Earth System Sciences, LLC

Oil and Gas Methane Emissions in the United States: Key Trends and Technologies

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Introduction

In the last decade, there has been intense focus on the management of methane emissions both globally and within the United States. Methane has a relatively high global warming potential[1] with a relatively short atmospheric lifetime, making it a short-term target for emission reductions. Methane is emitted to the atmosphere both by natural processes and anthropogenic (human-caused) activities, and regulators have actively pursued strategies to reduce anthropogenic emissions. Per the Intergovernmental Panel on Climate Change (IPCC), methane is the second most abundant greenhouse gas in the atmosphere, and accounts for ~25% of the immediate radiative forcing (warming influence) attributed to greenhouse gases.[2]

According to the US EPA Greenhouse Gas Inventory (GHGI), methane emissions from the oil and gas sector account for ~3% of anthropogenic greenhouse gas emissions nationally, and 34% of total anthropogenic methane emissions. Despite a 20% increase in domestic oil production and a 50% increase in domestic natural gas production since 1990, total methane emissions from the oil and gas sector have not increased according to EPA.[3] Methane emissions **per cubic foot of gas** produced have decreased by 41% over the same period. These large reductions in emissions per unit of production have been driven by a combination of voluntary and required actions that reduce methane emissions from the oil and gas sector. The oil and gas industry has a long history of cooperation with EPA, state and local agencies, and other interested stakeholders aimed at improving technology and practices to develop resources with lower overall air quality impacts, including methane emissions.

On a national scale, the large increase in domestic natural gas production has driven gas prices down, prompting a rapid shift toward using natural gas as a fuel source for electricity generation.[4] Natural gas is less carbon intensive than coal and natural gas power plants are more efficient. The shift toward natural gas has significantly contributed to the approximately 21% US-wide CO_2 emission reductions from electricity generation between 2007 and 2015. However, concern has been expressed that direct methane emissions from the oil and gas sector can negate the benefits of replacing coal with natural gas. Researchers have responded to these concerns by deploying a wide variety of techniques intended to estimate emissions, but there remains uncertainty in emissions estimates from oil and gas sources. Regulators at the local, state, and federal levels have responded to methane emission concerns by significantly increasing proposed and required controls on oil and gas sources. It remains unclear, however, whether additional regulatory pressure on domestic oil and gas production will bring a net climate benefit given the history of voluntary reductions, tradeoffs between cost of controls, reductions in domestic oil and gas development, and impacts on the price of natural gas. Given the role of natural gas in the overall reduction of carbon intensity of the US economy, it is important to consider the

[1] Global Warming Potential (GWP) is a relative measure of the potential warming impact of different gases. It compares the predicted quantity of heat radiated over a specified period by the emission of a unit mass of a gas compared to the quantity of heat radiated by the emission of the same unit mass of carbon dioxide.

[2] Adapted from IPCC AR5, Table 8.SM.6; Water vapor, the most abundant greenhouse gas in the atmosphere, is not considered in this work.

[3] EPA Greenhouse Gas Inventory (GHGI).

[4] Summarized from Energy Information Administration discussion at https://www.eia.gov/todayinenergy/detail.php?id=25392

implications of suppressing domestic natural gas production on total greenhouse gas emissions from the US.

We will discuss the role of the oil and gas sector on national greenhouse gas emissions in five sections:

I. Overview of the segments of the oil and gas sector;
II. Comparison of historical methane emissions from the oil and gas sector with greenhouse gas and methane emissions from other US economic sectors, as compiled by EPA;
III. Description of trends in methane emissions from the oil and gas sector in EPA Greenhouse Gas Inventories and Green House Gas Reporting Program data and comparison with trends from other sectors;
IV. Description of the role of domestic natural gas production in driving a decrease in overall greenhouse gas emissions from the US electricity generation sector;
V. An overview of the oil and gas industry's historic and current role in developing and deploying technologies and practices aimed at better understanding and reducing methane emissions from the sector; and

EPA manages the two primary sources of methane emission information from the oil and gas sector. The first source is the US Greenhouse Gas Inventory (GHGI), done annually, which covers reporting years (RY) 1990 through 2014. This inventory is developed from engineering calculations and covers all major sectors contributing to US Greenhouse Gas Emissions. The second source is the US Greenhouse Gas Reporting Program (GHGRP), which began in RY2011 for methane emissions from the oil and gas sector. This is a self-reported inventory of methane emissions by industry, where emission calculation methodologies are prescribed by EPA. Importantly, not all segments of the oil and gas sector are included in prior GHGRP reports, not all operations meet the 25,000 metric tonne of CO_2 equivalent emission threshold for reporting, and not all potential sources of methane emissions are reported. The GHGRP is not a "complete" national inventory. The GHGI will be used to evaluate overall contributions of the oil and gas sector to national emissions and both the GHGI and GHGRP will be used to evaluate trends over time.

I. Overview of the segments of the oil and gas sector

From a methane emissions perspective, the oil and gas sector consists of several discrete segments. In general, these segments are:

1. **Oil and gas production**: includes oil and gas wells, surface production equipment, and auxiliary equipment associated with drilling, completing, and producing oil and gas wells.
2. **Gas gathering and boosting:** composed of the network of gathering pipelines, central production facilities, and compressor stations which move gas from wells to gas processing facilities or transmission lines.
3. **Gas processing:** composed of the processing plants which remove contaminants (e.g. CO_2, water, H_2S) from produced gas; recover natural gas liquids (e.g. ethane, propane, butane, and

some pentanes) from the produced gas for use as petrochemical feedstocks, refinery feedstocks, fuel, and other uses; and render the natural gas ready for use.

4. **Gas transmission:** consists of the large interstate and intrastate pipeline networks and compressor stations that move gas from the gas processing segment to the end users. For many power plants and large industrial users, the gas supply comes directly from the transmission segment.
5. **Underground gas storage:** consists of the underground storage reservoirs, wells, and equipment used to store gas, which provides balance between supply and demand and leads to stability in seasonal gas supplies.
6. **Liquid natural gas (LNG) storage and import/export facilities**: facilities that store cryogenic liquid natural gas (mostly methane), re-gasify LNG for peak demand periods (peak shaving), load LNG on carriers for export, or receive and re-gasify imported LNG for use in the US.
7. **Natural gas distribution:** comprised of the local distribution companies that take gas from the transmission segment and deliver it to individual residential, consumer, and industrial users.

Methane emissions occur in each of these segments from various sources and equipment. This report will discuss emissions from the first six segments listed, but not discuss methane emissions from the distribution segment.

II. Comparison of historical methane emissions from the oil and gas sector with greenhouse gas and methane emissions from other US economic sectors

According to the RY2014 GHGI, methane emissions from the oil and gas sector accounted for approximately 3% of the total 2014 US anthropogenic greenhouse gas emissions on a CO_2 equivalent basis (Figure 1), which is roughly equal to methane emissions from the agriculture sector.[5,6]

Looking at methane emissions alone, the RY2014 GHGI attributes ~34% of US anthropogenic methane emissions to the oil and gas sector, 33% to the agriculture sector, 21% to landfill emissions, 9% to the coal sector, and the balance (3%) to other economic categories (Figure 2).

