	56	39	25
	Oil Well: Mud Degassing	33,839	28,805	24,148	20,423	25,620	4,188	4,070	2,696
	Gas Well: Mud Degassing	19,642	9,652	2,533	1,719	1,166	143	0	0
	Oil Well: Completions	8,670	7,098	5,950	5,228	6,460	1,785	1,275	808
	Gas Well: Completions	5,228	2,465	425	510	213	43	0	0
	Oil Well: Conventional Production_High Producing	799	1,036	235	671	410	267	176	271
	Oil Well: Conventional Production_Low Producing	26,721	25,928	29,790	29,198	30,324	23,857	21,877	22,915
	Gas Well: Conventional Production_High Producing	462,401	413,626	327,282	276,593	230,706	192,508	136,416	108,132
	Gas Well: Conventional Production_Low Producing	273,160	277,698	282,648	298,386	292,177	272,175	259,555	240,544
	Oil Well: Unconventional Production_High Producing	0	0	0	0	0	0	0	0
	Oil Well: Unconventional Production_Low Producing	0	0	0	0	0	0	0	0
	Gas Well: Unconventional Production_High Producing	0	0	0	0	0	0	0	0
	Gas Well: Unconventional Production_Low Producing	0	0	0	0	0	0	0	0
	Oil: Abandoned Wells	4,070	3,984	3,639	3,979	3,585	4,053	4,176	3,134
	Gas: Abandoned Wells	1,536	1,565	1,556	1,554	1,549	1,567	1,573	1,413
Midstream	Oil: Gathering and Processing	1,215	1,204	1,291	1,308	1,330	1,041	948	1,002
	Gas: Gathering and Processing	56,736	52,171	43,958	39,682	34,941	30,363	24,354	20,785
	Gathering Pipeline	46,267	47,680	42,840	11,053	15,493	11,107	9,800	10,840

Table 16 continued

	Oil: Truck Loading	0	0	0	0	0	0	0	0
	Gas: Truck Loading	0	0	0	0	0	0	0	0
	Gas Processing Plant	0	0	0	0	0	0	0	0
	Transmission Pipeline	70,510	70,510	70,510	71,021	71,021	71,021	71,021	71,021
	Gas Transmission Compressor Stations	1,072,000	1,072,000	1,072,000	1,072,000	1,072,000	1,072,000	1,072,000	1,072,000
	Gas Storage Compressor Stations	550,550	550,550	550,550	550,550	550,550	550,550	550,550	550,550
	Storage Reservoir Fugitives	0	0	0	0	0	0	0	0
	LNG Storage Compressor Stations	80,811	80,811	80,811	80,811	80,811	80,811	80,811	80,811
	LNG Terminal	0	0	0	0	0	0	0	0
Downstream	Cast-Iron Distribution Pipeline: Main	134,247	131,382	127,795	123,079	118,218	114,573	104,591	98,949
	Cast-Iron Distribution Pipeline: Services	3,720	3,607	3,430	2,927	3,113	2,608	2,389	1,824
	Unprotected Steel Distribution Pipeline: Main	182,611	177,486	168,830	162,538	157,530	153,447	147,862	140,426
	Unprotected Steel Distribution Pipeline: Services	2,192	2,176	2,132	1,927	1,910	1,772	1,667	1,597
	Protected Steel Distribution Pipeline: Main	34,589	34,639	35,081	34,752	35,079	34,913	34,910	35,053
	Protected Steel Distribution Pipeline: Services	119	135	127	133	138	120	117	145
	Plastic Distribution Pipeline: Main	14,547	14,856	15,206	15,738	16,201	16,662	17,250	17,762
	Plastic Distribution Pipeline: Services	174	184	187	193	200	204	208	208
	Copper Distribution Pipeline: Main	0	0	0	0	0	0	0	0
	Copper Distribution Pipeline: Services	221	225	220	212	216	201	186	178
	Commercial Meters	58,953	68,949	67,755	67,651	69,198	70,147	70,200	70,421
	Residential Meters	107,460	110,625	109,010	108,809	109,334	109,559	109,439	110,674

5.4 Emissions by County and Economic Region in Year 2017

Figure 17 shows the distribution of emissions by county in New York State. The counties with the largest emissions correspond to the high oil and natural gas exploration and production areas in the west of the state as well as to areas of high population and corresponding gas services around New York City and Long Island. As shown in Figure 17, Erie County had the highest total CH_4 emissions, accounting for 11.3% of statewide CH_4 emissions from oil and natural gas sector, followed by Steuben County (11.0%). Erie County had the second-highest gas production in New York State, as well as the largest miles of transmission pipeline (381.9 miles) and second-highest number of compressor stations (five gas transmission compressor stations and six gas storage compressor stations), resulting in high-midstream emissions. Steuben County ranked highest in conventional gas production and in number of compressor stations (five gas transmission compressor stations and seven gas storage compressor stations) and second highest in miles of transmission pipeline (320.4 miles), resulting in high upstream and midstream emissions. The top five counties (Erie, Steuben, Chautauqua, Cattaraugus, and Allegany) account for 41.7% of statewide CH_4 emissions. Data for each county are shown in Figure 18 and annual total emissions by county are shown in Table 17 through Table 20.

Figure 17. Map of CH_4 Emissions by County in New York State in 2017 (AR4 GWP_{100}).

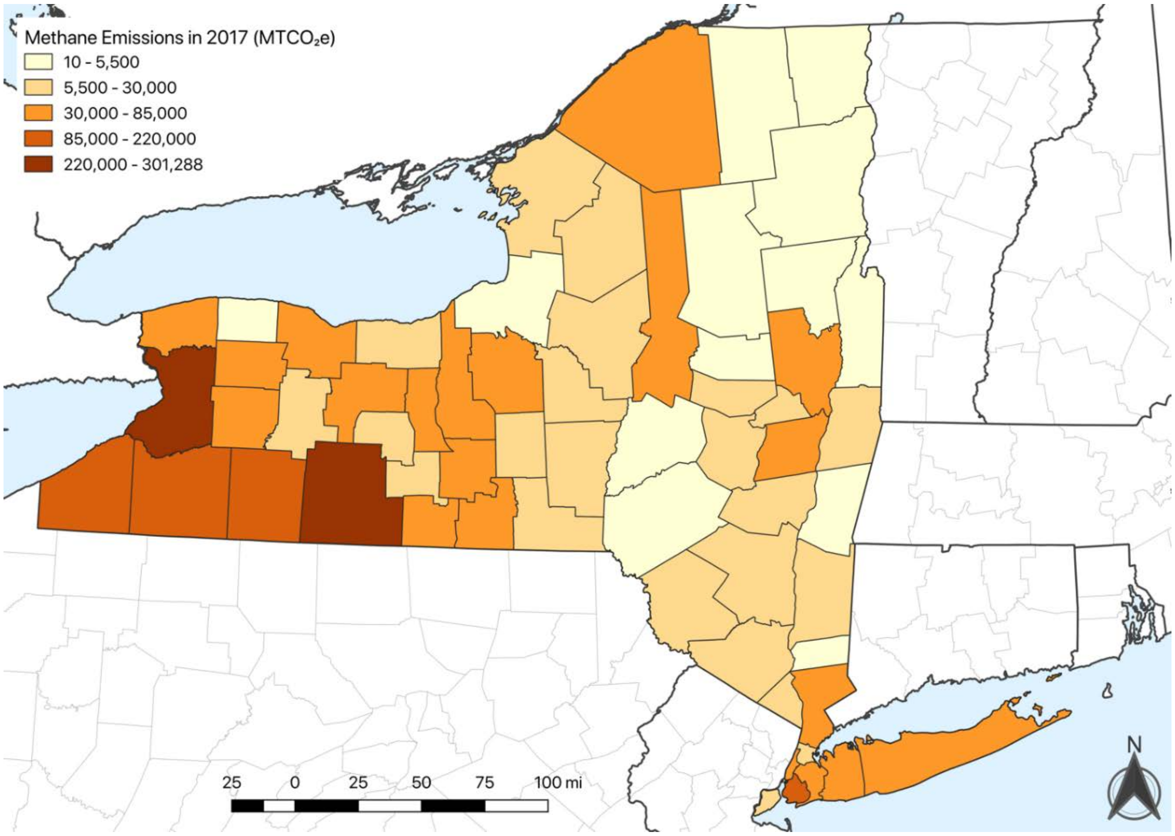


Figure 18. CH_4 Emissions by County in New York State in 2017 (AR4 GWP_{100})

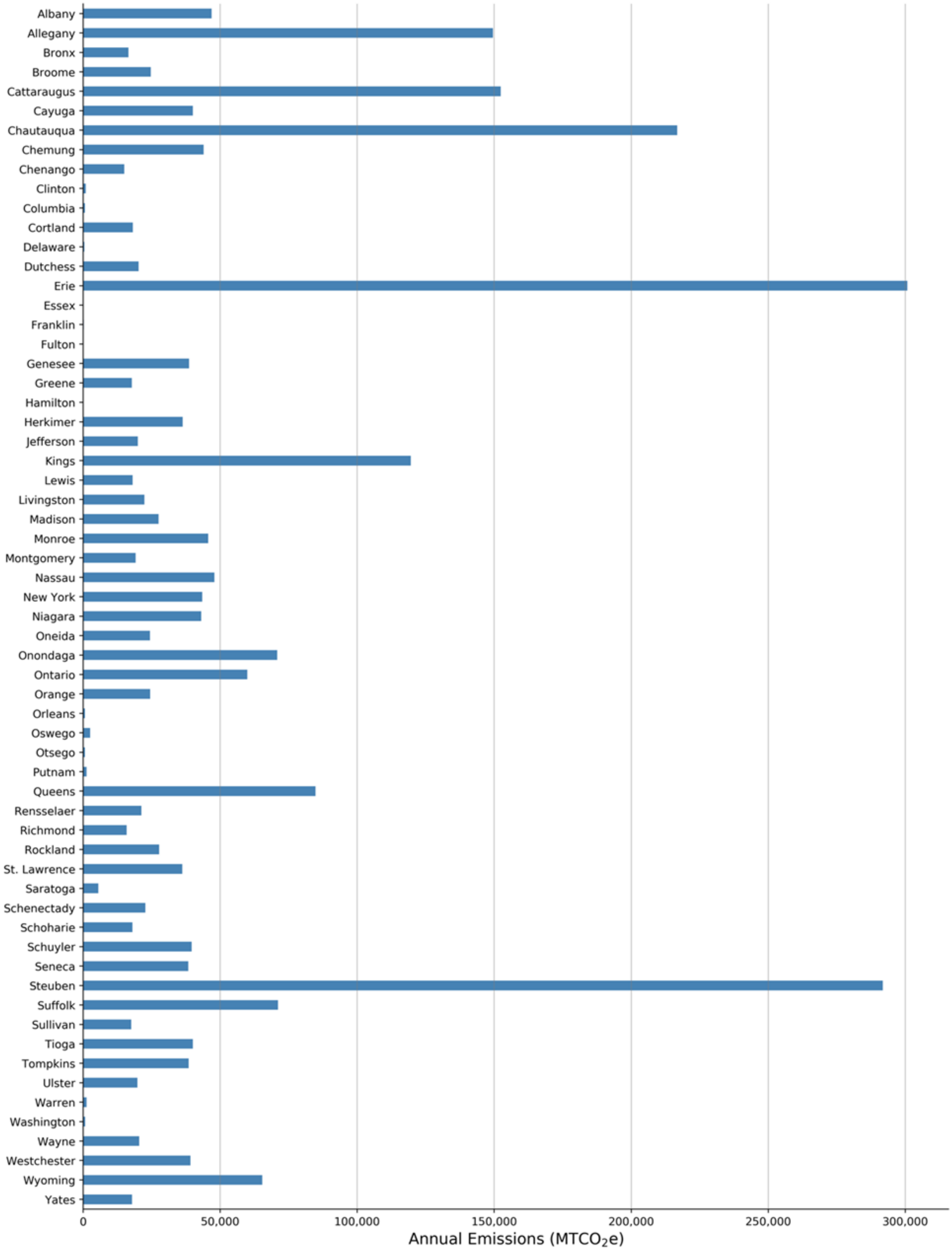


Table 17. CH_4 Emissions by County in New York State from 1990–1999 ($MTCO_2e$; AR4 GWP_{100})

County Name	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Albany	51,030	49,809	51,071	50,857	51,226	50,327	50,475	50,654	50,447	50,214
Allegany	127,855	127,217	134,075	126,927	130,668	128,051	126,855	130,288	126,542	126,337
Bronx	21,941	20,212	21,975	21,669	22,177	20,889	21,180	21,448	21,199	20,824
Broome	27,573	26,803	27,598	27,454	27,685	27,077	27,182	27,291	27,129	27,157
Cattaraugus	111,452	112,858	133,149	130,446	123,797	140,203	136,095	145,852	146,546	147,651
Cayuga	78,694	72,820	62,814	59,035	60,503	59,790	64,052	62,315	60,454	58,099
Chautauqua	400,036	410,222	399,939	394,741	406,686	381,425	405,294	368,855	344,817	331,005
Chemung	22,801	22,433	22,829	22,753	22,868	22,720	22,753	23,172	22,740	24,616
Chenango	93	83	92	93	96	94	92	97	101	101
Clinton	1,086	1,023	1,089	1,086	1,107	1,067	1,064	1,069	1,075	1,068
Columbia	574	561	577	580	586	583	583	586	601	606
Cortland	18,015	18,005	18,024	18,030	18,039	18,038	18,037	18,043	18,054	18,448
Delaware	402	400	405	407	410	411	410	413	416	417
Dutchess	20,314	20,110	20,323	20,313	20,379	20,276	20,299	20,350	20,385	20,363
Erie	308,654	303,452	312,453	321,709	308,144	324,551	321,585	318,499	316,738	310,199
Essex	137	127	137	135	138	129	131	133	130	128
Franklin	240	219	240	239	245	232	232	232	238	237
Fulton	109	97	108	109	112	111	109	114	118	117
Genesee	60,558	57,555	54,850	54,279	55,664	55,044	55,577	54,576	53,203	51,805
Greene	17,728	17,707	17,734	17,736	17,746	17,737	17,740	17,749	17,761	17,761
Hamilton	17	16	17	17	17	16	17	17	16	16
Herkimer	19,925	19,800	19,940	19,923	19,967	19,869	19,890	19,916	19,896	19,876
Jefferson	20,681	20,444	20,694	20,654	20,728	20,552	20,589	20,630	20,593	20,550
Kings	146,459	138,516	146,653	145,086	147,417	141,326	142,635	143,909	142,463	140,791
Lewis	17,999	17,982	18,008	18,010	18,020	18,007	18,014	18,021	18,030	18,029
Livingston	28,809	28,509	29,355	28,243	28,619	27,934	28,074	26,529	26,540	25,667
Madison	20,983	20,851	21,042	20,225	21,117	21,391	21,167	21,665	23,287	25,883
Monroe	56,892	53,849	56,970	56,391	57,289	54,957	55,391	55,827	55,239	54,621
Montgomery	19,533	19,400	19,545	19,525	19,570	19,472	19,493	19,521	19,499	19,475
Nassau	57,388	54,134	57,431	56,961	57,917	55,798	56,062	56,456	56,288	55,760
New York	53,694	49,099	53,699	53,197	54,537	52,091	52,435	53,388	53,754	53,050
Niagara	29,672	28,788	29,703	29,540	29,811	29,134	29,256	29,387	29,204	29,009
Oneida	26,935	26,221	26,959	26,831	27,046	26,506	26,588	26,690	26,550	26,399
Onondaga	77,911	75,963	77,976	77,620	78,205	76,707	76,959	77,232	76,865	76,468
Ontario	44,426	44,112	44,702	44,443	44,458	44,348	44,304	44,495	44,327	44,096

Table 17 continued

County Name	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Orange	26,100	25,458	26,121	26,021	26,216	25,763	25,871	25,981	25,937	25,824
Orleans	960	884	961	948	970	915	924	937	922	905
Oswego	3,575	3,303	3,601	3,536	3,619	3,406	3,446	3,487	3,434	3,371
Otsego	631	615	634	637	644	638	635	637	645	649
Putnam	1,149	1,084	1,152	1,150	1,172	1,159	1,174	1,201	1,226	1,229
Queens	105,066	98,975	105,203	104,041	105,828	101,295	102,236	103,137	102,114	100,862
Rensselaer	22,669	22,258	22,683	22,608	22,732	22,420	22,482	22,540	22,464	22,384
Richmond	21,958	20,279	22,002	21,669	22,163	20,865	21,134	21,386	21,055	20,708
Rockland	31,188	30,113	31,216	31,025	31,344	30,554	30,697	30,876	30,752	30,553
St. Lawrence	35,992	35,963	36,008	36,020	36,040	36,034	36,033	36,050	36,075	36,077
Saratoga	7,238	6,693	7,252	7,153	7,314	6,918	7,007	7,096	7,014	6,913
Schenectady	24,774	24,213	24,794	24,687	24,856	24,428	24,512	24,580	24,449	24,320
Schoharie	17,831	17,833	17,840	17,845	17,850	17,854	17,859	17,865	17,870	17,874
Schuyler	39,469	39,450	39,480	39,483	39,494	39,481	39,676	39,500	39,646	39,732
Seneca	53,806	50,542	44,741	40,658	41,718	38,644	42,887	42,518	37,580	38,265
Steuben	118,259	114,355	120,652	119,325	118,125	162,967	192,213	183,206	191,357	200,615
Suffolk	77,253	74,581	77,286	76,921	77,709	76,042	76,359	76,875	76,894	76,575
Sullivan	17,493	17,482	17,498	17,498	17,504	17,497	17,501	17,505	17,505	17,504
Tioga	19,375	19,100	19,199	19,002	19,031	18,973	18,991	19,016	19,267	18,997
Tompkins	39,318	39,030	39,342	39,296	39,392	39,180	39,220	39,272	39,355	39,464
Ulster	20,266	20,039	20,274	20,247	20,317	20,144	20,162	20,207	20,223	20,196
Warren	1,676	1,539	1,678	1,657	1,697	1,601	1,611	1,625	1,615	1,600
Washington	954	879	955	941	963	905	918	932	920	906
Wayne	20,925	20,706	20,979	20,907	20,977	20,868	20,852	20,939	20,861	20,866
Westchester	46,049	43,731	46,084	45,733	46,415	44,870	45,112	45,447	45,335	44,960
Wyoming	79,145	80,575	78,794	75,161	75,838	75,568	73,753	74,181	73,340	72,400
Yates	17,923	17,660	17,883	17,936	17,891	17,978	17,910	17,820	17,782	18,845

Table 18. CH$_4$ Emissions by County in New York State from 2000–2009 (MTCO$_2$e, AR4 GWP$_{100}$)

County Name	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Albany	49,286	48,605	48,247	47,972	47,650	47,511	47,546	47,242	49,179	48,687
Allegany	125,891	129,041	145,000	147,163	148,622	151,202	155,830	158,047	161,923	159,621
Bronx	21,970	21,857	22,176	22,694	23,086	23,620	24,368	24,779	19,410	18,727
Broome	25,830	25,637	25,720	31,066	27,139	25,546	24,498	24,313	26,334	25,964
Cattaraugus	148,517	147,400	144,989	138,381	139,956	153,683	183,497	192,193	183,922	170,004
Cayuga	54,960	52,879	52,060	49,379	47,656	40,376	48,618	48,536	49,579	54,924
Chautauqua	316,477	313,058	301,254	295,659	294,129	298,189	316,585	337,762	345,745	328,594
Chemung	25,458	148,892	271,019	263,180	247,177	417,673	394,936	358,858	271,933	208,631
Chenango	508	494	497	497	767	1,013	634	3,917	13,394	39,293
Clinton	1,133	1,157	1,160	1,178	1,148	1,132	1,126	1,124	1,086	1,030
Columbia	1,010	996	985	1,023	997	997	968	972	650	629
Cortland	19,306	19,248	19,212	19,605	19,458	19,370	19,150	19,343	18,153	18,128
Delaware	760	765	749	720	859	686	665	663	440	435
Dutchess	22,771	22,802	22,808	22,823	22,609	22,567	22,522	22,494	20,563	20,354
Erie	309,534	303,227	303,218	302,399	302,250	307,076	315,702	321,503	333,926	341,809
Essex	122	135	134	127	101	79	76	65	114	111
Franklin	283	281	265	229	225	212	212	211	221	206
Fulton	1,361	1,352	1,290	1,274	1,230	1,199	1,174	1,162	134	115
Genesee	49,992	47,820	48,658	46,025	47,198	45,077	45,479	52,074	49,122	46,498
Greene	17,800	17,811	17,815	17,811	17,815	17,832	17,846	17,838	17,818	17,790
Hamilton	14	13	11	8	7	4	5	4	14	14
Herkimer	20,018	20,027	19,992	19,958	19,917	19,878	19,808	19,764	36,573	36,528
Jefferson	20,520	20,485	20,463	20,401	20,334	20,259	20,155	20,055	20,365	20,272
Kings	137,673	136,758	136,659	136,138	135,461	134,907	135,417	134,502	133,226	130,716
Lewis	18,004	18,013	18,030	18,046	18,042	18,056	18,055	18,063	18,079	18,066
Livingston	26,327	25,182	24,623	24,363	25,553	24,884	24,364	25,174	24,768	24,241
Madison	23,401	26,113	25,995	26,072	25,804	25,626	26,926	29,812	36,062	43,136
Monroe	53,867	52,674	51,763	51,110	50,298	49,455	49,225	48,358	51,405	50,343
Montgomery	19,346	19,287	19,232	19,198	19,158	19,264	19,119	19,115	19,409	19,354
Nassau	54,289	53,707	53,424	53,749	53,533	53,652	54,307	54,231	53,552	51,765
New York	50,643	50,610	50,921	51,659	51,116	51,211	52,063	52,195	51,009	47,760
Niagara	28,634	28,364	28,025	27,709	27,468	27,242	27,125	27,056	44,768	44,475
Oneida	25,900	25,993	25,834	25,602	25,357	25,296	25,015	24,799	25,709	25,447
Onondaga	74,502	73,703	73,498	72,659	72,189	71,475	71,756	71,042	74,601	73,878
Ontario	44,667	44,360	44,343	44,455	44,617	44,051	44,244	43,900	62,019	60,876

Table 18 continued

County Name	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Orange	27,579	27,292	27,193	27,148	26,876	26,953	27,024	26,949	25,606	25,264
Orleans	1,017	984	972	935	930	906	921	901	823	794
Oswego	2,997	2,852	2,797	2,692	3,058	2,540	2,514	2,493	3,103	2,984
Otsego	1,154	1,176	1,198	1,196	1,143	1,152	1,156	1,486	701	862
Putnam	1,258	1,261	1,267	1,285	1,249	1,218	1,229	1,250	1,321	1,230
Queens	102,177	101,218	101,048	100,464	99,933	99,965	100,346	99,770	95,348	93,159
Rensselaer	21,944	21,738	21,675	21,579	21,436	21,438	21,413	21,417	22,022	21,867
Richmond	20,452	19,919	19,459	19,103	18,690	18,457	18,245	17,765	19,013	18,439
Rockland	31,086	30,724	30,369	30,016	29,638	29,401	29,354	29,092	29,659	29,193
St. Lawrence	37,922	37,886	37,930	37,889	37,857	37,810	37,812	37,797	36,235	36,186
Saratoga	7,623	7,608	7,426	7,333	7,317	7,219	7,201	7,180	6,519	6,292
Schenectady	23,930	23,692	23,501	23,355	23,205	23,016	22,823	22,599	23,764	23,582
Schoharie	17,939	17,958	17,970	17,960	17,956	17,963	17,981	17,978	17,945	17,940
Schuyler	40,132	39,807	40,127	39,471	61,318	98,369	99,964	78,712	60,715	58,067
Seneca	38,887	38,696	39,758	38,494	38,825	37,247	39,699	47,658	62,949	57,903
Steuben	235,834	291,425	287,720	365,664	587,122	590,699	541,378	562,885	546,971	493,211
Suffolk	76,425	75,925	75,834	75,940	75,370	75,249	75,540	75,331	75,791	74,013
Sullivan	17,485	17,489	17,485	17,469	17,470	17,465	17,464	17,475	17,526	17,522
Tioga	19,183	40,740	41,565	40,186	40,339	39,967	40,917	40,658	40,486	40,123
Tompkins	38,745	38,649	38,577	38,715	38,699	38,662	38,401	38,606	39,180	38,927
Ulster	20,036	19,997	19,992	19,947	19,899	19,908	19,890	19,920	20,178	20,027
Warren	2,039	1,965	1,924	1,882	1,857	1,787	1,759	1,716	1,497	1,431
Washington	834	822	778	755	717	699	694	654	838	809
Wayne	21,153	21,051	21,005	21,231	21,027	21,201	23,534	22,052	21,286	21,483
Westchester	43,126	42,596	42,304	41,980	41,490	41,237	41,491	41,652	43,398	42,136
Wyoming	72,454	71,327	71,080	70,742	71,298	71,980	73,355	72,769	70,666	70,463
Yates	18,947	18,593	18,256	18,121	18,044	18,010	17,910	18,228	18,900	17,842

Table 19. CH_4 Emissions by County in New York State from 2010–2017 ($MTCO_2e$, AR4 GWP_{100})

County Name	2010	2011	2012	2013	2014	2015	2016	2017
Albany	48,464	48,509	48,134	47,864	47,673	47,501	47,131	46,854
Allegany	158,844	158,573	166,232	158,604	160,796	152,445	149,866	149,559
Bronx	18,447	18,623	18,169	17,789	17,603	17,400	16,909	16,514
Broome	25,776	25,753	25,525	25,347	25,214	25,088	24,847	24,670
Cattaraugus	194,955	183,558	168,358	172,669	176,939	150,098	149,813	152,339
Cayuga	54,925	54,215	49,446	46,216	45,333	43,559	42,463	40,040
Chautauqua	304,232	300,492	296,274	288,976	276,509	258,767	240,423	216,771
Chemung	184,568	171,241	130,917	116,088	93,207	78,385	53,602	43,956
Chenango	42,526	41,058	33,266	27,849	23,637	20,357	17,638	14,957
Clinton	1,015	1,054	1,029	1,015	1,009	1,002	981	971
Columbia	624	644	644	645	645	650	649	647
Cortland	18,122	18,142	18,142	18,147	18,146	18,145	18,141	18,140
Delaware	435	440	436	438	438	436	436	436
Dutchess	20,297	20,438	20,376	20,335	20,316	20,305	20,264	20,225
Erie	352,652	347,052	336,587	323,383	316,598	309,937	304,894	300,783
Essex	110	108	105	102	100	98	95	92
Franklin	202	212	203	197	192	190	183	180
Fulton	110	121	118	115	117	114	115	113
Genesee	46,527	46,310	45,449	43,369	43,285	39,846	39,096	38,666
Greene	17,784	17,803	17,796	17,796	17,791	17,788	17,785	17,781
Hamilton	14	14	13	13	13	12	12	12
Herkimer	36,504	36,501	36,460	36,441	36,420	36,397	36,357	36,328
Jefferson	20,238	20,245	20,175	20,120	20,078	20,039	19,965	19,911
Kings	129,490	129,738	127,626	125,890	124,838	123,874	121,477	119,580
Lewis	18,063	18,072	18,065	18,067	18,063	18,061	18,056	18,052
Livingston	23,670	23,353	23,071	22,559	22,812	22,155	22,302	22,348
Madison	37,358	42,613	36,262	33,746	32,070	30,886	29,536	27,534
Monroe	49,789	49,749	48,896	48,178	47,689	47,220	46,299	45,597
Montgomery	19,331	19,335	19,297	19,269	19,245	19,221	19,183	19,152
Nassau	51,118	51,841	50,884	50,195	49,821	49,419	48,522	47,839
New York	46,866	48,987	47,689	46,724	46,384	45,788	44,357	43,462
Niagara	44,316	44,289	44,035	43,808	43,674	43,545	43,270	43,066
Oneida	25,315	25,314	25,111	24,931	24,827	24,724	24,496	24,334
Onondaga	73,506	73,492	72,932	72,475	72,173	71,868	71,241	70,795
Ontario	60,412	60,402	60,386	60,238	60,048	60,035	59,706	59,909

Table 19 continued

County Name	2010	2011	2012	2013	2014	2015	2016	2017
Orange	25,130	25,237	25,034	24,891	24,815	24,746	24,571	24,427
Orleans	777	781	758	737	726	715	691	674
Oswego	2,930	2,940	2,859	2,782	2,745	2,697	2,610	2,544
Otsego	670	692	689	687	685	687	681	679
Putnam	1,207	1,263	1,235	1,223	1,229	1,223	1,206	1,194
Queens	92,135	92,407	90,787	89,502	88,707	87,954	86,179	84,748
Rensselaer	21,790	21,795	21,674	21,576	21,507	21,448	21,319	21,224
Richmond	18,150	18,115	17,642	17,260	16,999	16,748	16,222	15,825
Rockland	28,994	29,063	28,745	28,515	28,373	28,263	27,962	27,715
St. Lawrence	36,177	36,211	36,197	36,197	36,195	36,193	36,186	36,182
Saratoga	6,192	6,236	6,083	5,953	5,884	5,807	5,641	5,514
Schenectady	23,476	23,449	23,291	23,157	23,063	22,971	22,795	22,664
Schoharie	17,938	17,942	17,939	17,947	17,950	17,951	17,949	17,949
Schuyler	50,425	50,472	48,646	46,717	46,923	46,099	40,120	39,542
Seneca	52,508	48,180	45,256	43,135	42,099	40,631	40,339	38,331
Steuben	405,524	374,846	352,937	334,571	331,188	316,940	300,019	291,832
Suffolk	73,471	74,345	73,582	73,008	72,725	72,371	71,641	71,074
Sullivan	17,520	17,518	17,514	17,515	17,512	17,511	17,506	17,503
Tioga	40,538	40,114	40,774	40,077	40,062	40,236	40,020	40,001
Tompkins	38,874	38,889	38,806	38,750	38,708	38,666	38,573	38,506
Ulster	19,979	20,054	19,990	19,936	19,920	19,893	19,839	19,791
Warren	1,405	1,427	1,389	1,352	1,328	1,314	1,274	1,245
Washington	794	796	775	753	737	724	705	688
Wayne	20,757	20,984	20,757	20,642	20,580	20,537	20,510	20,451
Westchester	41,668	42,128	41,421	40,889	40,591	40,288	39,636	39,139
Wyoming	70,052	69,446	69,646	67,631	66,920	66,089	65,284	65,306
Yates	17,742	17,733	17,612	17,828	17,827	17,683	17,870	17,823

New York State has 10 distinct economic regions, as defined by Empire State Development and shown in Figure 19. The CH_4 emissions for these regions are presented in Table 20. CH_4 emissions in 2017 were greatest in Western New York (32.4%) and the Southern Tier (18.5%). As discussed in section 2.2.3, the Western New York and Southern Tier regions have a large portion of oil and natural gas exploration and development, as well as a high density of pipelines. The New York City (10.5%) region has no oil or natural gas development, but does have a high number of distribution lines, natural gas services, and meters providing end-user populations with commercial and residential gas services.