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[5] Adapted from the "U.S. EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2014" Tables ES-6 & 2.1.

[6] CO_2 equivalents are an expression of a particular greenhouse gases' warming effect over a specified time frame (generally 20, 100, and 500 years) in a mass of CO_2 that would have the same warming effect. For example, 1 metric tonne of methane has the same warming effect over a 100 year time frame as 25 metric tonnes of CO_2 (AR-4) or 30 metric tonnes of CO2 (AR-5). This paper uses the AR-4 100 year value (aka Global Warming Potential - GWP) of 25, which is the value officially adopted by the US for the GHG inventory and other purposes.

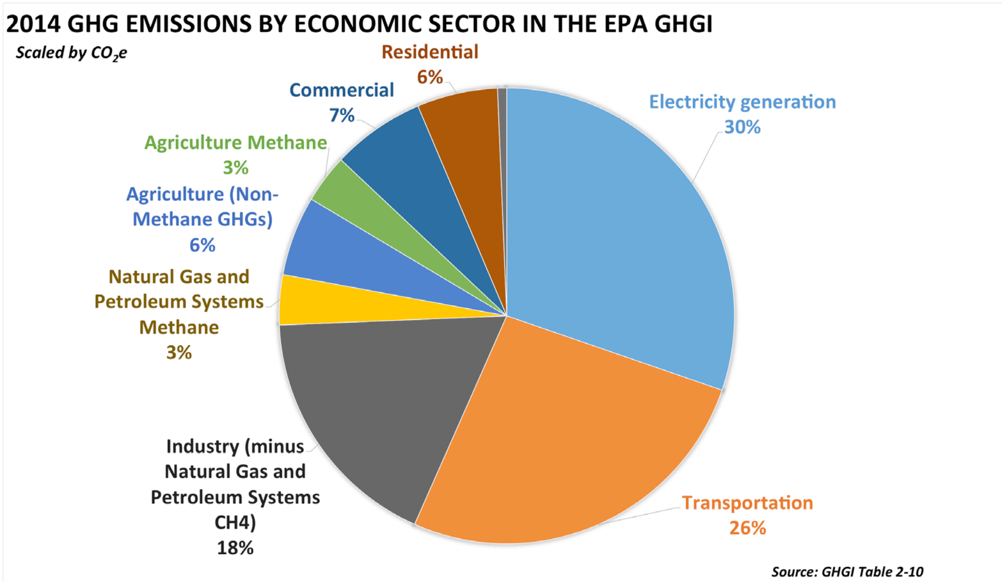

Figure 1. United States anthropogenic greenhouse gas emissions by economic sector estimated by the RY2014 EPA Greenhouse Gas Inventory.

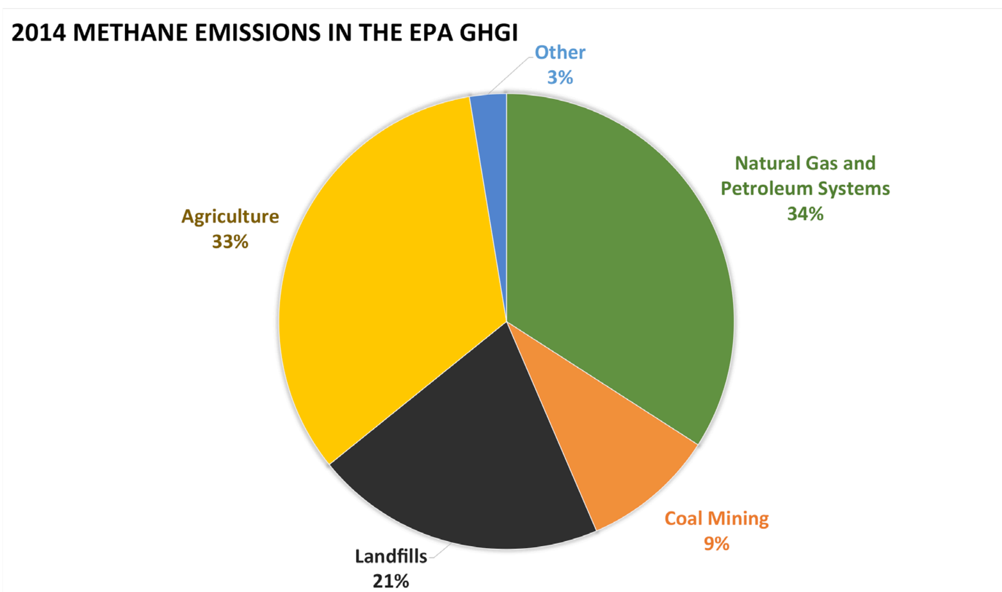

Figure 2. United States anthropogenic methane emissions by economic sector estimated by the EPA RY2014 Greenhouse Gas Inventory.

III. Trends in estimated methane emissions from the oil and gas sector in the EPA Greenhouse Gas Inventory (GHGI) and Green House Gas Reporting Program (GHGRP) and comparison with trends from other sectors

According to the reporting year (RY) 2014 GHGI, despite a 20% and 50% increase in domestic oil and gas production respectively since 1990,[7] absolute quantities of methane emissions have remained essentially unchanged over the same period. Methane emissions from the agriculture sector have remained steady while those from coal mining and landfills have decreased somewhat since 1990.[8]

For every barrel of oil equivalent (BOE) produced in the United States, GHGI estimated methane emissions have declined by 41% for the natural gas systems segments and 26% for the combined petroleum and natural gas systems segments between RY1990 and RY2014 (Figure 4). [9,10] This decrease in emissions per BOE is driven by a combination of a rapid increase in national production after RY2006 along with increased voluntary and regulatory driven emission controls after RY2005 (Figure 4). Methane emissions from the oil and gas sector reported to the GHGRP declined by approximately 18% between RY2011 and RY2015 (Figure 5). Conversely, the number of reporting facilities increased by approximately 20% over the same time. Combined, the emissions per reporting facility declined by ~32% over the same period (Figure 6).[11]

Looking more closely at the Onshore Production Segment, which accounted for ~82% of the GHGRP reported methane emissions from the oil and gas sector in RY2015, shows a similar pattern. Reported methane emissions declined by 21% while the number of reported wellheads, an indicator of the scope of GHGRP coverage, increased by 52%. When combined, the lower total reported emissions and greater coverage indicate a decline in reported methane emissions per wellhead of ~48% from RY2011 to RY2015 (Figure 7). As shown in Figure 4, these trends are driven by a combination of increased production, reduced methane emissions per unit production, and a combination of voluntary and required controls.

There has been considerable debate about the accuracy of the GHGI and GHGRP emission estimates and the methodologies used to calculate emissions are still evolving. The year-to-year change in the GHGI methane emissions attributed to the oil and gas sector from RY2008 to RY2014 (Figures 3 and 8) illustrates this well. Beginning with RY2009, EPA has made multiple revisions to the calculation methodologies used in the GHGI that have led to large changes in estimated emissions from the oil and gas sector. These changes do not reflect any change in actual emissions, but are an indication of the

[7] From www.eia.gov US Field Production of Crude Oil and US Natural Gas Gross Withdrawals.

[8] Adapted from the "U.S. EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2014" Table 2.1.

[9] Methane emissions were taken from the U.S. EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2014; Table 2.1. Production volumes were taken from the US Energy Information Administration's (EIA) "Crude Oil Production" report found at: http://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_a.htm and "U.S. Natural Gas Gross Withdrawals and Production report found at: http://www.eia.gov/dnav/ng/ng_prod_sum_dc_NUS_MMCF_m.htm .

[10] BOE is the amount of gas that equals the energy content of one barrel of oil. For this paper, 6,000 standard cubic feet of gas per barrel of oil equivalent (used by the EIA) is used to convert gas to BOE's.

[11] Note that the Gathering and Boosting segment of the oil and gas sector has not been reported in the past and will be reported for the RY2016 emission year in 2017.

uncertainty in calculation methodologies. The percent change from year to year shown in Figure 3 illustrates the variations in estimates of methane emissions from the oil and gas sector in the GHGI.

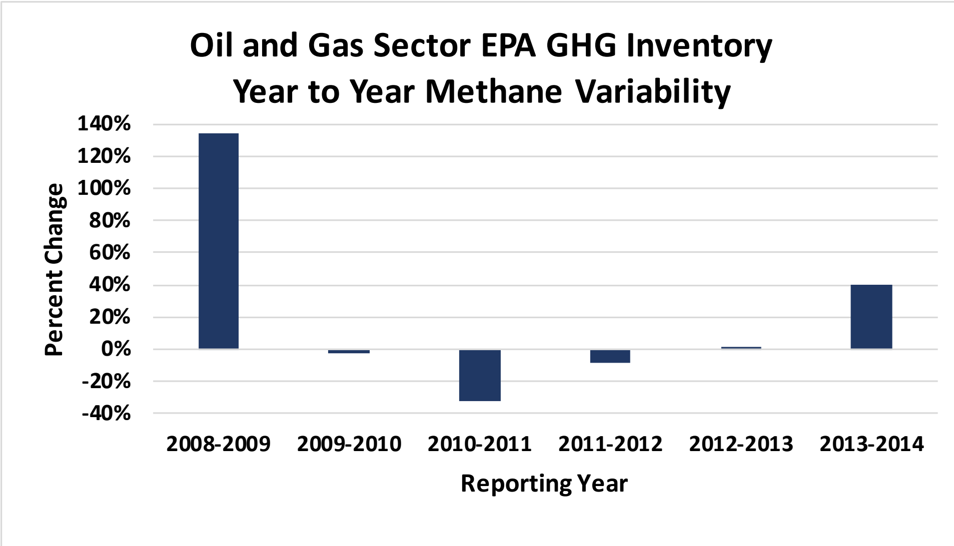

Figure 3. Year to year percent change in the EPA GHGI estimated methane emissions from the oil and gas sector

As Table 1 shows, for the combination of segments discussed here, the annual change of estimated methane emissions has varied from an increase of 134% to a decrease of 32% on a year-to-year basis, driven by changes in methodology rather than changes in any underlying emissions processes.

For the production segment, the annual changes have been even more dramatic, ranging from an increase of 822% to a decrease of 58% on a year-to-year basis. Again, these changes are not driven by changes in production characteristics or underlying drivers of emissions, but rather by year-to-year changes in how the emissions are calculated.

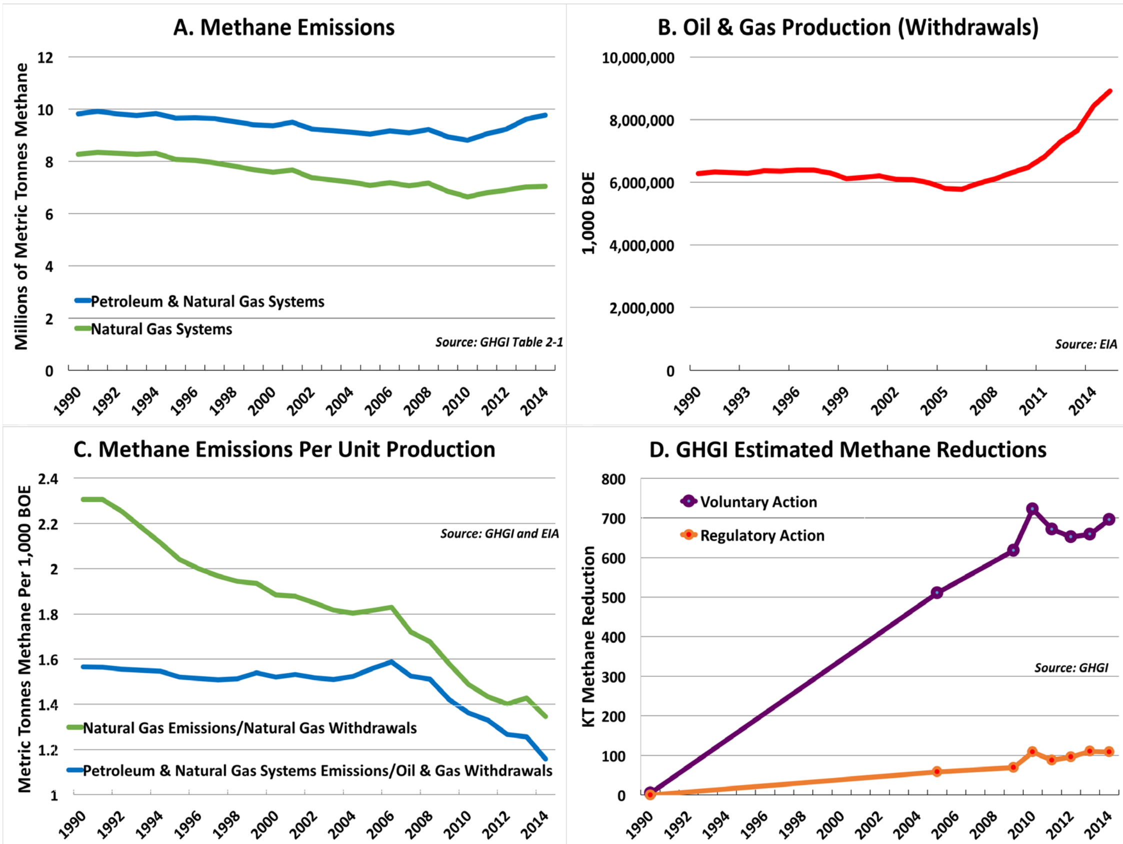

Figure 4. **A) Methane emissions from the Combined Petroleum and Natural Gas Systems and Natural Gas Systems sectors of the GHGI from RY1990 to RY2014. B) Combined oil and gas production volume (Barrels of Oil Equivalent (BOE)) in the United States from 1990 to 2014 as estimated by the EIA. C) Methane emissions per unit of production for the Natural Gas Systems and Combined Petroleum and Natural Gas Systems. Notice that the relatively small changes in methane emissions over time, coupled with the large increase in domestic production after 2006 leads to significant decreases in the estimated methane emissions per unit production. D) GHGI estimated methane emission reductions from both voluntary (86%) and regulatory (14%) actions.**