Figure 19. New York State Economic Regions as Identified by Empire State Development

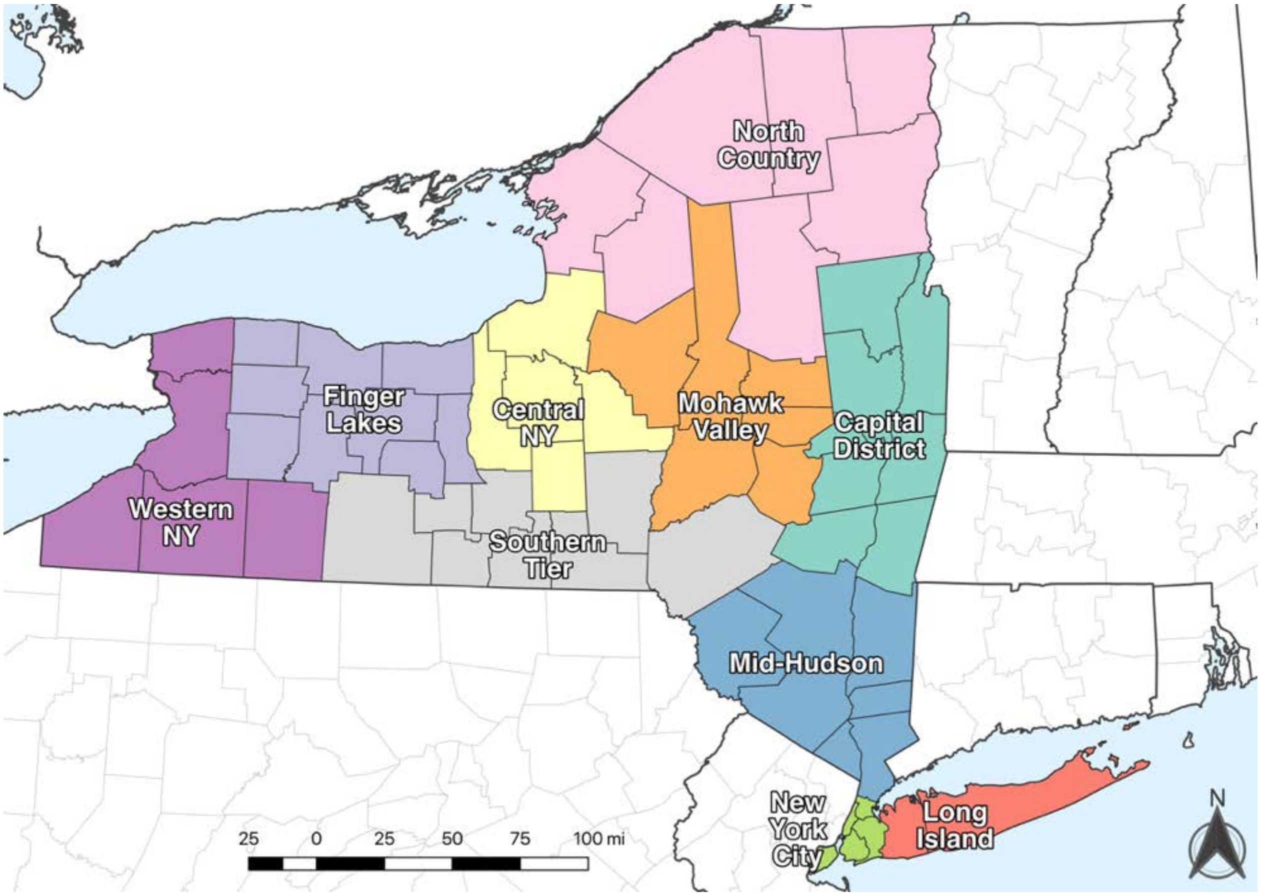


Figure 20. CH_4 Emissions by Economic Region in New York State in 2017 (AR4 GWP_{100})

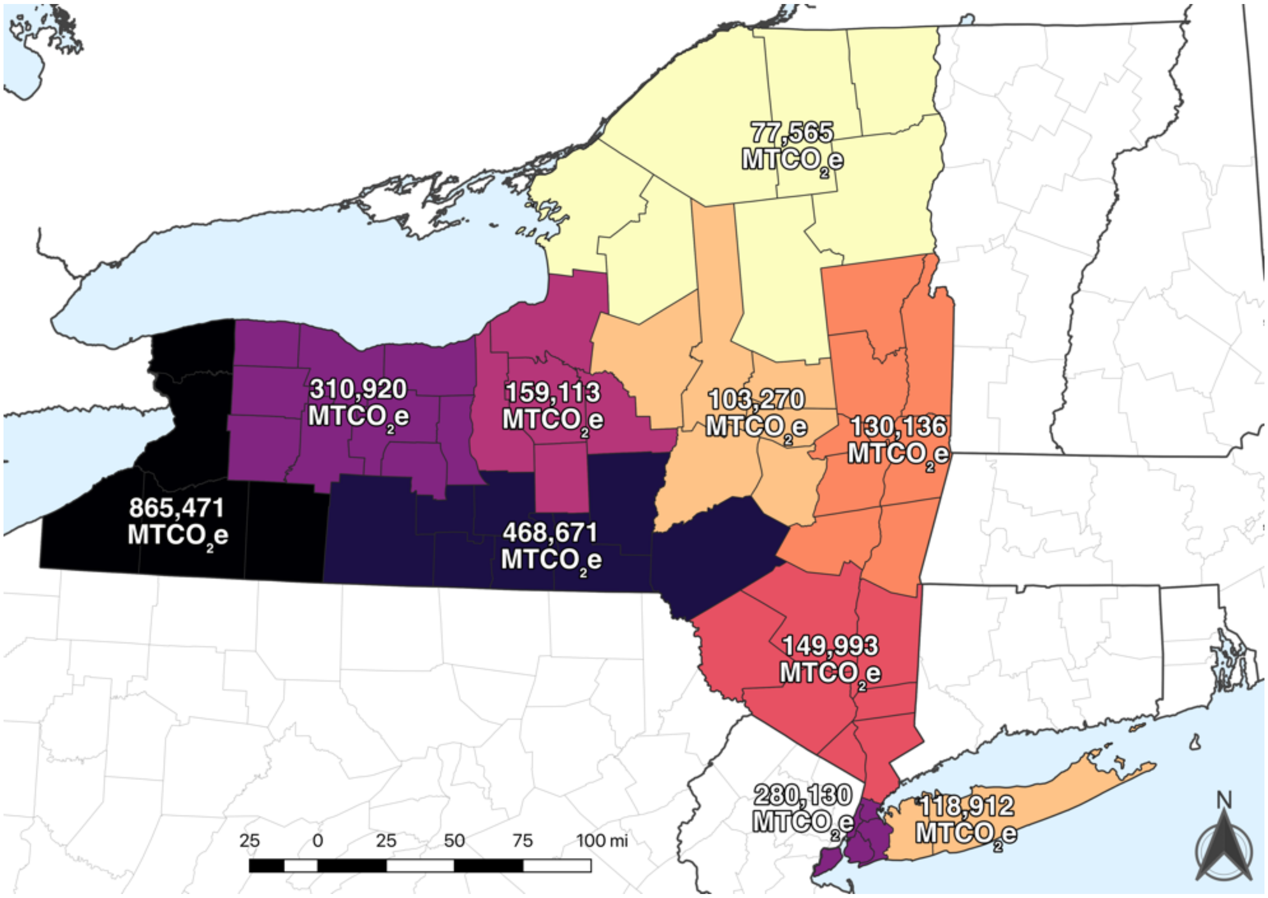


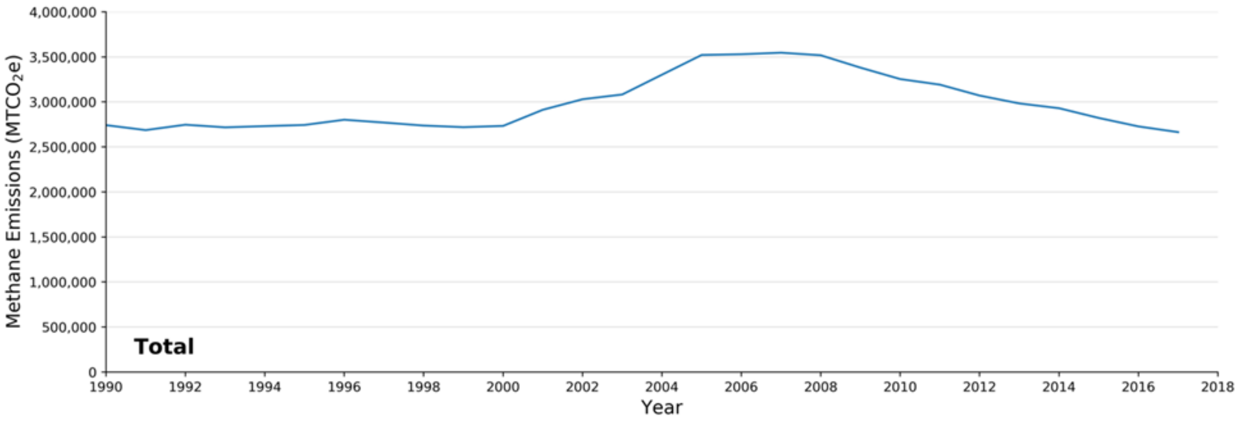
Table 20. CH_4 Emissions by Economic Region in New York State in 2017

Upstate/Downstate	Region	% of CH_4 Emissions
Upstate	Western New York	32.4%
Upstate	Finger Lakes	11.6%
Upstate	Southern Tier	18.5%
Upstate	Central New York	6.0%
Upstate	North Country	2.8%
Upstate	Mohawk Valley	3.7%
Upstate	Capital District	4.4%
Downstate	Hudson Valley	5.6%
Downstate	New York City	10.5%
Downstate	Long Island	4.5%

5.5 Emissions Time Series

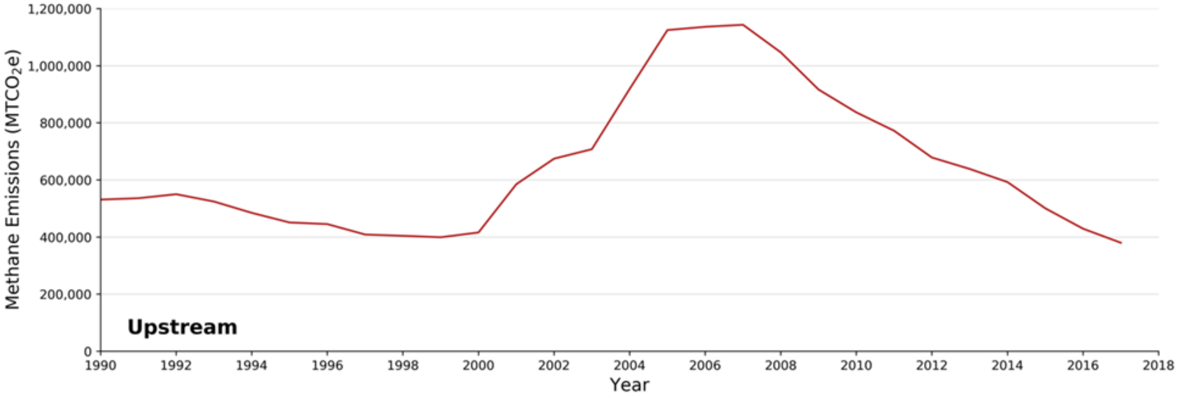
Figure 21 shows total CH_4 emissions in New York State from 1990–2017. As noted previously, retrospective emissions are estimated by applying current methodologies and EFs to past activity data. Figure 21 shows that total CH_4 emissions followed a generally increasing trend from 1990 until peaking at 3.546 $MMTCO_2e$ in 2007. Since 2007 CH_4 emissions decreased each year and are currently at levels last seen in 2000. Total CH_4 emissions have decreased 11.5% since their peak in 2007. The following describes this trend in more detail.

Figure 21. Total CH_4 Emissions in New York State from 1990–2017 (AR4 GWP_{100})



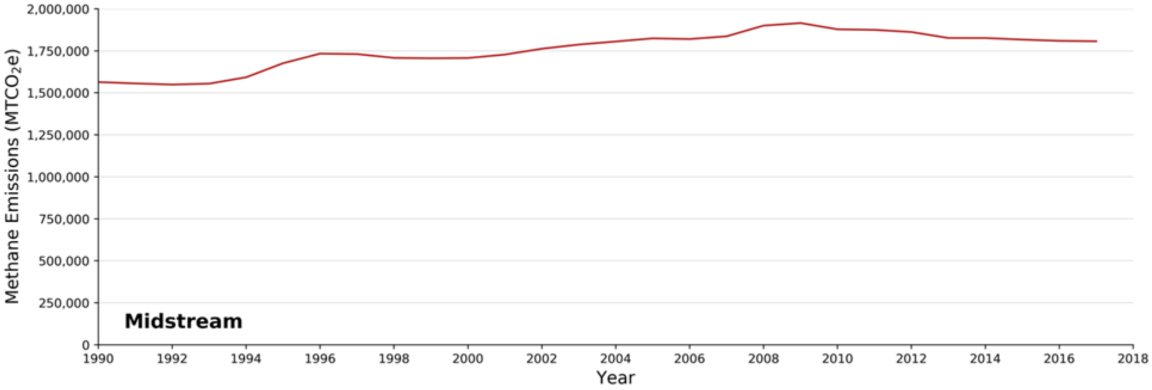
Total emissions are the sum of upstream (Figure 22), midstream (Figure 23), and downstream (Figure 24) emissions. Upstream emissions, though smaller in magnitude than midstream and downstream emissions, have shown greater variation over time, more closely mirroring the cyclical nature of oil and gas exploration and well completions in New York State. Upstream CH_4 emissions peaked at 1.143 $MMTCO_2e$ in 2007, corresponding with the observed peak in natural gas production (shown in Figure 4) and well completions (shown in Figure 2), which both correspond with peak natural gas prices and which have declined since 2007. Correspondingly, well completions have fallen to near-zero and natural gas production is around one-fifth of the peak production observed in 2007, resulting in an overall decline in emissions associated with upstream source categories. Overall upstream emissions decreased 28.5% from 1990–2017, and by 66.8% from 2007–2017.

Figure 22. Upstream CH_4 Emissions in New York State from 1990–2017 (AR4 GWP_{100})



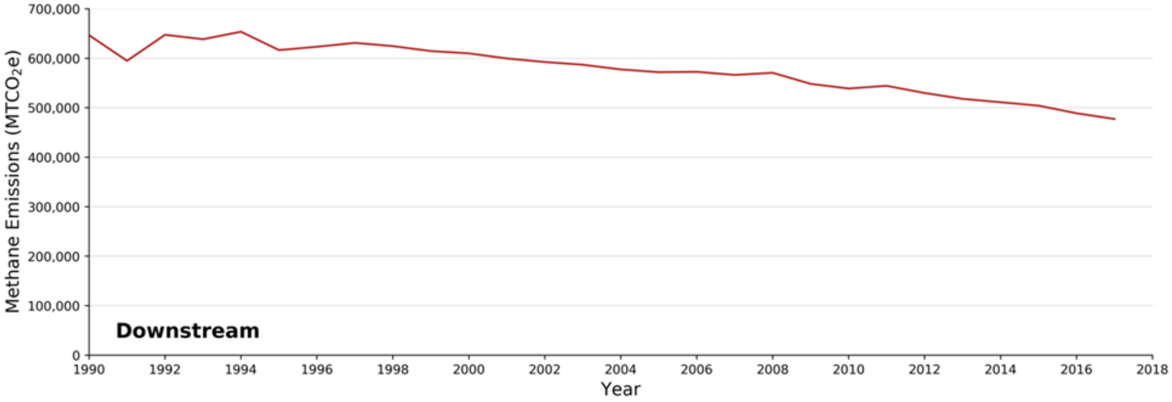
Midstream CH_4 emissions (Figure 23) increased from 1990–2017 by 15.5%. However, since 2009 midstream emissions have declined by 5.7% as a result of declining natural gas production and subsequent midstream throughput. As shown in Figure 16, midstream CH_4 emissions are largely a function of transmission and storage compressor stations and transmission pipelines. DEC data show increasing compressor counts and throughput in New York State, resulting in generally increasing midstream CH_4 emissions. Although natural gas production in the State has declined since 2006, natural gas consumption has increased, rising by 16.2% from 1,080,215 million cubic feet (MMcf) in 2005 to 1,255,344 MMcf in 2017 (EIA 2018). Correspondingly, emissions from transmission compressor stations have risen in order to accommodate increased natural gas throughput, driven by consumption.

Figure 23. Midstream CH_4 Emissions in New York State from 1990–2017 (AR4 GWP_{100})



Downstream CH_4 emissions (Figure 24) decreased by 26.2% from 1990–2017. The two largest source categories in downstream emissions, cast-iron and unprotected steel distribution main pipeline mileage, have both decreased since 1990 and have largely been replaced with plastic distribution mains. Plastic mains have much lower leak rates and therefore a lower EF, resulting in the downward trend observed in Figure 24. Additionally, increasing consumption in New York State has driven increases in the number of residential services and meters, though this growth is outweighed by the transition from cast-iron and unprotected steel distribution lines to plastic.