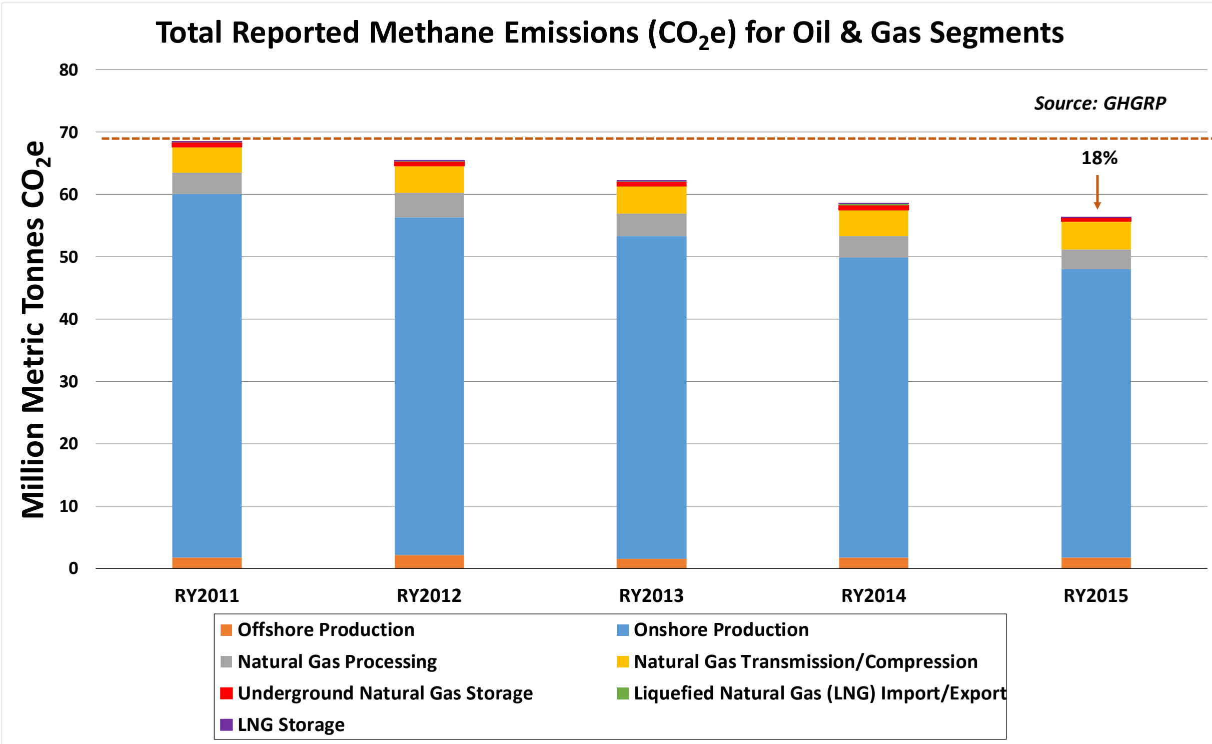

Figure 5. Total GHGRP reported methane emissions by in-scope oil and gas segments. Note that not all facilities are required to report their emissions to EPA, thus this is not a complete inventory.

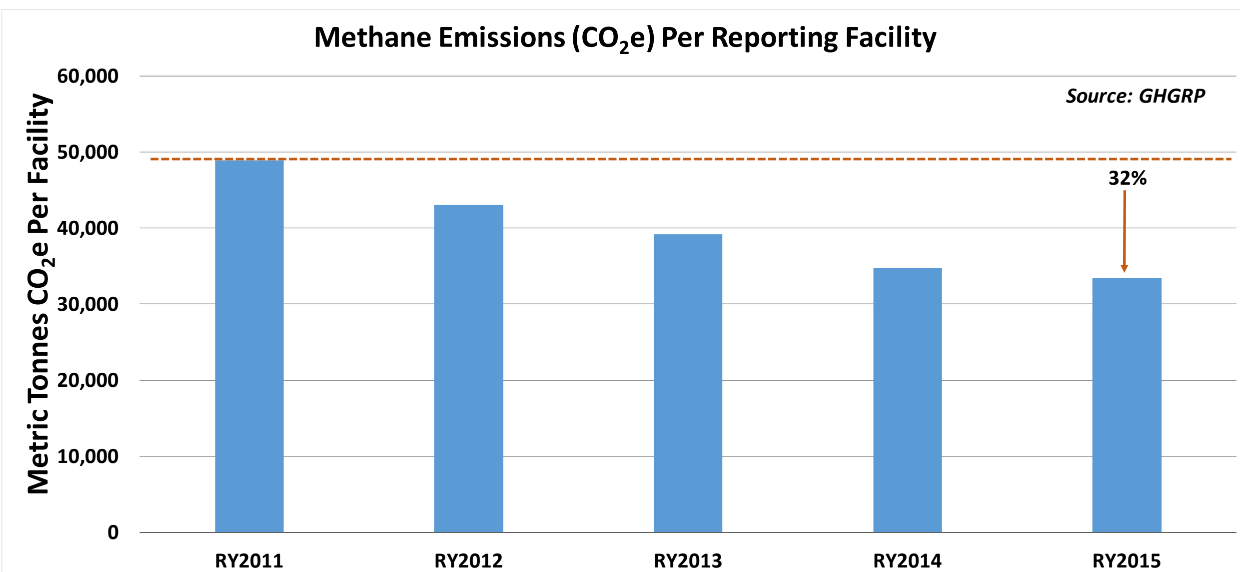

Figure 6. Methane Emissions per GHGRP Reporting Facility[12] for the in-scope segments. Note that not all facilities are required to report their emissions to EPA, thus this is not a complete inventory.

[12] Note that a facility for the onshore production segment is a unique combination of an operator and basin and includes all wells and other production facilities in the basin for the reporting operator. Facilities in other in-scope segments are reported if they meet the reporting threshold of 25,000 metric tonnes of CO_2 equivalent emissions.

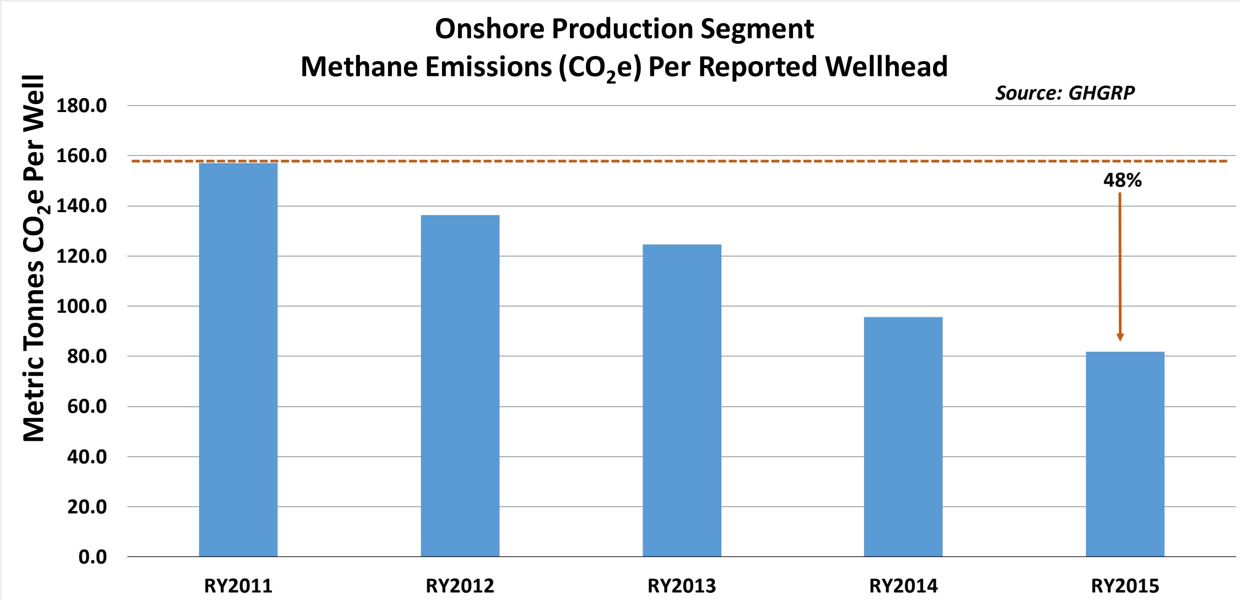

Figure 7. Emissions per wellhead reported in the GHGRP onshore production segment. Note that not all facilities are required to report their emissions to EPA, thus this is not a complete inventory.

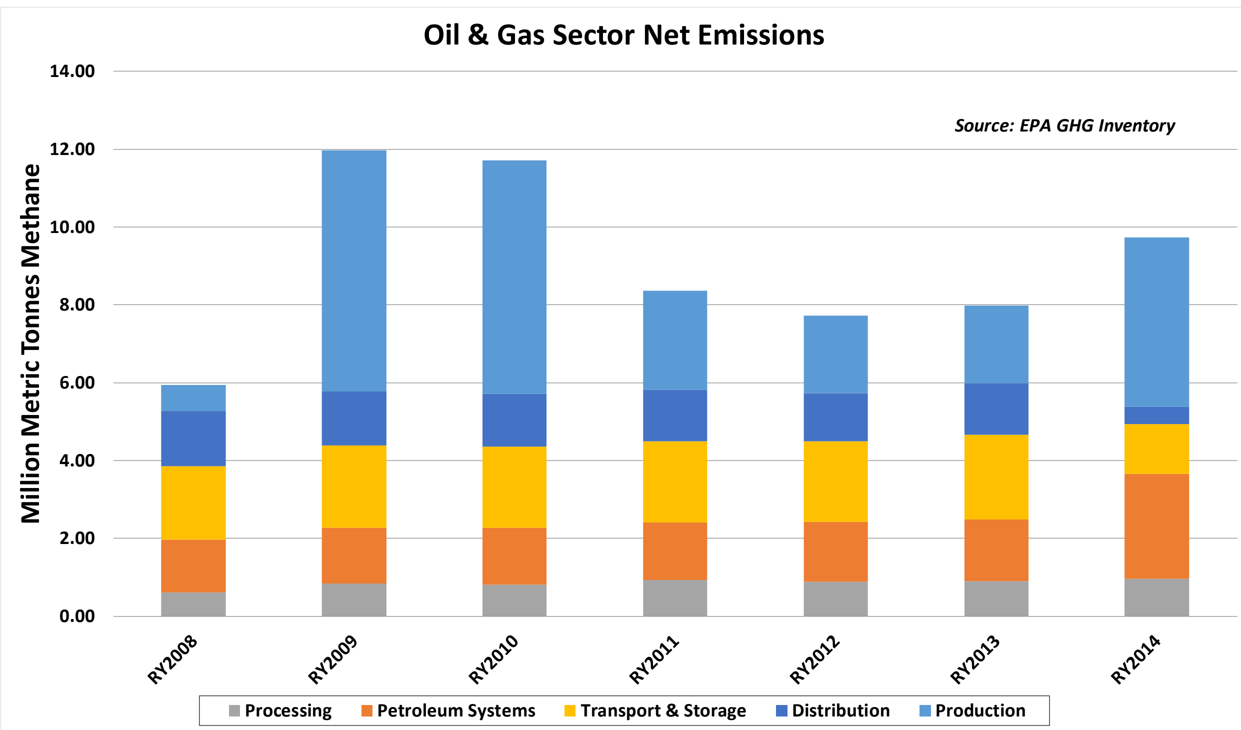

Figure 8. Annual Methane Emission per Segment estimated by the GHGI using the different methodologies employed by EPA during each year for the RY2008 thru RY2014 period.

The wide variability in estimated oil and gas methane emissions has given rise to a broad array of studies aimed at better quantifying and understanding methane emissions. These studies include direct emission measurements, emissions estimated from observed methane concentrations in offsite ambient air, inventory analyses, and lifecycle analyses. These studies have been further evaluated by meta-analysis studies that attempt to quantify emissions statistically at a variety of scales to estimate emissions. Despite the significant attention, the question of how much methane is emitted by the US oil and gas sector has not been settled, and significant uncertainty remains in the quantification of emissions.

In general, ambient concentration based emission estimates have shown higher methane emissions from the oil and gas sector than the GHGI or the GHGRP data would indicate.[13] A spirited debate continues regarding the accuracy of many of these studies, particularly those using ambient methane concentration measurement coupled with inversion modeling or flux plane techniques to estimate emissions. Extrapolating short-term measurements (e.g., seconds to minutes) typical for ambient studies to more meaningful time periods, such as annual, is one source of uncertainty. Attribution of total measured methane concentrations amongst background, biogenic, and fossil sources is another challenge for accurate estimates, even when using hydrocarbon ratios, such as methane:ethane, or isotopic ratios to help constrain estimates of fossil methane. When coupled with the inherent uncertainty of inverse modeling or flux plane techniques, the accuracy of ambient concentration studies remains an active area of research. In their development of “Other Test Method 33 & 33a” the US EPA Office of Research and Development concluded downwind measurement of methane concentrations from a site coupled with inversion algorithms/models can be used as a “screening” technique with an expected accuracy of +/-60%. EPA notes that the measurement site must be within close proximity (20 – 200 meters) of the facility and that several measurement periods of 15-30 minutes are needed to achieve this screening level accuracy.[14] The Environmental Defense Fund (EDF), an environmental non-governmental organization, has been heavily involved in the arena of oil and gas methane emission studies. Beginning in 2012, EDF has organized and/or sponsored 16 separate studies of oil and gas methane emissions. Industry companies partnered with EDF and academic researchers and co-sponsored several of these studies. To date, 27 peer-reviewed papers have been published from the results of these studies, Appendix 1.[15] Their most recently published work argues that emissions are higher than the GHGI or GHGRP suggest, but are lower than initial estimates reported early in their campaigns.

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[13] Note that the GHGRP reporting threshold for oil and gas is 25,000 metric tonnes of CO_2 equivalency hence the GHGRP is not intended to be a full inventory of methane emissions from the oil and gas sector. Despite this, researchers regularly compare the estimates from their work to both the GHGI and GHGRP methane emissions.

[14] Other Test Method 33A v1.2: Geospatial Measurement of Air Pollution, Remote Emissions Quantification - Direct Assessment (GMAP-REQ-DA); https://www3.epa.gov/ttn/emc/prelim/otm33a.pdf .