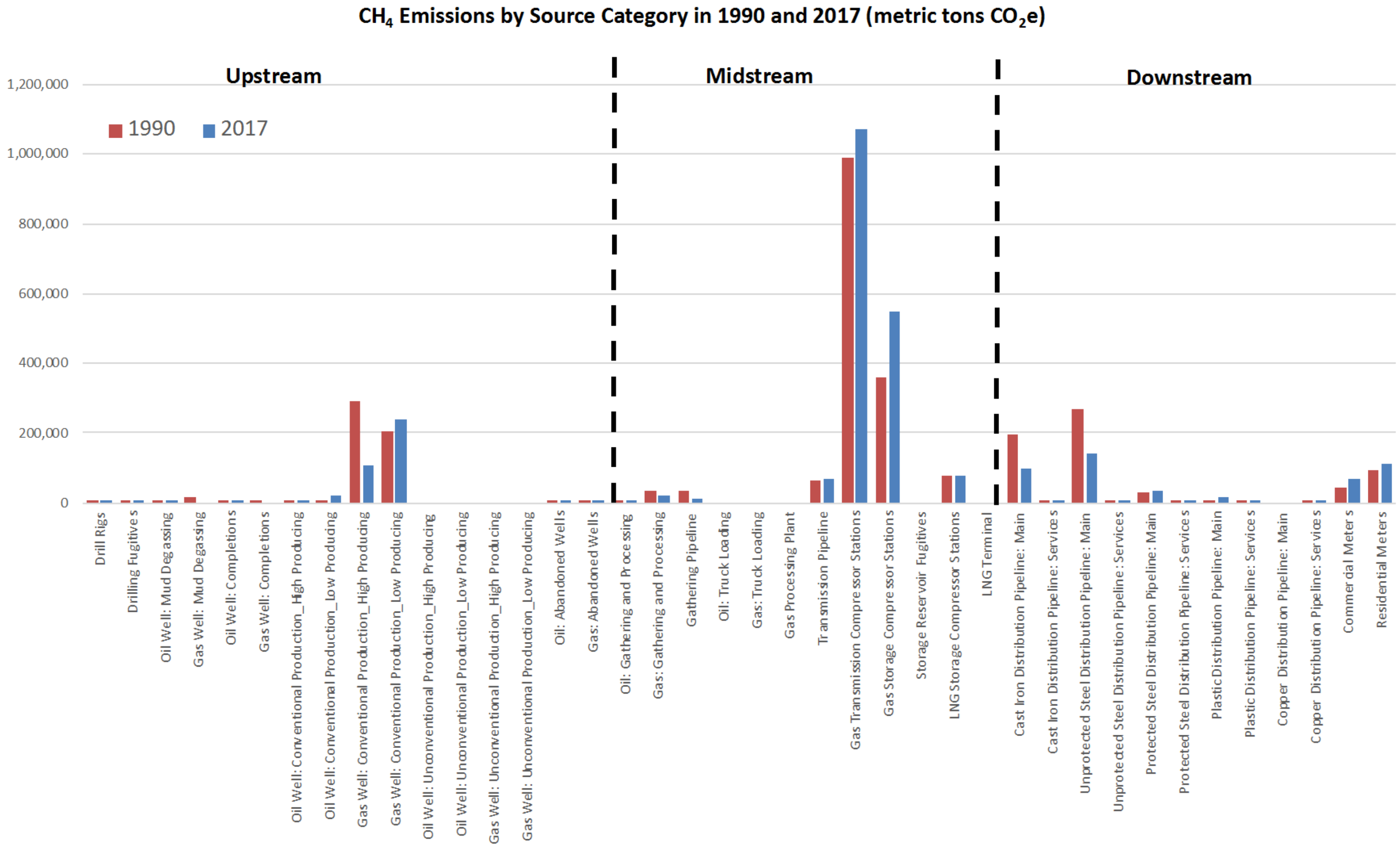
Figure 24. Downstream CH_4 Emissions in New York State from 1990–2017 (AR4 GWP_{100})



5.6 Summary of Source Category Comparison: 1990–2017

All upstream source categories, except low-producing oil and gas wells (+17.9%), declined from 1990–2017. The largest upstream decrease in emissions was from conventional natural gas production from high-producing wells (-62.9%), which follows the decreasing completion and production patterns shown in Figures 2 and 4 and discussed in section 2.2. The midstream source categories saw increases in emissions from transmission pipelines (+11.1%) due to increases in overall pipeline mileages in New York State over that time period as well as large increases in CH_4 emissions from transmission (+8.5%) and gas storage compressor stations (+52.9%), resulting from increases in the number of compressor stations during that time period in order to accommodate increased pipeline capacity. Increases in pipeline and storage capacity and associated compressors reflect trends toward increasing natural gas consumption, as identified by EIA (2018). In the downstream source categories, there was a large shift away from cast-iron and unprotected steel distribution mains towards lower emitting plastic pipes, resulting in a net decrease in downstream emissions. Cast-iron and unprotected steel distribution mains decreased by 50.0% and 47.5%, respectively, and plastic pipes increased by 261%. Although the plastic distribution mains and services along with residential and commercial meter emissions have increased, they were offset by larger reductions in emissions from replacing cast-iron and unprotected steel pipelines.

Figure 25. Comparison of Source Category CH_4 Emissions from 1990 and 2017 in New York State, Using AR4 GWP_{100} Conversion Factors for CH_4

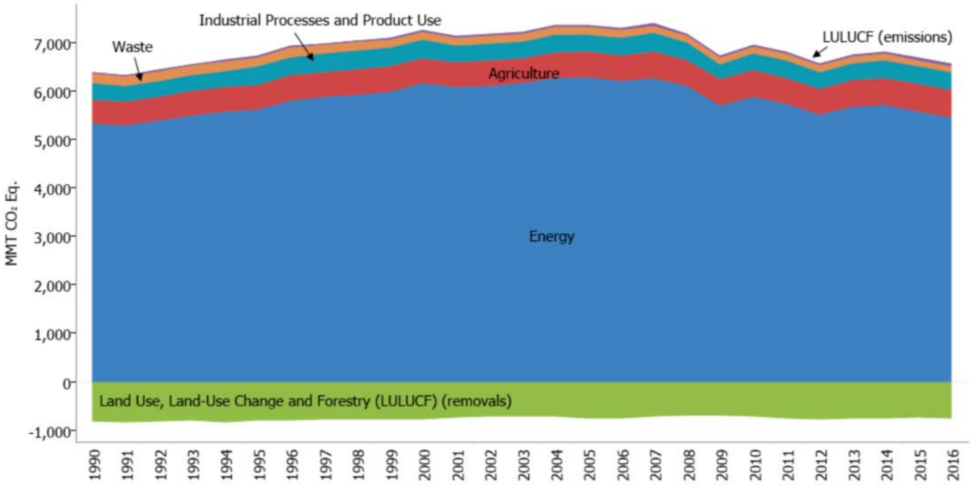


5.7 Emissions Inventory Validation

5.7.1 Comparison to the 2018 EPA GHG Inventory

Prior versions of the New York State oil and natural gas sector methane emissions inventory used a scaling approach to scale the national inventory to New York State based on the ratio of national to State natural gas consumption. This inventory applies a bottom-up, activity driven methodology to estimate emissions form the oil and natural gas sector. The updated and improved methodology allows for direct comparison with other activity-based, bottom-up inventories, including the 2018 EPA GHG Inventory (EPA 2018a). The 2018 EPA GHG Inventory estimated total CH_4 emissions from oil and natural gas systems to be 163.5 $MMTCO_2e$ in 2016. The inventory finds total CH_4 emissions from the oil and natural gas sector to be 2.664 $MMTCO_2e$ in 2016 (AR4 GWP_{100}), equivalent to 1.62% of the total national inventory. Nationwide, EPA estimates a 16% decrease in emissions since 1990 and a 1.7% decrease from 2015–2016, and finds a 3.3% decrease from 2015–2016, which agrees with national trends, and only a 2.8% decrease since 1990 due to increased emissions in the midstream source categories in the State. Despite these discrepancies, when viewing nationwide energy emissions trends described in the 2018 EPA GHG Inventory (EPA 2018a), the New York State time series CH_4 emissions follows the shape of the Energy sector emissions in the national inventory, shown in Figure 26. These data show a similar pattern to that shown in Figure 21, growing to a peak in emissions in 2005 and subsequently declining. As such, patterns in CH_4 emissions in New York State described in this report accurately reflect large-scale nationwide energy shifts.

Figure 26. Reproduction of Figure ES-12 from (EPA 2018a), Showing Time Series Trends in Emissions from the Energy and Other Sectors



5.7.2 Comparison to EPA GHGRP Values

As discussed in section 3.3.1, the EPA FLIGHT database shows Subpart W reported emissions totaled 1.334 $MTCO_2e$ in 2016, while this inventory estimates a greater amount for the 2016 CH_4 emissions at 2.727 $MTCO_2e$. One explanation for this discrepancy is that Subpart W reporting is required only for facilities emitting more than 25,000 $MTCO_2e$ annually, whereas New York State has a large number of smaller facilities that emit CH_4, but do not reach the Subpart W reporting threshold. Most notably, Subpart W does not require emissions from meters or pipelines to be reported, and more specifically, Subpart W data for 2016 show 1.249 $MMTCO_2e$ emitted by local distribution companies, 0.054 $MMTCO_2e$ from transmission/compression, and 0.031 $MMTCO_2e$ from underground natural gas storage. This inventory estimates emissions from natural gas distribution to be 0.309 $MMTCO_2e$ or 24.7% of emissions reported under Subpart W—highlighting the importance of identifying proper distribution pipeline leak rates in New York State in order to update EFs from national averages. The inventory shows that transmission compressor stations are the largest single source category, with estimated emissions of 1.072 $MMTCO_2e$, indicating that total transmission compression emissions are underestimated by Subpart W. The inventory estimates emissions from underground natural gas storage to be 0.551 $MMTCO_2e$ in 2016, which is an order of magnitude greater than reported under Subpart W.

If pipelines and meter emissions are subtracted from the total inventory, this inventory estimates 2.116 $MMTCO_2e$, which is 59% higher than emissions reported under Subpart W taken as a whole. The finding is consistent with Alvarez et al. (2018), who estimate CH_4 emissions from the oil and natural gas supply chain to be ~ 60% greater than EPA estimates.

5.7.3 Comparison to Other State Inventories

New York State is bordered by Pennsylvania, New Jersey, Connecticut, Massachusetts, and Vermont. This section provides a breakdown of the most recent inventory year for each of the adjacent states.

Pennsylvania primarily uses the default EPA SIT tool to estimate emissions from the residential, commercial, industrial, transportation, electricity production, agriculture, waste management, forestry, and land use sectors in Pennsylvania, and uses AR4 GWP_{100} values to report CO_2 equivalents.[20] Pennsylvania estimate total natural gas and oil system emissions to be 10.76 $MMTCO_2e$ in 2015, largely governed by production (7.02 $MMTCO_2e$), transmission (1.96 $MMTCO_2e$) and distribution (1.7 $MMTCO_2e$). As expected, Pennsylvania's estimated emissions from the oil and natural gas sector are much higher than in New York State. Pennsylvania is the second largest producer of natural gas in the United States, second only to Texas and produced about 5.364 billion Mcf of natural gas in 2017, compared with 5.499 million Mcf in New York State in 2017. New York State had no well completions in 2017, compared to Pennsylvania's 810 unconventional and 103 conventional wells drilled.

New Jersey derives 50% of electricity generation from natural gas and has seen a total of 36 exploration wells drilled, none of which were drilled after 1982, due to a lack of natural gas resources and regulations. As such, New Jersey is primarily a consumer of natural gas, as identified by the 2015 GHG inventory,[21] which estimates emissions of 2.2 $MMTCO_2e$ from the natural gas transmission and distribution segments. New Jersey employs the EPA SIT to estimate emissions from natural gas transmission and distribution segments.

Connecticut relies heavily on the EPA SIT to calculate GHG emissions by sector. Connecticut is primarily a natural gas consuming state, as they have minimal oil and natural gas resources. Based on review of the 2016 inventory[22] and supporting data, Connecticut does not explicitly estimate emissions from the oil and natural gas sector, instead emissions are reported for the Agriculture, Commercial, Electric Power (consumption), Industrial, Residential, Transportation, and Waste sectors. Total emissions in Connecticut in 2016 were estimated to be 40.4 to 41.1 $MMTCO_2e$ depending on whether emission estimates were based on electric consumption or generation. Given the aggregated nature of the Connecticut GHG inventory, it is challenging to draw direct comparisons to the New York State inventory.

Massachusetts identifies only the transmission and distribution segments of the oil and natural gas sector as relevant to Massachusetts, using the EPA SIT to estimate emissions from leaks in pipelines and services, customer meters, and metering/regulating stations and venting. Estimated emissions from natural gas transmission and distribution systems in 2016,[23] the most recent year of complete data, were 0.8 $MMTCO_2e$.

Vermont's GHG Inventory[24] uses the EPA SIT along with methodologies developed by the Vermont Agency of Natural Resources, Vermont Department of Public Service and the Center for Climate Strategies. Vermont has no upstream production of oil or natural gas, and midstream and downstream emissions estimates are very small, reflecting low consumption of natural gas in the state (11,930 MMcf in 2017) compared with New York State (1,255,334 MMcf in 2017). Vermont estimates total emissions from the midstream and downstream segments of the oil and natural gas sector to be 0.0050 $MMTCO_2e$.

A comparison of the New York State inventory with each of the discussed state inventories is shown in Table 21. As shown, the ratio of estimated emissions to consumption is consistent for most states, with the exception of Pennsylvania and Vermont, which both have very different natural gas profiles than the other states. Pennsylvania has much higher upstream production of natural gas, resulting in a much higher ratio of emissions to consumption, as emissions associated with production increase the ratio. Vermont has minimal natural gas infrastructure and very low consumption, resulting in a ratio of emissions to consumption that is an order of magnitude lower than the other states in the region.

Table 21. Comparison of This Inventory to the 2015 New York State Inventory and the Most Recent Year of Adjacent State Inventories

	This Inventory	New York State	Pennsylvania	New Jersey	Connecticut	Massachusetts	Vermont
Year	2017	2016	2015	2015	2016	2016	2015
Oil and Gas CH_4 ($MMTCO_2e$)	2.664	2.22	10.76	2.2	*	0.8	0.005
Consumption (MMcf)	1,255,344	1,296,270	1,255,621	745,789	247,958	427,946	11,950
Production (MMcf)	11,395	13,523	8,799,465	0	0	0	0
Emissions/ consumption	$2.12x10^{-06}$	$1.71x10^{-06}$	$8.57x10^{-06}$	$2.95x10^{-06}$	N/A	$1.87x10^{-06}$	$0.42x10^{-06}$

* Connecticut data are not broken out for the oil and natural gas sector.

Note: Consumption and production are derived from EIA data for the year of the inventory.

5.7.4 Comparison to Top-Down and Bottom-Up Studies

Validation of an emission inventory using alternate methodologies is an important step in determining the robustness of the inventory. This inventory uses a bottom-up methodology to estimate emissions using site-level activity data and EFs. Recent efforts in the literature have shown discrepancies between bottom-up and top-down methodology (See e.g. Marchese et al. 2015; Mitchell et al. 2015; Omara, Sullivan, Li, Subramanian, et al. 2016; Subramanian et al. 2015; Alvarez et al. 2018). One of the challenges with validating bottom-up emission inventories with top-down studies is the availability of top-down study data. As discussed in section 3.2.3, top-down studies require detailed atmospheric measurements and modeling to estimate emission flux. Thorough review of the available literature, and consultation with the Project Advisory Committee (PAC) and other experts, revealed a lack of available top-down data specific to New York State. As identified throughout the discussion of EFs in section 4, it will be beneficial for the State to validate that the EFs applied accurately reflect local conditions. Top-down studies can provide this validation, but at the site and regional level, and therefore, New York State should consider top-down validation of the higher emitting segments of this inventory at a minimum. Such validation will reduce the uncertainty in the inventory.

5.8 Uncertainty

Uncertainty is widely addressed in section 4 in a discussion about uncertainty in relation to the limitations of the EFs used. Although best practices are followed and EFs are employed from a number of EPA tools, several sources have been identified that warrant discussion.

First, emissions from gathering, transmission, and distribution pipelines comprise a large fraction of the total emissions estimated in this inventory. The literature on emission rates from pipelines is not deep, with most studies focusing specifically on certain cities. Therefore, the EFs used are based on guidance from the EPA Oil and Gas Tool and EPA's SIT; however, upon inspection, many of those EFs are derived from older studies that were performed in other states. As such, there is a research need to produce new empirical data on per-mile leak rates that better reflect present conditions in New York State.

Second, transmission and storage compressor stations have been identified as large sources of CH_4 in the State. The emission estimation methodology applies an EF based on peer-reviewed literature, which employs best practices to measure and estimate emissions from compressors. However, those studies, along with others, identify a potentially wide range of emission rates from compressor stations under normal operating conditions, with a non-normal distribution. Therefore, applying a central estimate to estimate emissions inherently introduces uncertainty into the estimate.

Third, this inventory is based on the best available activity data and EFs. However, given data limitations, this inventory is limited to site-level estimates, as component counts are unavailable for New York State facilities. As such, State facilities may have different component compositions to those applied in this inventory, resulting in the possible application of EFs that could be better tailored to New York State.

Fourth, emissions from high-emitting sources are not explicitly estimated. High-emitting sources have been widely observed and described in the literature along all stages of the upstream, midstream, and downstream process, with a small number of sites or facilities contributing a majority of regional emissions in many instances. However, given the unknown distribution of high-emitting sources in New York State, it is challenging to apply statistical methods to estimate the likelihood of high-emitting sources.