[15] https://www.edf.org/climate/methane-studies ; see Appendix 1 for a listing of papers published from the study results.

Table 1. Year-to-year change in methane emissions with changes in EPA calculation methodology.

Year to Year Change							
Period	Total O & G Sector	Total O & G Sector w/o Distribution	Petroleum Systems	Production	Processing	Transport & Storage	Distribution
RY2008-RY2009	101%	134%	6.6%	821.6%	34.9%	12.7%	-3.0%
RY2009-RY2010	-2%	-2%	0.8%	-3.3%	-2.6%	-1.3%	-1.6%
RY2010-RY2011	-29%	-32%	1.4%	-57.6%	14.8%	0.0%	-2.2%
RY2011-RY2012	-8%	-8%	3.8%	-21.7%	-4.4%	-0.7%	-7.4%
RY2012-RY2013	3%	2%	3.0%	-0.6%	1.8%	5.1%	8.2%
RY2013-RY2014	22%	40%	70.8%	120.1%	5.8%	-41.1%	-66.7%

Note: The period column denotes the two annual inventories being compared – for example RY2013-RY2014 is a comparison of the two inventories published for the 2013 and 2014 emission years. These annual changes are shown for different portions/segments of the oil and gas sector.

IV. The role of domestic natural gas production in driving a decrease in overall greenhouse gas emissions from the US electricity generation sector

Generation of electricity is the largest source of US anthropogenic greenhouse gases and accounted for 30% of total GHG emissions (CO_2e) in the 2014 GHGI (Figure 1). Since peaking at 2.425 billion metric tonnes of CO_2 in 2007, CO_2 emissions from the electric power sector have declined by 21% to 1.919 billion metric tonnes in 2015 (Figure 9), while also absorbing growth in electrical demand and generation.[16] This decline is driven partly from increased natural gas use in the sector, which nearly matched coal as the primary power generation fuel source in 2015 (Figure 10).

As Figure 11 depicts, the GHG intensity, metric tonnes of CO_2 per megawatt hour of electricity generated, of the US power sector has declined about 29% percent from 1990 to present. According to the Energy Information Agency, total reductions during this period amounted to 2.048 billion metric tonnes of CO_2 with the majority (61%) of this reduction due to the shift towards natural gas as the fuel for power generation (Figure 12).[17] Natural gas has nearly tripled its share of the electricity generation market since 1990, driven by decreases in the price of natural gas as domestic production has increased

[16] Energy Information Administration - September 2016 Monthly Energy Review Table 12.6.

[17] US Energy Information Administration, October 2015 Monthly Energy Review, Table 12.6 Carbon dioxide emissions from energy consumption: electric power sector; Table 7.2b Electricity net generation: electric power sector; from 2004 to 2014, includes an estimate of distributed solar generation from the National Energy Modeling System; Table 16. Renewable Energy Generating Capacity and Generation.

(Figure 10). Domestic natural gas production has enabled an overall decline in greenhouse gas emissions from the electric power generation sector, which dominates US greenhouse gas emissions.

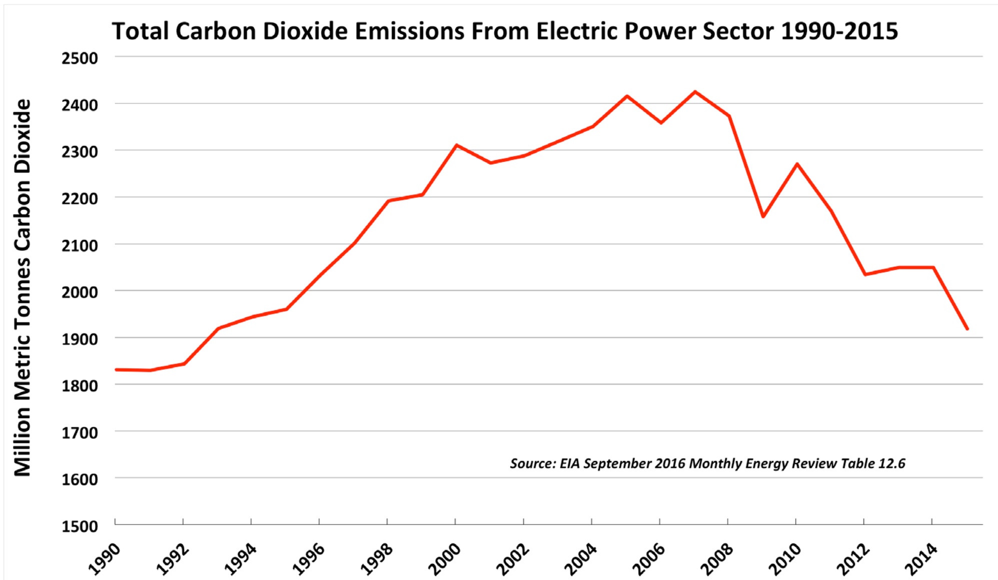

Figure 9. Electric Power Sector CO_2 Emissions over time as compiled by the EIA Monthly Energy Review.

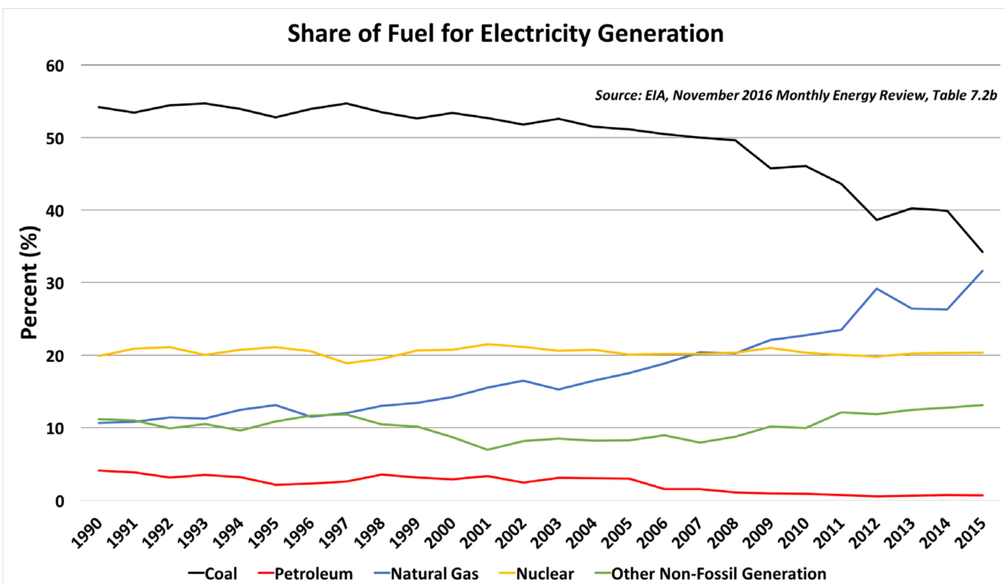

Figure 10. Share of fuel for electricity generation in the United States as compiled by the EIA Monthly Energy Review. Notice that by 2015, natural gas is nearly matching coal as the dominant fuel source for electrical generation.

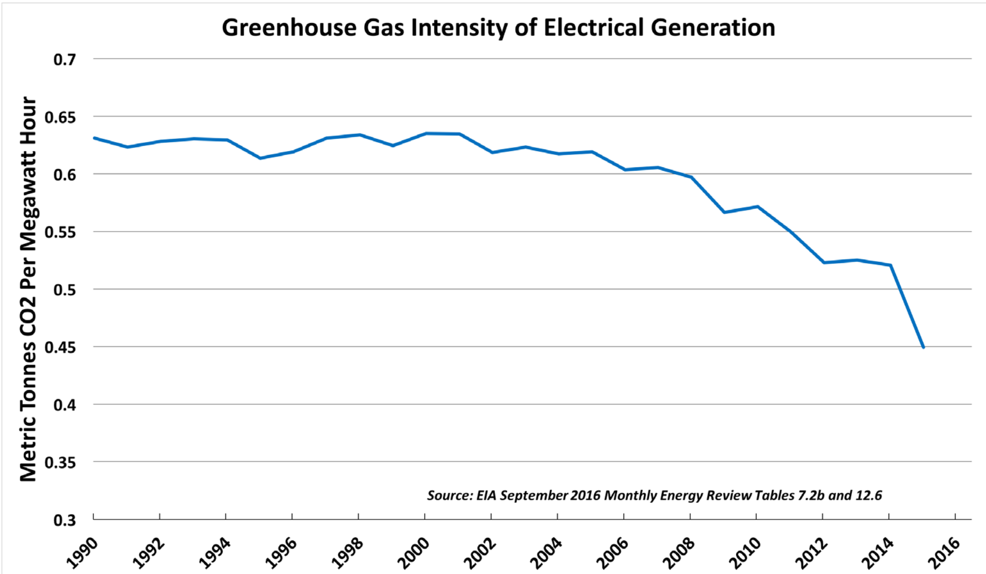

Figure 11. GHG Intensity of US Electricity Generation as compiled by the EIA Monthly Energy Review.

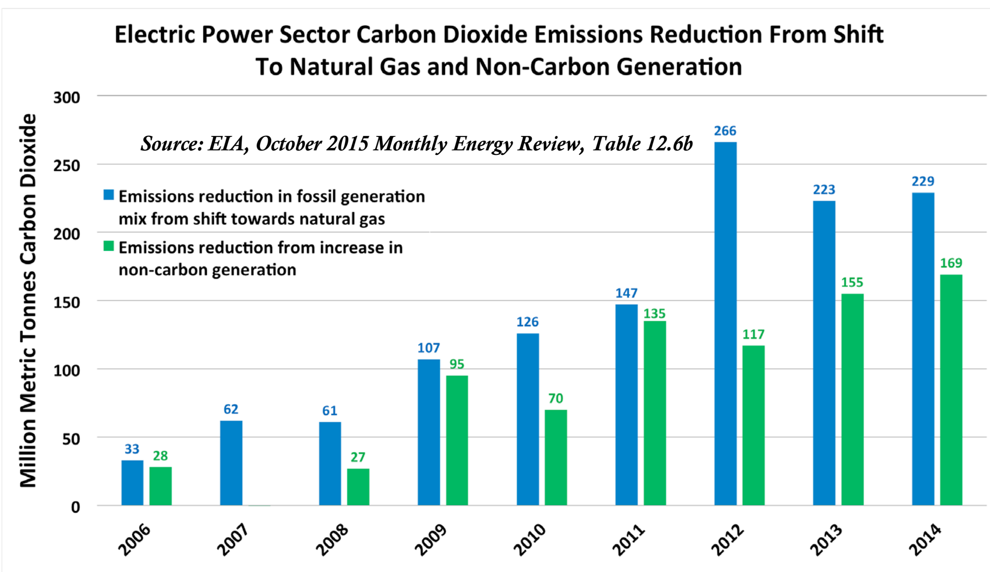

Figure 12. Share of carbon dioxide emissions reductions from shifts toward natural gas and non-fossil fuels for electricity generation. Data taken from EIA Monthly Energy Review, Table 12.6b.

V. The oil and gas industry's role in technology development, methane emission understanding, and methane reduction

The oil and gas industry, both in the US and globally, has a long history of proactive and positive engagement with governmental authorities, agencies, and stakeholders regarding methane and greenhouse gas emissions. This section provides a short summary of the oil & gas industry's efforts to address methane emissions.

1992-1993 - Seminal study of oil and gas industry methane emissions; published in 1996, "Methane Emissions from the Natural Gas Industry by the Gas Research Institute and EPA" (EPA/GRI 1996)

1993 – Launch of the Natural Gas Star Partnership – aimed at the reduction of methane emissions from the oil and gas sector

2001 – Publication of the pilot edition of the American Petroleum Institute (API) Compendium of Greenhouse Gas Emissions Methodologies for the Oil and Gas Industry; Updated in 2004 & 2009

2002 – Formation of the World Bank led Global Gas Flaring Reduction Partnership

2003 – Publication of the 1st edition of the IPIECA "Petroleum Industry Guidelines for Reporting Greenhouse Gas Emissions" developed in conjunction with the American Petroleum Institute (API) and the Oil and Gas Producers (OGP) organizations; Updated in 2011

2004 – Launch of the "Methane to Markets Partnership"; although official partners were countries, industry operating companies and service companies engaged as project network partners; The Methane to Markets Partnership was rebranded as the Global Methane Initiative

2009 – Publication of the API, CONCAWE, IPIECA guidelines for: Addressing Uncertainty in Oil & Natural Gas Industry Greenhouse Gas Inventories: Technical Considerations and Calculation Methods

2012 – UT-EDF study followed by subsequent EDF organized studies across the natural gas value chain

2013 – Launch of the EDF Methane Detector Challenge in conjunction with eight industry partner companies

2014 – Launch of the Climate and Clean Air Coalition Oil & Gas Methane Partnership

Besides participation in these more formal initiatives and efforts, industry companies engaged with technology developers to develop a broad range of tools and technologies, such as optical gas imaging cameras, aimed at improving management of methane emissions.

Voluntary reductions in the Greenhouse Gas Inventory

In constructing the greenhouse gas inventory for methane emissions from the oil and gas sector (Natural Gas Systems and Petroleum Systems) EPA first estimates potential emissions and then subtracts reductions from voluntary actions and regulatory requirements. For the 2014 emission year, voluntary reductions accounted for over 86% of the reductions in potential emissions or 989,900 metric tonnes of methane (not CO_2e), which represents about 36.3 billion standard cubic feet of methane,[18] while regulatory actions accounted for about 15% of the reductions in potential emissions. The voluntary reductions in 2014 were equivalent to about 7.5% of total methane emissions attributed to the Petroleum and Natural Gas Systems segments discussed.

Natural Gas STAR Partnership

The Natural Gas STAR Partnership (Gas STAR) was arguably one of the most successful industry/government voluntary cooperation programs. Gas STAR provided a forum and venue for exchange of ideas, technologies, and practices between industry companies and between companies and technology developers. Successes and learnings were captured and documented via annual reports, partner reported opportunity documents, case studies, and lessons learned documents. Periodic technology exchange workshops and the annual implementation workshop provided a venue for exchange of information and technologies. Virtually all the technologies, practices, and approaches now contained in finalized or proposed regulation were developed and shared via EPA under the Gas STAR umbrella. Table 2 shows the regulatory requirements alongside the corresponding Gas STAR documentation of the technology or practice.