5.8.1 Emission Inventory Uncertainty

Using the uncertainty bounds identified in Table 12, the following figures present the total time series emissions including upper and lower confidence bounds. Comparing Figure 27 and Figure 29 it is clear that the lower bound on the uncertainty estimate is driven by midstream emissions. This is because for the upstream and downstream EFs, it was determined that selecting the lower-bound value represented the most applicable value to New York State, and so the best estimate and the lower-bound estimate are the same for those sectors.

Upper-bound emissions estimates were determined by selecting the upper bound EF provided by the sources chosen for the best estimate EFs. As such, upper-bound emission estimates may be thought of as representing the upper limit of emissions for New York State, based on EFs from other states which employ high-emitting techniques in the oil and natural gas sector. These upper-bound estimates also reflect literature estimates of EFs for many source categories with identified high-emitting sources, as discussed in section 4. As such, these EFs also likely capture the possible range of uncertainty that arises from accounting for high-emitting sources in the State. This is especially notable in the upstream and downstream source categories, where upper-bound emission estimates are four and two times the best estimate values, respectively, reflecting the wide range of uncertainty that arises from incorporating EFs that are derived with high-emitting sources in the sample population.

Figure 27. Total Emissions Including Best Estimate and Upper and Lower Bounds (AR4 GWP_{100})

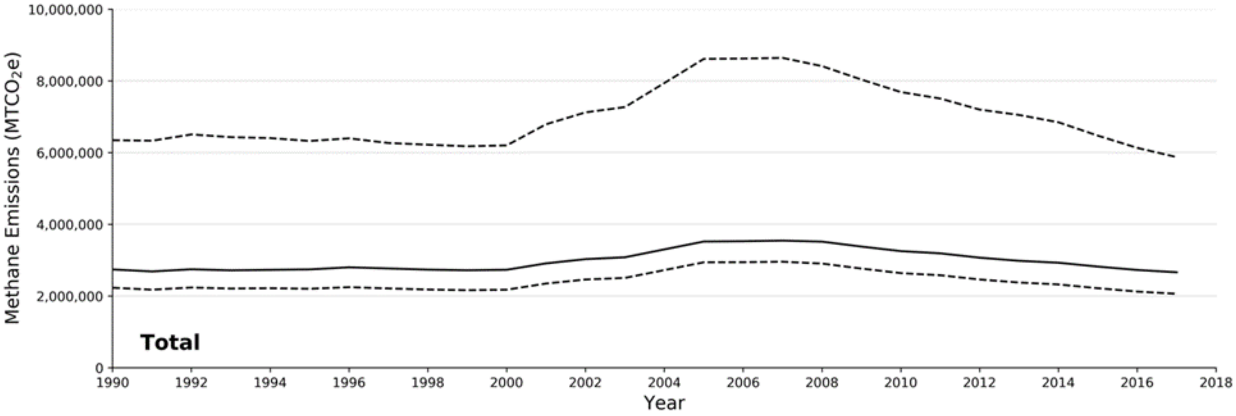


Figure 28. Upstream Emissions Including Upper and Lower Bounds (AR4 GWP_{100})

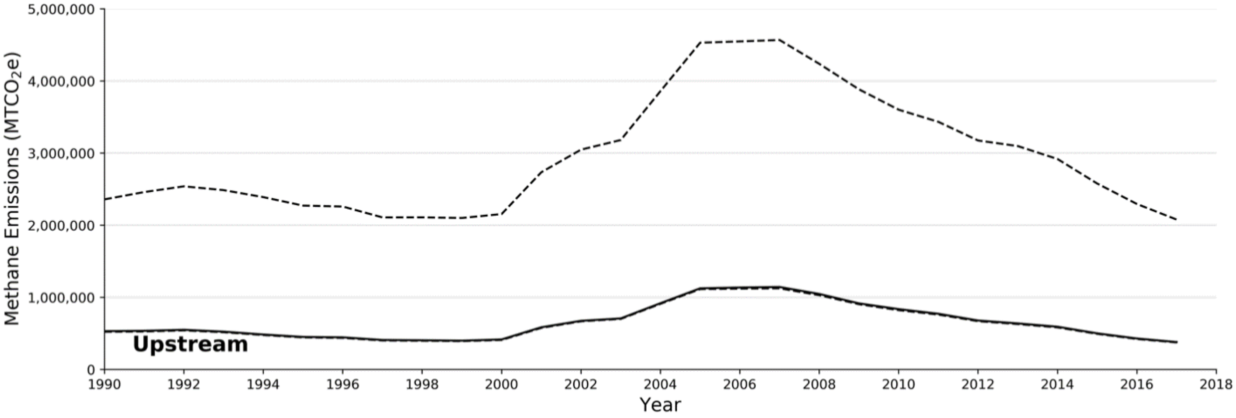


Figure 29. Midstream Emissions Including Upper and Lower Bounds (AR4 GWP_{100})

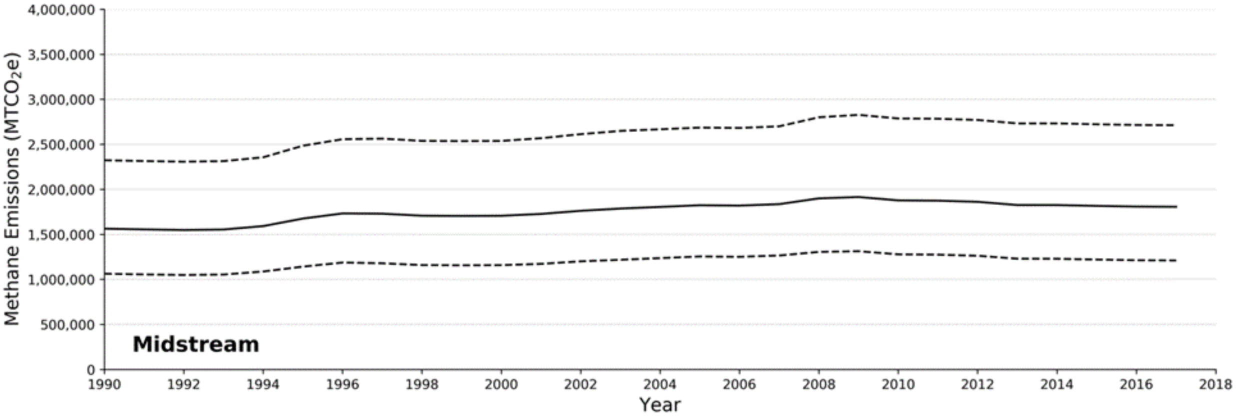
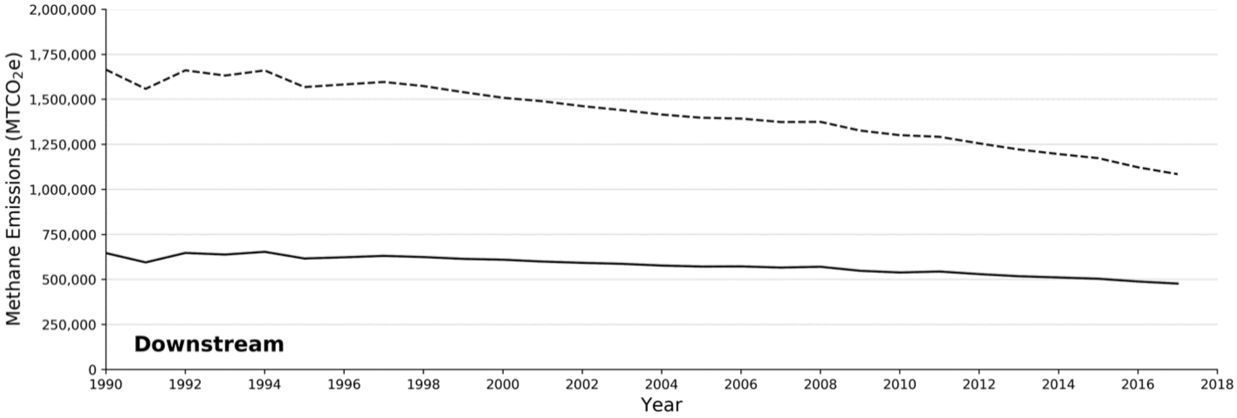


Figure 30. Downstream Emissions Including Upper and Lower Bounds (AR4 GWP_{100})



5.9 Comparing AR4 and AR5 Emissions Estimates

Section 2.6 of this report discusses global warming potential (GWP) in detail. The CH_4 emissions estimates presented throughout this report are the AR4 GWP_{100} estimates, though recent literature has indicated that it is important to consider the short-lived effects of CH_4, described by the GWP_{20}. Under AR4, GWP_{100} for CH_4 is 25, and GWP_{20} is 72. AR4 estimates from 2007 were updated in 2014 in IPCC's AR5, which increased the GWP_{100} to 28, and GWP_{20} to 84. This section describes the 2016 and 2017 emissions estimated in the context of both AR4 and AR5 GWPs and the statewide inventory.

As shown in Table 22, simply changing the GWP from AR4 GWP_{100} to GWP_{20} for the prior New York State inventory increases CH_4 emissions from 2.22 $MMTCO_2e$ to 6.39 $MMTCO_2e$ for the oil and natural gas sector. This inventory finds emissions of 2.73 $MMTCO_2e$ (AR4 GWP_{100}), which is an increase of 23% over the prior inventory. Under AR5 GWP_{100}, this inventory finds CO_2e emissions are 11.7% higher than under AR4 estimates for GWP_{100} and 16.5% higher under AR5 GWP_{20} relative to AR4 GWP_{20} estimates.

Table 22. Comparison of AR4 and AR5 GWP_{100} and GWP_{20} Values Applied to the 2016 and 2017 Oil and Gas Systems CH_4 Emissions in New York State ($MTCO_2e$)

	AR4 GWP_{100}	AR4 GWP_{20}	AR5 GWP_{100}	AR5 GWP_{20}
CH_4 GWP (CO_2e)	25	72	28	84
N_2O GWP (CO_2e)	298	289	265	264
NYSERDA 2015 Inventory				
Oil and Gas CH_4 ($MMTCO_2e$)	2.22	6.39	2.49	7.46
This Inventory				
2016 Oil and Gas CH_4 ($MMTCO_2e$)	2.73	7.86	3.05	9.16
2017 Oil and Gas CH_4 ($MMTCO_2e$)	2.66	7.67	2.98	8.95

Methane is a short-lived climate pollutant, with a lifetime of approximately 12 years. For the purposes of consistency with prior reports and inventories, results are reported in terms of AR4 GWP_{100}. However, these results, along with prior discussion in section 2.6, show that reporting emissions using a range of GWPs, including AR4, AR5, and both short-term and long-term climate effects, can provide a more comprehensive illustration of climate impact.

6 Conclusions

New York State has committed to reducing greenhouse gas (GHG) emissions 40% by 2030 and 80% by 2050, from 1990 levels. While efforts to date have focused on the reduction of carbon dioxide (CO_2) emissions—the dominant cause of the rise in global average temperature—New York State is now turning its attention to CH_4. In May 2017, the State released its Methane Reduction Plan[25] that provides a framework for enhancing CH_4 accounting methodologies and reducing CH_4 emissions from methane emitting sectors, including the oil and natural gas sector. Consequently, there is a need to better understand CH_4 emissions from the sector so that the State will be better positioned to create effective policies to achieve the GHG reduction commitments under the REV.

Based on the four areas of best practices and recommendations developed under the project (described in section 2.5 and presented in the following table and discussion), this inventory presents a marked improvement compared to prior iterations of the New York State oil and natural gas sector methane emission inventories. Table 23 summarizes the best practice recommendations, implementation of these recommendations when developing the current inventory and areas for future inventory improvement.

Table 23. Summary of Best Practice Recommendations, Implementation of Best Practices and Areas for Future Inventory Improvements

✓	**Recommendation #1** New York State should develop a more detailed set of activity data, including site- and component-level data, for its CH_4 inventory in order to create an inventory with the detail needed to capture the impacts of CH_4 mitigation strategies targeted at the site- or component-level. **Implementation in Current Inventory:** Applied the best available activity data, using publicly available inputs as well as data provided by New York State agencies. **Areas for Future Improvement:** ▪ Collect/compile data on the number and location of transmission and storage compressor stations in the State, including stations that only have electric compressors. ▪ Collect/compile data on the county-level miles of distribution pipeline by pipeline material. ▪ Collect/compile data on the county-level number of residential and commercial/industrial gas meters.
✓	**Recommendation #2** New York State should estimate and apply EFs for upstream and downstream oil and gas activities in the State using best available data, validated by both bottom-up and top-down studies, and specific to geographic location. **Implementation in Current Inventory:** Applied the best available EFs from the published literature. **Areas for Future Improvement:** ▪ Develop New York State-specific EFs for well pads during production. ▪ Develop New York State-specific EFs for transmission and storage compressor stations. ▪ Develop an EF for fugitive emissions from storage reservoirs.
✓	**Recommendation #3** New York State should align available geospatial data with inventory data as much as possible to create a geospatial emissions inventory that allows greater consideration of identifying hot spots and air quality concerns as well as verification of emission inventories with empirical data. **Implementation in Current Inventory:** Results are presented geospatially, allocated to the county-level, with the ability to produce sub-county results for many segments. **Areas for Future Improvement:** ▪ Collect air quality data on ambient CH_4 concentrations throughout New York State and use the observed concentrations to verify emission estimates.
✓	**Recommendation #4** New York State should conduct uncertainty analysis when calculating and reporting its CH_4 inventory. At a minimum, that uncertainty analysis should account for uncertainties in published EFs, but it could also include an assessment of high-emitting sources across the State. New York State should develop and apply models that help account for the existence of high-emitting sources either in cases where emission releases are known (e.g., reported leakage) or in cases where emission releases are not known (e.g., estimated leakage based on pipeline age or material). **Implementation in Current Inventory:** Assessed uncertainty in the applied EFs to identify the most likely range of CH_4 emission from the oil and natural gas sector. With better information on the statistical distribution of high-emitting sources, this inventory methodology may also be applied to explicitly include high-emitting sources. **Areas for Future Improvement:** ▪ Develop a better understanding of the distribution of high-emitting sources and the frequency of operation in the high-emitting state.

In the current inventory, total CH_4 emissions in 2017 were estimated to be 2.664 $MMTCO_2e$ (AR4, GWP_{100}), and estimates for 2016 were equivalent to 1.62% of the total nationwide emissions estimated by EPA. Based on prior inventories developed by New York State, and using 2015 as the most recent common year, this study estimates CH_4 emissions to be 20% higher than previous estimates from the oil and natural gas sector (2.22 $MMTCO_2e$ in 2015). Largely driven by decreases in high-producing well activity—and a transition away from more leak-prone cast-iron and unprotected steel pipelines to plastic—results from this inventory show that, despite an increase in natural gas consumption, total CH_4 emissions have continued to decline since 2007, with an average annual decrease of 2.8% per year. This trend agrees with observed large-scale nationwide energy shifts. The largest methane emission source categories identified in the State inventory developed under this project include transmission compressor stations (1,072 $MMTCO_2e$ or 40.2% CH_4 emissions in the oil and natural gas sector), natural gas and LNG storage compressor stations (631 $MMTCO_2e$ or 23.7%), conventional oil and natural gas production (372 $MMTCO_2e$ or 14.0%), unprotected steel distribution and service pipelines (142 $MMTCO_2e$ or 5.3%), residential meters (111 $MMTCO_2e$ or 4.2%), cast-iron distribution and service pipelines (101 $MMTCO_2e$ or 3.8%), and commercial meters (70 $MMTCO_2e$ or 2.6%).

The inventory developed under this project incorporates findings from the most current empirical research and utilizes the most accurate, current, and inventory-appropriate available data sources. The application of state-of-the-art practices and EFs represents a significant methodological advancement over other available tools that are often based on out-of-date EFs and do not reflect the modern oil and natural gas sector. By applying established best practices based on a thorough review of the literature and expert consultation, this inventory establishes a rigorous and robust methane emissions baseline in New York State. These inventory results, and the accompanying inventory tool, provide important resources to the State for supporting policy decisions and regulations. This inventory lays the foundation for a geospatially refined inventory that can capture the impacts of future mitigation strategies for CH_4 emissions from the oil and natural gas sector as well as current regulations, such as EPA's proposed changes to the 2016 New Source Performance Standards for the oil and gas industry (EPA 2018d). In addition, the inventory tool provides New York State with the flexibility to revise the current inventory or generate future inventories by updating activity data and EFs as more sophisticated and up-to-date data become available and as future advancements in the industry lead to technological changes.

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8 Glossary

Abandoned wells—Unplugged wells (primarily oil or gas) that have not been operated and maintained in accordance with prevailing statute and regulation. Many abandoned wells have fallen into advanced states of disrepair.

Associated gas—Gas produced as a byproduct of the production of crude oil.

Conventional reservoir—A reservoir in which buoyant forces keep hydrocarbons in place below a sealing caprock. Reservoir and fluid characteristics of conventional reservoirs typically permit oil or natural gas to flow readily into wellbores. The term is used to make a distinction from shale and other unconventional reservoirs, in which gas might be distributed throughout the reservoir at the basin scale, and in which buoyant forces or the influence of a water column on the location of hydrocarbons within the reservoir are not significant.

Global warming potential—The index used to translate the level of emissions of various gases into a common measure in order to compare the relative radiative forcing of different gases without directly calculating the changes in atmospheric concentrations. GWPs are calculated as the ratio of the radiative forcing that would result from the emissions of one kilogram (kg) of a GHG to that from the emissions of 1 kg of CO_2 over a period of time (usually 100 years).

Green completions—Reduced emissions well completions that capture the flowback and collect the natural gas rather than venting the natural gas to the atmosphere.

Orphan wells—A subset of abandoned wells that are abandoned for which no owner can be determined. In most instances, these wells were drilled prior to the existence of a regulatory framework in New York. Due to their advanced age and the lack of comprehensive well information, these wells may present significant public health and environmental hazards.

Plugged well—A well that has been permanently closed, usually after either logs determine there is insufficient hydrocarbon potential to complete the well, or after production operations have drained the reservoir. Different regulatory bodies have their own requirements for plugging operations. Most require that cement plugs be placed and tested across any open hydrocarbon-bearing formations, across all casing shoes, across freshwater aquifers, and perhaps several other areas near the surface, including the top 20 to 50 feet (6 to 15 meters) of the wellbore. The well designer may choose to set bridge plugs in conjunction with cement slurries to ensure that higher density cement does not fall into the wellbore. In that case, the bridge plug would be set and cement pumped on top of the plug through a drillpipe, and then the drillpipe withdrawn before the slurry thickens.

Super-emitters—Super-emitter is a term that has been used in the literature to describe sources with much higher emission rates than the average from that source type. The exact definition of super-emitters varies among the various references [e.g., it may refer to the top 5% highest-emitting sources that are responsible for the majority of that source type's total emissions (Brandt et al. 2016) or sites with the highest proportional loss rates (Zavala-Araiza et al. 2015)]. Depending on the definition, the term super-emitters may include chronic, episodic, routine, and malfunctioning sources. Due to the various uses of this term in the literature and its ambiguity, ITRC and the recent National Academies' report on CH_4 (https://www.nap.edu/catalog/24987/improving-characterization-of-anthropogenic-methane-emissions-in-the-united-states) have chosen to use the term "high-emitting sources" to describe these emission sources.

Unconventional resource—An umbrella term for oil and natural gas that is produced by means that do not meet the criteria for conventional production. What has qualified as unconventional at any particular time is a complex function of resource characteristics; the available exploration and production technologies; the economic environment; and the scale, frequency, and duration of production from the resource. Perceptions of these factors inevitably change over time and often differ among users of the term. At present, the term is used in reference to oil and gas resources whose porosity, permeability, fluid trapping mechanism, or other characteristics differ from conventional sandstone and carbonate reservoirs. Coalbed CH_4, gas hydrates, shale gas, fractured reservoirs, and tight gas sands are considered unconventional resources.

Well completions—A generic term used to describe the assembly of downhole tubulars and equipment required to enable safe and efficient production from an oil or gas well. The point at which the completion process begins may depend on the type and design of well. However, many options applied, or actions performed during the construction phase of a well have significant impact on the productivity of the well.

Appendix A. Details of EPA Subpart W Methodology

This appendix provides a more detailed description of the EPA Subpart W methodology, along with tables detailing the Subpart W EFs.

A.1 Subpart W Industry Segments

Subpart W requires reporting of GHG emissions for each facility with emissions greater than 25,000 $MTCO_2e$ for the following 10 industry segments. Unless otherwise noted, each facility refers to an individual site. Tables show applicable source forms required for each facility.

Effective January 1, 2017, EPA updated the Subpart W methodology to align the leak detection methods and reporting requirements with those in New Source Performance Standards (NSPS) subpart OOOOa.

Emissions are estimated for each source type under one of four methodologies, including engineering estimates, direct measurement, leak detection and leaker EF, and equipment count and population EF. The breakdown of acceptable methodologies is shown in Table A-1, replicated from EPA's overview of Subpart W.[26] As shown, most of the emission estimates are informed by engineering estimates, with options to use direct measurements.

Table A-1. Breakdown of Subpart W Emissions Estimation Methodology by Source Type

Source Type	Engineering Estimates	Direct Measurement	Leak Detection and Leaker EF	Equipment Count and Population EF
Natural gas pneumatic device venting				X
Natural gas driven pneumatic pump venting				X
Well venting for liquids unloading	X	X		
Gas well venting during completions without hydraulic fracturing	X			
Gas well venting during completions with hydraulic fracturing	X	X		
Gas well venting during workovers without hydraulic fracturing	X			
Gas well venting during completions with hydraulic fracturing	X	X		

Table A-1 Continued

Source Type	Engineering Estimates	Direct Measurement	Leak Detection and Leaker EF	Equipment Count and Population EF
Onshore production storage tanks	X			X
Transmission storage tanks		X		
Reciprocating compressor venting	X	X		X
Well testing venting and flaring	X			
Associated gas venting and flaring	X			
Dehydrator vent stacks	X			X
EOR injection pump blowdown	X			
Acid gas removal vent stack	X	X		
EOR hydrocarbon liquids dissolved CO_2		X		
Centrifugal compressor venting	X	X		X
Other emissions from equipment leaks			X	X
Blowdown vent stacks	X			
Flare stacks emissions	X	X		
Onshore petroleum, natural gas production, and natural gas distribution combustion emissions	X	X		
Above ground M-R station and T-D transfer station equipment leaks			X	X
Below ground M-R station and T-D transfer station equipment leaks				X
Pipeline main equipment leaks				X
Service line equipment leaks				X

A.1.1 Onshore Petroleum and Natural Gas Production [98.230(a)(2)]

Per Subpart W guidelines, each owner or operator of onshore petroleum and natural gas production wells should report combined emissions for all wells operational within a given hydrocarbon basin. All wells owned or operated by a single entity in a given basin will be considered as one facility.

Table A-2. Sections Applicable to Onshore Petroleum and Natural Gas Production

Onshore Petroleum and Natural Gas Production [98.230(a)(2)]	Onshore Production [98.236(aa)(1)]
	Natural Gas Pneumatic Devices [98.236(b)]
	Natural Gas Driven Pneumatic Pumps [98.236(c)]
	Acid Gas Removal Units [98.236(d)]
	Dehydrators [98.236(e)]
	Well Venting for Liquids Unloading [98.236(f)]
	Completions and Workovers with Hydraulic Fracturing [98.236(g)]
	Completions and Workovers without Hydraulic Fracturing [98.236(h)]
	Atmospheric Storage Tanks [98.236(j)]
	Well Testing [98.236(l)]
	Associated Gas Venting and Flaring [98.236(m)]
	Flare Stacks [98.236(n)]
	Centrifugal Compressors [98.236(o)]
	Reciprocating Compressors [98.236(p)]
	Equipment Leaks Surveys and Population Counts [98.236(q,r)]
	Enhanced Oil Recovery Injection Pumps [98.236(w)]
	Enhanced Oil Recovery Hydrocarbon Liquids [98.236(x)]
	Combustion Equipment at Onshore Petroleum and Natural Gas Production Facilities, Onshore Petroleum and Natural Gas Gathering and Boosting Facilities, and Natural Gas Distribution Facilities [98.236(z)]

A.1.2 Offshore Petroleum and Natural Gas Production [98.230(a)(1)]

Offshore petroleum and natural gas production facilities are those comprised of any platform, fixed or floating, affixed to offshore submerged lands that houses equipment to extract oil and or natural gas from the ocean or lake floor, and processes and transfers those hydrocarbons ashore. Offshore facilities also include secondary structures, and storage and offloading equipment. All wells owned or operated by a single entity in a given basin will be considered as one facility.

Table A-3. Sections Applicable to Offshore Petroleum and Natural Gas Production

Offshore Petroleum and Natural Gas Production [98.230(a)(1)]	Facility Overview [98.236(aa)(2-11)]
	Offshore Petroleum and Natural Gas Production [98.236(s)]

A.1.3 Onshore Natural Gas Processing [98.230(a)(3)]

This segment refers to onshore plants that receive natural gas from gathering lines and separate natural gas liquids from raw produced natural gas. In some cases, processing plants also fractionate the removed natural gas liquids into their component parts. This segment includes all processing facilities that fractionate, and all processing facilities that do not fractionate but have a daily throughput of 25 MMscf or more.

Table A-4. Sections Applicable to Onshore Natural Gas Processing

Onshore Natural Gas Processing [98.230(a)(3)]	Facility Overview [98.236(aa)(2-11)]
	Acid Gas Removal Units [98.236(d)]
	Dehydrators [98.236(e)]
	Blowdown Vent Stacks [98.236(i)]
	Flare Stacks [98.236(n)]
	Centrifugal Compressors [98.236(o)]
	Reciprocating Compressors [98.236(p)]
	Equipment Leaks Surveys and Population Counts [98.236(q,r)]

A.1.4 Onshore Natural Gas Transmission Compression [98.230(a)(4)]

This section includes stationary compressors involved in moving natural gas from production, processing, and transmission facilities, through transmission pipelines. Compressors move gas through transmission pipelines to either distribution lines, LNG storage facilities, or underground storage. All compression equipment, dehydrators, and storage tanks are considered part of the facility.

Table A-5. Sections Applicable to Onshore Natural Gas Transmission Compression

Onshore Natural Gas Transmission Compression [98.230(a)(4)]	Facility Overview [98.236(aa)(2-11)]
	Natural Gas Pneumatic Devices [98.236(b)]
	Blowdown Vent Stacks [98.236(i)]
	Transmission Storage Tanks [98.236(k)]
	Flare Stacks [98.236(n)]
	Centrifugal Compressors [98.236(o)]
	Reciprocating Compressors [98.236(p)]
	Equipment Leaks Surveys and Population Counts [98.236(q,r)]
	Facility Overview [98.236(aa)(2-11)]

A.1.5 Underground Natural Gas Storage [98.230(a)(5)]

This source includes emissions from infrastructure associated with subsurface storage of natural gas in underground formations, depleted oil and gas reservoirs, and salt dome caverns. Operations include compressions, dehydration and flow measurement, as well as all injection or recovery wellheads connected to compression units at the facility.

Table A-6. Sections Applicable to Underground Natural Gas Storage

Underground Natural Gas Storage [98.230(a)(5)]	Facility Overview [98.236(aa)(2-11)]
	Natural Gas Pneumatic Devices [98.236(b)]
	Flare Stacks [98.236(n)]
	Centrifugal Compressors [98.236(o)]
	Reciprocating Compressors [98.236(p)]
	Equipment Leaks Surveys and Population Counts [98.236(q,r)]

A.1.8 Liquefied Natural Gas (LNG) Storage [98.230(a)(6)]

This source includes emissions from onshore LNG storage facilities and storage tanks located above ground, including associated equipment such as liquefaction equipment, compressors to capture and re-liquefy boil off, re-condensers, and vaporization units.

Table A-7. Sections Applicable to Liquefied Natural Gas (LNG) Storage

Liquefied Natural Gas (LNG) Storage [98.230(a)(6)]	Facility Overview [98.236(aa)(2-11)]
	Flare Stacks [98.236(n)]
	Centrifugal Compressors [98.236(o)]
	Reciprocating Compressors [98.236(p)]
	Equipment Leaks Surveys and Population Counts [98.236(q,r)]

A.1.7 LNG Import and Export Equipment [98.230(a)(7)]

This source refers to all equipment, both onshore and offshore, that receives or transfers LNG. Import equipment receives LNG from ocean-going vessels and provides storage before delivering gas to transmission or distribution systems. Export equipment receives, liquefies, and stores natural gas; and transfers the gas to ocean-going vessels.

Table A-8. Sections Applicable to LNG Import and Export Equipment

LNG Import and Export Equipment [98.230(a)(7)]	Facility Overview [98.236(aa)(2-11)]
	Blowdown Vent Stacks [98.236(i)]
	Flare Stacks [98.236(n)]
	Centrifugal Compressors [98.236(o)]
	Reciprocating Compressors [98.236(p)]
	Equipment Leaks Surveys and Population Counts [98.236(q,r)]
	Facility Overview [98.236(aa)(2-11)]

A.1.8 Natural Gas Distribution [98.230(a)(8)]

The natural gas distribution source includes reports from local distribution companies regarding emissions from distribution pipeline leaks, regulating equipment, and transfer stations. This segment also includes customer meters and regulators, infrastructure, and pipelines. For natural gas distribution, the facility is defined as all of a given utility's or operator's assets in a state.

Table A-9. Sections Applicable to Natural Gas Distribution

Natural Gas Distribution [98.230(a)(8)]	Facility Overview [98.236(aa)(2-11)]
	Equipment Leaks Surveys and Population Counts [98.236(q,r)]
	Combustion Equipment at Onshore Petroleum and Natural Gas Production Facilities, Onshore Petroleum and Natural Gas Gathering and Boosting Facilities, and Natural Gas Distribution Facilities [98.236(z)]

A.1.9 Onshore Petroleum and Natural Gas Gathering and Boosting [98.230(a)(9)]

This source includes gathering pipelines and associated equipment for collecting oil and natural gas from onshore production sites, and provides transport to processing facilities, transmission pipelines, or distribution pipelines. All gathering and boosting lines and facilities owned or operated by a single entity in a given basin are considered as one facility.

Table A-10. Sections Applicable to Onshore Petroleum and Natural Gas Gathering and Boosting

Onshore Petroleum and Natural Gas Gathering and Boosting [98.230(a)(9)]	Facility Overview [98.236(aa)(2-11)]
	Natural Gas Pneumatic Devices [98.236(b)]
	Natural Gas Driven Pneumatic Pumps [98.236(c)]
	Acid Gas Removal Units [98.236(d)]
	Dehydrators [98.236(e)]
	Blowdown Vent Stacks [98.236(i)]
	Atmospheric Storage Tanks [98.236(j)]
	Flare Stacks [98.236(n)]
	Centrifugal Compressors [98.236(o)]
	Reciprocating Compressors [98.236(p)]
	Equipment Leaks Surveys and Population Counts [98.236(q,r)]
	Combustion Equipment at Onshore Petroleum and Natural Gas Production Facilities, Onshore Petroleum and Natural Gas Gathering and Boosting Facilities, and Natural Gas Distribution Facilities [98.236(z)]

A.1.10 Onshore Natural Gas Transmission Pipeline [98.230(a)(10)]

This source delivers gas from processing facilities to local distribution facilities. Transmission pipelines often include compressor stations.

Table A-11. Sections Applicable to Onshore Natural Gas Transmission Pipeline

Onshore Natural Gas Transmission Pipeline [98.230(a)(10)]	Facility Overview [98.236(aa)(2-11)]
	Natural Gas Pneumatic Devices [98.236(b)]

A.2 Subpart W Emission Factors and Component Counts

This section details the default EFs for Subpart W for the eastern United States.