[18] Adapted from the U.S. EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2014; Annex 3.5 Table A-127 and Annex 3.6 Tables A-134, A-136, A-137.

Table 2. Regulatory requirements and corresponding Gas STAR documentation.

Regulatory Requirement	Gas STAR Documentation
Combustion Control in General	Install Flares, Pro Fact Sheet
Control of VOCs and Methane from Storage Tanks	Installing Vapor Recovery Units on Storage Tanks, Lessons Learned
Control of VOCs, Methane, and Hazardous Air Pollutants from Glycol Dehydrators	Pipe Glycol Dehydrator to Vapor Recovery Unit, Pro Fact Sheet Optimize Glycol Circulation and Install Flash Tank Separators in Glycol Dehydrators, Lessons Learned Replacing Gas-Assisted Glycol Pumps with Electric Pumps, Lessons Learned
Limitations on the Type of Pneumatic Controllers Using Natural Gas That Can Be Installed	Convert Gas Pneumatic Controls to Instrument Air, Lessons Learned Options for Reducing Methane Emissions From Pneumatic Devices in the Natural Gas Industry, Lessons Learned
Control of VOCs and Methane from Pneumatic Pumps	Convert Natural Gas-Driven Chemical Pumps, PRO Fact Sheet
Requirement for Periodic Leak Inspections to Identify Equipment Leaks	Conduct Directed Inspection and Maintenance at Remote Sites, PRO Fact Sheet Directed Inspection and Maintenance at Gate Stations and Surface Facilities, Lessons Learned Directed Inspection and Maintenance at Compressor Stations, Lessons Learned Directed Inspection and Maintenance at Gas Processing Plants and Booster Stations, Lessons Learned
Control of VOCs and Methane from Reciprocating Compressor Rod Packing	Reducing Methane Emissions from Compressor Rod Packing Systems, Lessons Learned
Control of VOCs and Methane from Wet-Seal Centrifugal Compressor Seals.	Wet Seal Degassing Recovery System for Centrifugal Compressors, PRO Fact Sheet Replacing Wet Seals with Dry Seals in Centrifugal Compressors, Lessons Learned
Control of Venting Wells to Assist with Unloading Liquids (Liquids Unloading) to Limit Emissions (BLM Waste Minimization Rule)	Options for Removing Accumulated Fluid and Improving Flow in Gas Wells, Lessons Learned

Conclusion

According to the GHGI, methane emissions from the oil and gas sector represented approximately 3% of the US total anthropogenic greenhouse gas emissions (on a CO_2 equivalent basis) in 2014. Overall, methane emissions from the oil and gas sector have not significantly increased since RY1990 (GHGI), despite large increases in the production volume of both crude oil and natural gas over the same period. On a per-unit-production basis, methane emissions have decreased by about 26% from RY1990 through RY2014 overall and by about 41% for the natural gas portion of the sector. Methane emissions from the oil and gas sector reported into the GHGRP show a decline of 18% between 2011 and 2015, despite a 20% increase in the number of facilities reporting. Methane emissions per reporting facility declined by about 32% over the same period. Methane emissions from the production segment declined by 21% between 2011 and 2015 despite a 52% increase in the number of wells represented. Reported emissions per wellhead declined by 48% over the same period.

The oil and gas industry has long been in the forefront of developing technologies to enable better detection, quantification, and reduction of methane emissions. Voluntary actions taken by the industry accounted for more than 86% of the reductions noted in the RY2014 GHGI with regulatory requirements accounting for less than 14% of the reductions.

Greenhouse gas emissions from the electric power sector, the sector with the largest overall greenhouse gas emissions in the US, have declined about 21% since GHGI RY2007 and the greenhouse gas intensity of electricity has declined about 29%. The Energy Information Administration (EIA) attributes the bulk of this decline to the increasing share of natural gas as a fuel for power generation. EIA information shows that 61% of the reductions (over 2 billion metric tonnes) in greenhouse gas emissions from the power industry since 2006 has come from the increasing fuel share of natural gas.

There remains significant uncertainty regarding the magnitude of methane emissions from the oil and gas sector as reported by studies conducted by academia, government, and other stakeholders. Despite the volume of studies conducted, the range of emission estimates has not narrowed and uncertainty persists. Recently adopted requirements such as the NSPS OOOO and OOOOa, the natural replacement of older wells with newer wells, continued voluntary actions, and improving technology will continue to reduce the intensity of methane emissions from the oil and gas sector in the future.

Appendix 1 – Published Papers from EDF Organized/Sponsored Studies

Published Papers

1. December 2013: UT Production study: http://www.pnas.org/lookup/doi/10.1073/pnas.1304880110

2. May 2014: NOAA DJ Basin Flyover: http://onlinelibrary.wiley.com/doi/10.1002/2013JD021272/pdf

3. November 2014: HARC/EPA Fence-line study: http://pubs.acs.org/doi/abs/10.1021/es503070q

4. December 2014 UT Pneumatics Study: http://pubs.acs.org/doi/abs/10.1021/es5040156

5. December 2014 UT Liquid Unloadings Study: http://pubs.acs.org/doi/abs/10.1021/es504016r

6. January 2015: Harvard Boston Urban Methane Study: http://www.pnas.org/content/early/2015/01/21/1416261112

7. February 2015: CSU T&S study: Measurement paper: http://pubs.acs.org/doi/abs/10.1021/es5060258

8. February 2015: CSU G&P study: Measurement paper: http://pubs.acs.org/doi/abs/10.1021/es5052809

9. March 2015: WSU Local Distribution study: http://pubs.acs.org/doi/abs/10.1021/es505116p

10. May 2015: CSU G&P study, Methods paper: http://www.atmos-meas-tech.net/8/2017/2015/amt-8-2017-2015.html

11. July 2015: CSU T&S study, National results paper: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b01669

12. August 2015: CSU G&P, study National results paper: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b02275

Barnett Coordinated Campaign Papers (July 2015) papers 13-24

13. Overview: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b02305

14. NOAA led Top-down study: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b00217

15. Bottom-up inventory - EDF: http://pubs.acs.org/doi/abs/10.1021/es506359c

16. Functional super-emitter study - EDF: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b00133

17. Michigan airborne study: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b00219

18. WVU compressor study: http://pubs.acs.org/doi/abs/10.1021/es506163m

19. Princeton near-field study: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b00705

20. Purdue aircraft study: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b00410

21. Aerodyne mobile study: http://pubs.acs.org/doi/abs/10.1021/es506352j

22. U of Houston mobile study: http://pubs.acs.org/doi/abs/10.1021/es5063055

23. Picarro mobile flux study: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b00099

24. Cincinnati tracer apportionment: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b00057

25. December 2015: Barnett Synthesis: http://www.pnas.org/content/112/51/15597.abstract

26. March 2016: Gap Filling**:** Abandoned & Orphaned Wells:
http://onlinelibrary.wiley.com/doi/10.1002/2015GL067623/full

27. April 2016: Gap Filling**:** Aerial survey of 8,000 production sites:
http://pubs.acs.org/doi/abs/10.1021/acs.est.6b00