Table A-12. Leaker CH_4 Emission Factors from EPA's GHGRP Subpart W

Industry Segment	Major Equipment	Service	Component	CH_4 EF[a] (scf/hr-component)	
				Non-Method 21	Method 21
Onshore Petroleum and Natural Gas Production, Gathering, and Boosting	Onshore production or gathering and boosting components	Light crude	Valve	3.2	2.2
			Flange	2.7	1.4
			Connector (other)	1	0.6
			Open-ended line	1.6	1.1
			Pump	3.7	2.6
			Agitator seat	3.7	2.6
			Other	3.1	2
		Heavy crude	Valve	3.2	2.2
			Flange	2.7	1.4
			Connector (other)	1	0.6
			Open-ended line	1.6	1.1
			Pump	3.7	2.6
			Agitator seat	3.7	2.6
			Other	3.1	2
		Gas	Valve	4.9	3.5
			Flange	4.1	2.2
			Connector (other)	1.3	0.8
			Open-ended line	2.8	1.9
			Pressure relief valve	4.5	2.8
			Pump seal	3.7	1.4
			Other	4.5	2.8
Onshore Natural Gas Processing	Compressor components	Gas	Valve	14.84	N/A
			Connector	5.59	N/A
			Open-ended line	17.27	N/A
			Pressure relief valve	39.66	N/A
			Meter	19.33	N/A
	Non-compressor components	Gas	Valve	6.42	N/A
			Connector	5.71	N/A
			Open-ended line	11.27	N/A
			Pressure relief valve	2.01	N/A
			Meter	2.93	N/A
Onshore Natural Gas Transmission Compression	Compressor components	Gas	Valve	14.84	9.51
			Connector	5.59	3.58
			Open-ended line	17.27	11.07
			Pressure relief valve	39.66	25.42
			Meter/instrument	19.33	12.39
			Other	4.1	2.63

Table A-12 continued

Onshore Natural Gas Transmission Compression	Non-compressor components	Gas	Valve	6.42	4.12
			Connector	5.71	3.66
			Open-ended line	11.27	7.22
			Pressure relief valve	2.01	1.29
			Meter/instrument	2.93	1.88
			Other	4.1	2.63
Underground Natural Gas Storage	Storage station	Gas	Valve	14.84	9.51
			Connector	5.59	3.58
			Open-ended line	17.27	11.07
			Pressure relief valve	39.66	25.42
			Meter/instrument	19.33	12.39
			Other	4.1	2.63
	Storage wellhead	Gas	Valve	4.5	3.2
			Connector	1.2	0.7
			Open-ended line	3.8	2
			Pressure relief valve	2.5	1.7
			Meter/instrument	4.1	2.5
			Other	4.1	2.5
LNG Storage LNG Import and Export Equipment	LNG storage LNG terminal	LNG terminal	Valve	1.19	0.23
			Connector	0.34	0.11
			Pump seal	4	0.73
			Other	1.77	0.99
		Gas	Valve	14.84	9.51
			Connector	5.59	3.58
			Open-ended line	17.27	11.07
			Pressure relief valve	39.66	25.42
			Meter/instrument	19.33	12.39
			Other	4.1	2.63
Natural Gas Distribution above Grade Transfer Stations	Local distribution company	Transmission-distribution stations	Connector	1.69	N/A
			Block valve	0.557	N/A
			Control valve	9.34	N/A
			Pressure relief valve	0.27	N/A
			Orifice meter	0.212	N/A
			Regulator	0.772	N/A
			Open-ended line	26.131	N/A

[a] Subpart W provides only one EF if no Method 21 emission factor is shown.

Table A-13. Population EFs from EPA's GHGRP Subpart W

Industry Segment	Major Equipment	Service	Component	EF	Units
Onshore Petroleum and Natural Gas Production, Gathering and Boosting	Onshore (eastern United States)	Light crude	Valve	0.05	Whole gas EF [standard cubic foot (scf)/hr-component]
			Flange	0.003	
			Connector	0.007	
			Open-ended line	0.05	
			Pump	0.01	
			Other	0.3	
		Heavy crude	Valve	0.0005	
			Flange	0.0009	
			Connector	0.0003	
			Open-ended line	0.006	
			Pump	0.003	
		Gathering pipelines	Protected steel	0.47	
			Unprotected steel	16.59	
			Plastic/composite	2.5	
			Cast iron	27.6	
		Gas	Valve	0.027	Whole gas EF (scf)/hr-component)
			Connector	0.003	
			Open-ended line	0.061	
			Pressure relief valve	0.04	
Underground Natural Gas Storage	Storage wellheads	Gas	Valve	0.1	Total hydrocarbon EF (scf-hr/component)
			Connector	0.01	
			Open-ended line	0.03	
			Pressure relief valve	0.17	
LNG Storage and Import Export Equipment	LNG compressor		Vapor recovery compressor	4.17	CH_4 EF (scf-hr/component)
Natural Gas Distribution	Below-grade M&R station	Inlet pressure	< 100 pounds per square inch gauge (psig)	0.1	CH_4 EF (scf/hr-station)
			100 to 300 psig	0.2	
			> 300 psig	1.3	
	Distribution mains	Gas	Cast iron	27.25	CH_4 EF (scf/hr-mile)
			Plastic	1.13	
			Protected steel	0.35	
			Unprotected steel	12.58	
	Distribution services	Gas	Copper	0.03	CH_4 EF (scf/hr-service)
			Plastic	0.001	
			Protected steel	0.02	
			Unprotected steel	0.19	

Table A-14. Major Equipment Component and Activity Count Data from EPA's GHGRP Subpart W for the Eastern United States

Industry Segment	Major Equipment	Valves	Connectors	Open-ended Lines	Pressure Relief Valves	Flanges
Crude Oil Production	Wellheads	5	4	0		10
	Separators	6	10	0		12
	Heater-treater	8	20	0		12
	Header	5	4	0		10
Onshore Natural Gas Production, Gathering and Boosting	Wellheads	8	38	0.5	0	
	Separators	1	6	0	0	
	Meters/piping	12	45	0	0	
	Compressors	12	57	0	0	
	In-line heaters	14	65	2	1	
	Dehydrators	24	90	2	2	

Table A-15. EFs for Pneumatic Device and Pump Venting from EPA GHGRP Subpart W

Industry Segment	High-Bleed Pneumatic Devices	Intermittent Bleed Pneumatic Devices	Low-Bleed Pneumatic Devices	Natural Gas Driven Pneumatic Pumps
Onshore Petroleum and Natural Gas Production	37.3	13.5	1.39	13.3
Onshore Natural Gas Transmission Compression	18.2	2.35	1.37	
Underground Natural Gas Storage	18.2	2.35	1.37	
Onshore Petroleum and Natural Gas Gathering and Boosting	37.3	13.5	1.39	13.3

Appendix B. Supporting Tables from Literature Review

From Kirchgessner (1997), showing pre-1997 loss assumptions:

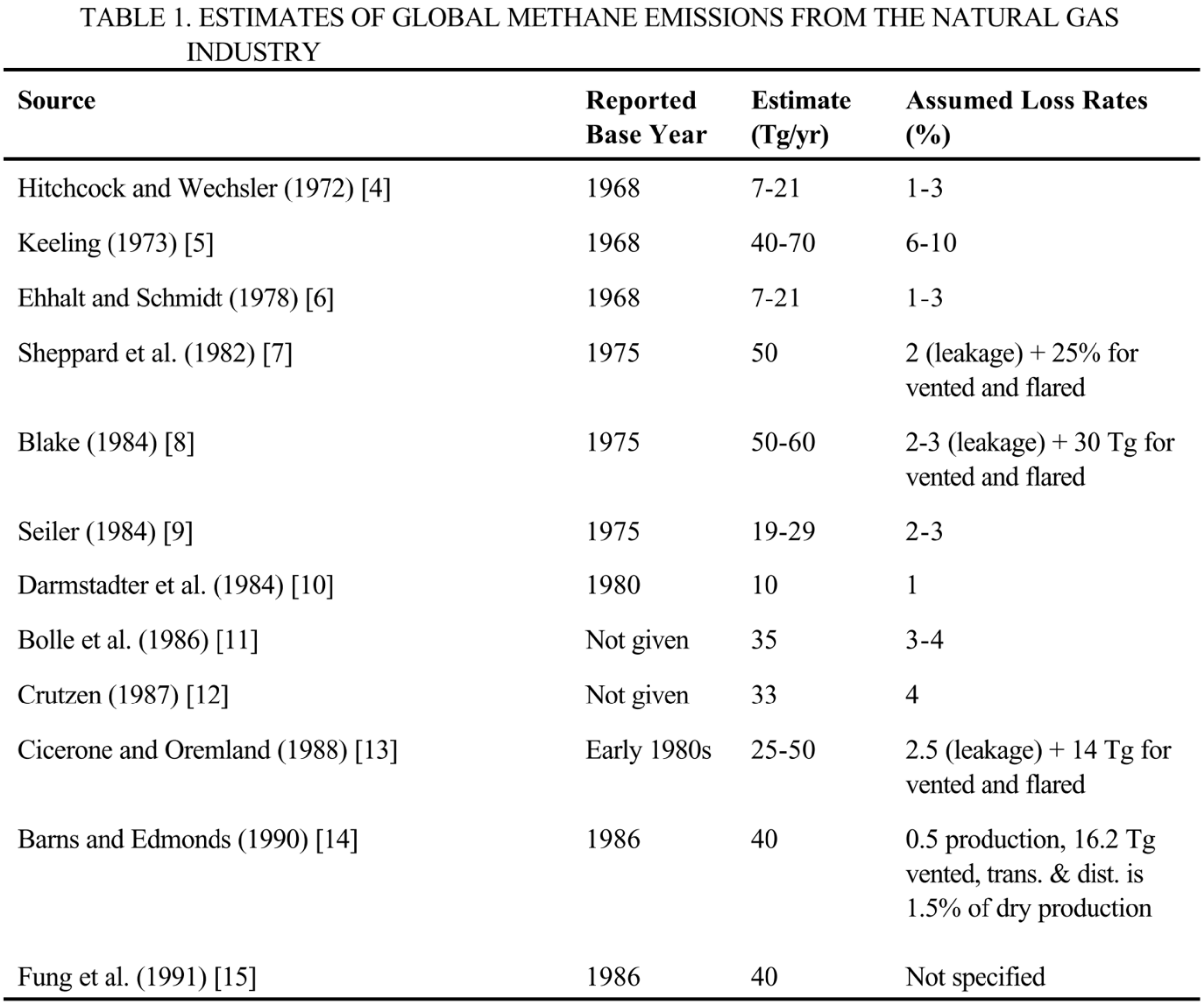

TABLE 1. ESTIMATES OF GLOBAL METHANE EMISSIONS FROM THE NATURAL GAS INDUSTRY

Source	Reported Base Year	Estimate (Tg/yr)	Assumed Loss Rates (%)
Hitchcock and Wechsler (1972) [4]	1968	7-21	1-3
Keeling (1973) [5]	1968	40-70	6-10
Ehhalt and Schmidt (1978) [6]	1968	7-21	1-3
Sheppard et al. (1982) [7]	1975	50	2 (leakage) + 25% for vented and flared
Blake (1984) [8]	1975	50-60	2-3 (leakage) + 30 Tg for vented and flared
Seiler (1984) [9]	1975	19-29	2-3
Darmstadter et al. (1984) [10]	1980	10	1
Bolle et al. (1986) [11]	Not given	35	3-4
Crutzen (1987) [12]	Not given	33	4
Cicerone and Oremland (1988) [13]	Early 1980s	25-50	2.5 (leakage) + 14 Tg for vented and flared
Barns and Edmonds (1990) [14]	1986	40	0.5 production, 16.2 Tg vented, trans. & dist. is 1.5% of dry production
Fung et al. (1991) [15]	1986	40	Not specified

From Littlefield et al. (2017), showing work by Allen on emissions from different components:

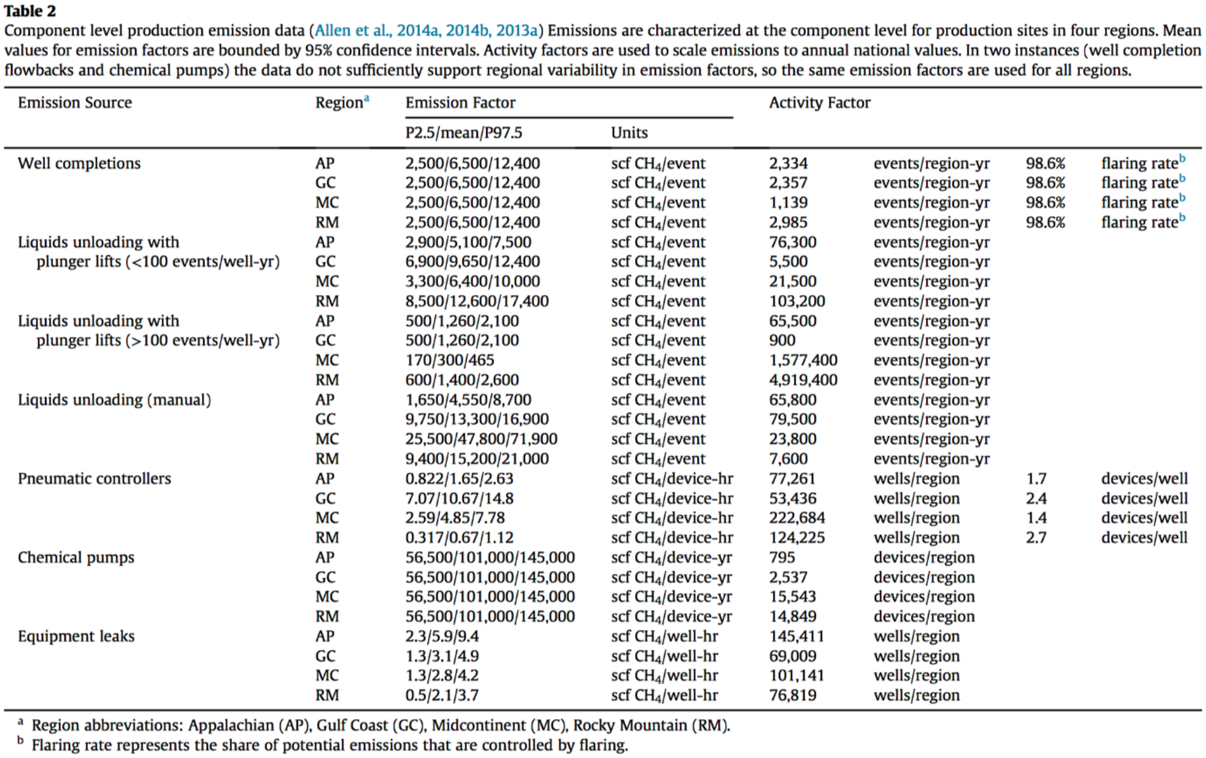

Table 2

Component level production emission data (Allen et al., 2014a, 2014b, 2013a) Emissions are characterized at the component level for production sites in four regions. Mean values for emission factors are bounded by 95% confidence intervals. Activity factors are used to scale emissions to annual national values. In two instances (well completion flowbacks and chemical pumps) the data do not sufficiently support regional variability in emission factors, so the same emission factors are used for all regions.

Emission Source	Region[a]	Emission Factor		Activity Factor			
		P2.5/mean/P97.5	Units				
Well completions	AP	2,500/6,500/12,400	scf CH_4/event	2,334	events/region-yr	98.6%	flaring rate[b]
	GC	2,500/6,500/12,400	scf CH_4/event	2,357	events/region-yr	98.6%	flaring rate[b]
	MC	2,500/6,500/12,400	scf CH_4/event	1,139	events/region-yr	98.6%	flaring rate[b]
	RM	2,500/6,500/12,400	scf CH_4/event	2,985	events/region-yr	98.6%	flaring rate[b]
Liquids unloading with plunger lifts (<100 events/well-yr)	AP	2,900/5,100/7,500	scf CH_4/event	76,300	events/region-yr		
	GC	6,900/9,650/12,400	scf CH_4/event	5,500	events/region-yr		
	MC	3,300/6,400/10,000	scf CH_4/event	21,500	events/region-yr		
	RM	8,500/12,600/17,400	scf CH_4/event	103,200	events/region-yr		
Liquids unloading with plunger lifts (>100 events/well-yr)	AP	500/1,260/2,100	scf CH_4/event	65,500	events/region-yr		
	GC	500/1,260/2,100	scf CH_4/event	900	events/region-yr		
	MC	170/300/465	scf CH_4/event	1,577,400	events/region-yr		
	RM	600/1,400/2,600	scf CH_4/event	4,919,400	events/region-yr		
Liquids unloading (manual)	AP	1,650/4,550/8,700	scf CH_4/event	65,800	events/region-yr		
	GC	9,750/13,300/16,900	scf CH_4/event	79,500	events/region-yr		
	MC	25,500/47,800/71,900	scf CH_4/event	23,800	events/region-yr		
	RM	9,400/15,200/21,000	scf CH_4/event	7,600	events/region-yr		
Pneumatic controllers	AP	0.822/1.65/2.63	scf CH_4/device-hr	77,261	wells/region	1.7	devices/well
	GC	7.07/10.67/14.8	scf CH_4/device-hr	53,436	wells/region	2.4	devices/well
	MC	2.59/4.85/7.78	scf CH_4/device-hr	222,684	wells/region	1.4	devices/well
	RM	0.317/0.67/1.12	scf CH_4/device-hr	124,225	wells/region	2.7	devices/well
Chemical pumps	AP	56,500/101,000/145,000	scf CH_4/device-yr	795	devices/region		
	GC	56,500/101,000/145,000	scf CH_4/device-yr	2,537	devices/region		
	MC	56,500/101,000/145,000	scf CH_4/device-yr	15,543	devices/region		
	RM	56,500/101,000/145,000	scf CH_4/device-yr	14,849	devices/region		
Equipment leaks	AP	2.3/5.9/9.4	scf CH_4/well-hr	145,411	wells/region		
	GC	1.3/3.1/4.9	scf CH_4/well-hr	69,009	wells/region		
	MC	1.3/2.8/4.2	scf CH_4/well-hr	101,141	wells/region		
	RM	0.5/2.1/3.7	scf CH_4/well-hr	76,819	wells/region		

[a] Region abbreviations: Appalachian (AP), Gulf Coast (GC), Midcontinent (MC), Rocky Mountain (RM).

[b] Flaring rate represents the share of potential emissions that are controlled by flaring.

From Alvarez et al. (2018), showing the data sets that were used for their assessment:

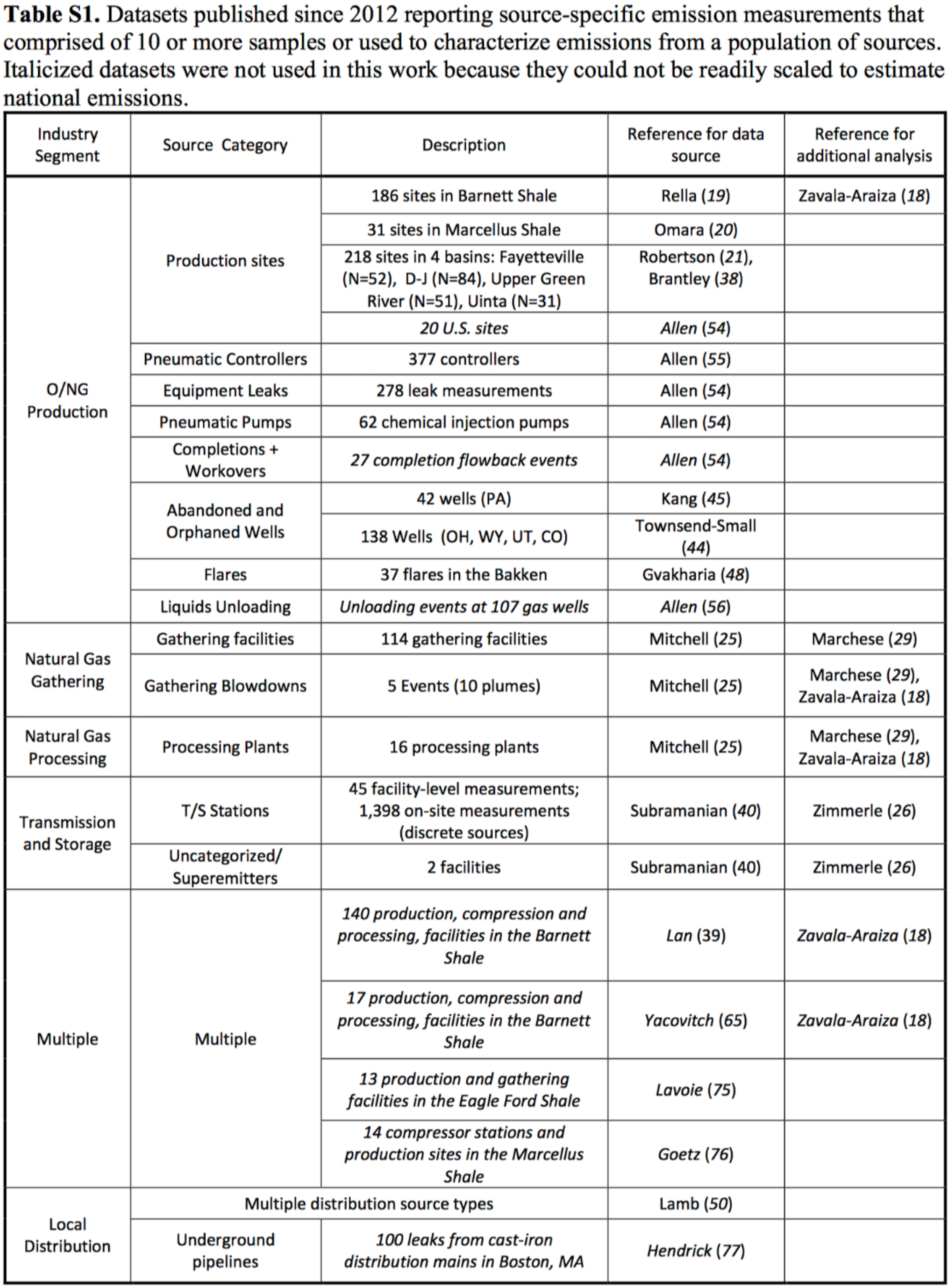

Table S1. Datasets published since 2012 reporting source-specific emission measurements that comprised of 10 or more samples or used to characterize emissions from a population of sources. Italicized datasets were not used in this work because they could not be readily scaled to estimate national emissions.

Industry Segment	Source Category	Description	Reference for data source	Reference for additional analysis
O/NG Production	Production sites	186 sites in Barnett Shale	Rella (*19*)	Zavala-Araiza (*18*)
		31 sites in Marcellus Shale	Omara (*20*)	
		218 sites in 4 basins: Fayetteville (N=52), D-J (N=84), Upper Green River (N=51), Uinta (N=31)	Robertson (*21*), Brantley (*38*)	
		20 U.S. sites	*Allen* (*54*)	
	Pneumatic Controllers	377 controllers	Allen (*55*)	
	Equipment Leaks	278 leak measurements	Allen (*54*)	
	Pneumatic Pumps	62 chemical injection pumps	Allen (*54*)	
	Completions + Workovers	*27 completion flowback events*	*Allen* (*54*)	
	Abandoned and Orphaned Wells	42 wells (PA)	Kang (*45*)	
		138 Wells (OH, WY, UT, CO)	Townsend-Small (*44*)	
	Flares	37 flares in the Bakken	Gvakharia (*48*)	
	Liquids Unloading	*Unloading events at 107 gas wells*	*Allen* (*56*)	
Natural Gas Gathering	Gathering facilities	114 gathering facilities	Mitchell (*25*)	Marchese (*29*)
	Gathering Blowdowns	5 Events (10 plumes)	Mitchell (*25*)	Marchese (*29*), Zavala-Araiza (*18*)
Natural Gas Processing	Processing Plants	16 processing plants	Mitchell (*25*)	Marchese (*29*), Zavala-Araiza (*18*)
Transmission and Storage	T/S Stations	45 facility-level measurements; 1,398 on-site measurements (discrete sources)	Subramanian (*40*)	Zimmerle (*26*)
	Uncategorized/ Superemitters	2 facilities	Subramanian (40)	Zimmerle (*26*)
Multiple	Multiple	*140 production, compression and processing, facilities in the Barnett Shale*	*Lan* (39)	*Zavala-Araiza* (*18*)
		17 production, compression and processing, facilities in the Barnett Shale	*Yacovitch* (*65*)	*Zavala-Araiza* (*18*)
		13 production and gathering facilities in the Eagle Ford Shale	*Lavoie* (*75*)	
		14 compressor stations and production sites in the Marcellus Shale	*Goetz* (*76*)	
Local Distribution	Multiple distribution source types		Lamb (*50*)	
	Underground pipelines	*100 leaks from cast-iron distribution mains in Boston, MA*	*Hendrick* (*77*)	

Table S3. CH$_4$ emissions from the U.S. O/NG supply chain in 2015 as estimated in the 2017 U.S. EPA Greenhouse Gas inventory (GHGI) (*17*) and in this work based on source-based (i.e., individual components inside sites or facilities, Section S1.4) and site-based (i.e., all sources at a site, Section S1.2) methodologies. Bold categories denote emission sources for which recent measurements have been reported.

Industry Segment	Source Category	2015 U.S. Emissions (Gg CH$_4$ y^{-1})		
		GHGI	This work (source–based)	This work (site–based)
O/NG Production	**Pneumatic Controllers**	1,800	1,100 (1,100 - 1,200)	7,200 (5,600 - 9,100)
	Equipment Leaks* $	360	620 (570 - 670)	
	Liquids Unloading	210	170 (170 - 200)	
	Pneumatic Pumps*	210	190 (180 - 200)	
	Oil & Condensate Tanks	100	100 (97 - 120)	
	Produced Water Tanks	40	360 (340 - 380)	
	Fuel combustion	240	98 (91 - 210)	
	Associated gas flaring and venting	150	71 (69 - 86)	
	Other production sources*	40	60 (58 - 68)	
	Routine Operations Subtotal	3,100	2,800 (2,700 - 2,900)	7,200 (5,600 - 9,100)
	Completions + Workovers	100	86 (80 - 120)	
	Abandoned and Orphaned Wells	NA	61 (59 - 360)	
	Onshore Production Subtotal	3,200	2,900 (2,900 - 3,300)	7,300 (5,700 - 9,300)
	Offshore Platforms	300	300 (240 - 380)	
	Production Total	3,500	3,200 (3,100 - 3,600)	7,600 (6,000 - 9,600)
Natural Gas Gathering	**Gathering Stations**	2,000	2,100 (2,100 - 2,200)	
	Gathering Episodic Events	200	170 (7 - 750)	
	Gathering Pipelines	160	310 (300 - 330)	
	Gathering Total	2,300	2,600 (2,400 - 3,200)	
Natural Gas Processing	**Processing Plants**	410	680 (610 - 880)	
	Routine Maintenance	36	36 (29 - 46)	
	Processing Total	450	720 (650 - 920)	
Transmission and Storage (T/S)	**T/S Stations**	1,100	1,100 (860 - 1,400)	
	T/S Uncategorized/Superemitters	NA	440 (350 - 570)	
	Transmission Pipelines	220	220 (180 - 290)	
	LNG Storage and Import Terminals	70	67 (54 - 87)	
	T/S Total	1,300	1,800 (1,600 - 2,100)	
Local Distribution	All sources through customer meters	440	440 (220 - 950)	
Petroleum Midstream	Oil Transportation + Refining	34	34 (26 - 84)	
Total U.S. Oil and Gas Supply Chain		8,100 (6,800 – 10,000)	8,800 (8,400 - 9,700)	13,000 (12,000 - 15,000)

* Denotes multiple GHGI source categories are combined into this source type.

$ GHGI combines compressor venting with compressor fugitives, thus we combine 48 Gg derived from GHGRP for compressor venting with 523 Gg for equipment leaks.

Table S8. Sources of activity and emissions data used for the alternative, component-level estimates of source-specific methane emissions. Emission factor values are reported when applicable. Additional details are provided in the text description.

Sector	Source	Activity Data	Emissions Data	Emission Factors
Production	Associated Gas Venting	DI (*13*)	GHGRP (county-level CH4) (*46*)	NA
	Associated Gas Flaring			
	Liquids Unloading			
	Hydrocarbon Tanks			
	Centrifugal Compressors		GHGRP (basin-level CH4) (*46*)	
	Reciprocating Compressors			
	Dehydrators			
	Flares			
	Well Testing			
	Completions			
	Workovers			
	Combustion Exhaust		GHGRP (county-level CO2) (*46*); AP-42 (*57*)	100 (4 — 660) g CH4 MMBTU-1
	Equipment Leaks		Allen (*54*)	Zavala-Araiza (*18*)
	Pneumatic Controllers	DI production (*13*); GHGRP pump counts (*46*)	Allen (*55*)	High-bleed: 2.0 (1.5 – 2.5) MT CH4 yr-1
				Low-bleed: 0.42 (0.56 – 0.70) MT CH4 yr-1
				Intermittent-bleed: 0.15 (0.09 – 0.23) MT CH4 yr-1
				Malfunctioning: 7.3 (5.5 – 9.4) MT CH4 yr-1
				7% malfunctioning devices
	Pneumatic Pumps	DI production (*13*); GHGRP controller counts (*46*)	Allen (*54*)	1.9 (1.2 – 2.9) MT CH4 yr-1
	Produced Water Tanks	DI production (*13*); (*58*)	EPA O&G Tool (*59*)	Gas wells: 50 g CH4 bbl-1
				Oil wells: 14 g CH4 bbl-1
	Abandoned Wells	DI inactive wells (*13*)	Townsend-Small (*44*); Kang (*45*)	Plugged: 1.8 x 10-5 MT CH4 well-1 yr-1
				Unplugged: 8.8 x 10-2 MT CH4 well-1 yr-1
	Offshore	NA	GHGI (*17*)	NA
Gathering	Gathering Stations	DI gas production (*13*); Marchese (*29*)	Mitchell (*25*); Marchese (*29*); Zavala-Araiza (*18*)	NA
	Gathering Blowdowns	Gathering station emissions from Marchese (*29*)	Marchese (*29*); Zavala-Araiza (*18*)	10% (0.3 - 42%) station emissions
	Gathering Pipelines	DI gas producing wells (*13*)	GHGI (*17*)	0.95 miles pipeline well-1
				0.40 MT CH4 mile-1 yr-1
Processing		Maasakkers (*53*)	Marchese (*29*); Zavala-Araiza (*18*)	NA
Transmission & Storage	T&S Stations	Maasakkers (*53*)	GHGI (*17*); Zimmerle (*26*)	200 MT CH4 station-1 yr-1
	T&S Station Super-emitters		Zimmerle (*26*)	
	Transmission Pipelines		GHGI (*17*)	
	LNG Import and Export Terminals		GHGI (*17*)	
Local Distribution		Maasakkers (*53*)	GHGI (*17*); Lamb (*50*)	NA
Petroleum Transportation & Refining		Maasakkers (*53*)	GHGI (*17*); GHGRP (*46*)	NA
Other fossil and biogenic		Maasakkers (*53*)	GHGI (*17*)	NA

Endnotes

[1] https://www.spe.org/industry/unit-conversion-factors.php

[2] https://www.eia.gov/dnav/ng/NG_CONS_NUM_DCU_SNY_A.htm

[3] https://www.eia.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm

[4] https://www.eia.gov/state/seds/

[5] https://www.epa.gov/ghgreporting/resources-subpart-ghg-reporting

[6] Note: The EPA SIT, an Excel-based tool for completing a governmental GHG inventory that complements the U.S. inventory and international GHG protocols, is separate from the EPA Oil and Gas Tool, which encompasses sectors other than the oil and natural gas sector and is meant for criteria pollutant inventories. https://www.epa.gov/statelocalenergy/download-state-inventory-and-projection-tool

[7] See EPA SIT

[8] https://www3.epa.gov/enviro/

[9] https://www.epa.gov/emc/method-21-volatile-organic-compound-leaks

[10] https://ghgdata.epa.gov/ghgp/main.do

[11] https://www.eea.europa.eu/publications/european-union-greenhouse-gas-inventory-2018

[12] https://www.ipcc-nggip.iges.or.jp/public/2006gl/

[13] Zimmerle et al. 2015; Zavala-Araiza, Lyon, Alvarez, Palacios, et al. 2015; Zavala-Araiza et al. 2015, 2017; Yacovitch et al. 2015; Lavoie et al. 2015; Zavala-Araiza, Lyon, Alvarez, Davis, et al. 2015a; Lyon et al. 2016.

[14] https://pvnpms.phmsa.dot.gov/PublicViewer/

[15] https://data.ny.gov/d/449k-yfe4?category=Energy-Environment&view_name=NYS-Gas-Utility-Service-Territories

[16] https://www.eia.gov/dnav/ng/hist/na1501_sny_8a.htm

[17] https://www.census.gov/programs-surveys/acs/

[18] https://www.census.gov//programs-surveys/cbp.html

[19] https://www.eia.gov/dnav/ng/ng_cons_num_a_EPG0_VN5_Count_a.htm and https://www.eia.gov/dnav/ng/ng_cons_num_a_EPG0_VN7_Count_a.htm

[20] https://www.dep.pa.gov/Business/Energy/OfficeofPollutionPrevention/climatechange/PublishingImages/Pages/ CCAC/Inventory%20-%202018%20write%20-up.pdf

[21] https://www.nj.gov/dep/aqes/NJ_GHGinventory2015Update.pdf

[22] https://www.ct.gov/deep/cwp/view.asp?a=4423&Q=568752&deepNav_GID=2121

[23] https://www.mass.gov/files/documents/2016/11/xv/gwsa-update-16.pdf

[24] https://dec.vermont.gov/sites/dec/files/aqc/climate-change/documents/_Vermont_Greenhouse_Gas_Emissions_Inventory_Update_1990-2015.pdf

[25] Methane Reduction Plan, May 2017, available at https://www.dec.ny.gov/docs/administration_pdf/mrpfinal.pdf, accessed October 2018.

[26] https://www.epa.gov/ghgreporting/overview-subpart-w

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