COMMONWEALTH OF VIRGINIA
DEPARTMENT OF ENVIRONMENTAL QUALITY

METHANE LEAKAGE FROM NATURAL GAS INFRASTRUCTURE REVISION A19

AD HOC WORK GROUP, SECOND MEETING MINUTES

THIRD FLOOR CONFERENCE ROOM
1111 EAST MAIN STREET, RICHMOND, VIRGINIA
MAY 29, 2019

Members Present:
Joshua Ball, CNX
Braven Beaty, The Nature Conservancy
Lisa S. Beal, Dominion
James Bradbury, Georgetown Climate
Andres Clarens, UVA
Emily Wyche for Will Cleveland, SELC
Kevin Elkins, Coronado Global
Richard Lutz, Transco
Shepelle Watkins-White, VA Natural Gas
Andrew Williams, EDF

Guest Speakers:
James McCarthy, IES
David Lyon, EDF

Staff:
Department of Environmental Quality
Michael G. Dowd, Air Division
Tamera Thompson, Air Division
Tom Ballou, Air Division
Ann M. Regn, Communications
Karen Sabasteanski, Regulatory Affairs
Dept. of Mines, Minerals and Energy
Michael Skiffington, Policy and Planning

The meeting began at approximately 10:05 a.m.

Meeting Purpose: This ad hoc work group has been established to advise and assist DEQ in the development of a framework for limiting methane leakage from natural gas infrastructure. This group will support DEQ in its collection and evaluation of data to inform the regulation development process. The agenda (Attachment A) and a copy of the staff presentation (Attachment B) follow.

Welcome and Introductions: Mr. Dowd welcomed the group. Members introduced themselves individually. Ms. Regn reviewed meeting rules and summarized the agenda.

Issues Overview: Mr. Dowd briefly reviewed the overarching issues that the group is considering, including needs identified at the previous meeting. Mr. Ballou discussed the summary of Virginia methane emissions based on EPA data, and indicated that staff is in the process of establishing an emissions inventory for methane in Virginia. There is a lot of debate about the level of methane coming from natural gas infrastructure, and staff are in the process of working out approaches for addressing this.

Presentations: Mr. McCarthy from Innovative Environmental Solutions (IES) provided detailed information on methane emissions and sources from natural gas infrastructure, including natural gas and energy use throughout the U.S. and Virginia, historical and current inventories, and an overview of methane mitigation strategies (Attachment C).

Mr. Lyon from the Environmental Defense Fund (EDF) along with Mr. Williams presented information on EDF's methane synthesis study for the quantification of methane emissions from the U.S. oil and gas supply chain (Attachment D), and discussed the associated implications of its findings for Virginia. The assessment was a collaborative project with input from technical and academic organizations, and essentially established that site measurements revealed higher emissions levels than inventories.

Each presentation was followed by group questions and discussion.

Work Plan/Group Discussion: The group discussed the types of and need for additional data, opportunities to anticipate and prevent situations that contribute to emissions, and current "triage" approaches for identifying and correcting leaks. Mr. Dowd reiterated that the department's goal is to find the most flexible and cost-effective approach while achieving real reductions in methane emissions, as well as identifying the specific sectors and processes where the "most bang for the buck" can be obtained.

Mr. Lyon and Mr. Williams agreed to locate and share additional emissions data. Ms. Sabasteanski reminded the group to be mindful of FOIA: inter-member contacts are limited to one-on-one, and two members may directly contact staff.

Ms. Thompson requested that the group plan on identifying specific, easily identified and implemented control opportunities ("low-hanging fruit") that should be considered as a starting point for any program that may come out of this process.

Wrap-up/Next Steps: Ms. Regn concluded the meeting. The next meeting is scheduled for June 26, 2019.

The meeting adjourned at approximately 3:15 p.m.

Attachments
REG\DEV\A19-AH04-2-minutes

ATTACHMENT A

COMMONWEALTH OF VIRGINIA
DEPARTMENT OF ENVIRONMENTAL QUALITY

METHANE LEAKAGE FROM NATURAL GAS INFRASTRUCTURE
AD HOC WORK GROUP

DRAFT AGENDA, SECOND MEETING

May 29, 2019

10:00 – 10:10	WELCOME
10:10 – 10:30	ISSUES OVERVIEW
10:30 – 11:30	PRESENTATION: industry overview, GHG inventories, lessons learned (James McCarthy, IES)
11:30 - 12:30	LUNCH BREAK (on your own)
12:30 - 1:30	PRESENTATION: sectors and emissions (Andrew Williams and David Lyon, EDF)
1:30 – 2:45	GROUP DISCUSSION
2:45	WRAP UP/NEXT STEPS

ATTACHMENT B

Methane Leakage from Natural Gas Infrastructure Ad Hoc Work Group

Second Meeting

DEQ Air and Renewable Energy Division

May 29, 2019

Agenda

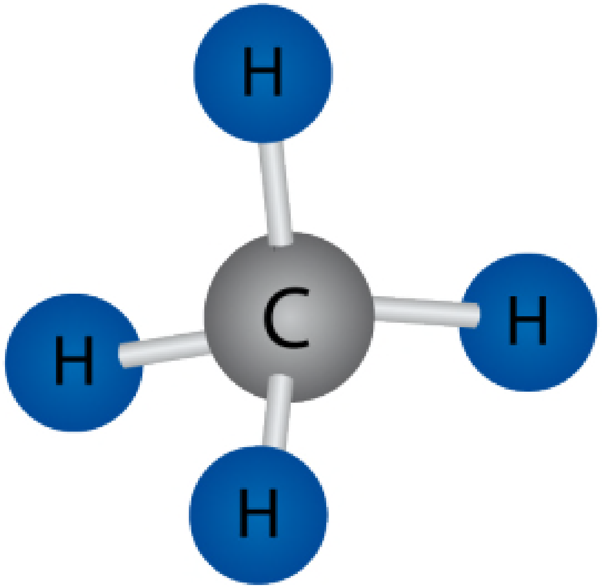
10:00 a.m. – 10:10 a.m.	Welcome
10:10 a.m. – 10:30 a.m.	Issues overview
10:30 a.m. – 11:30 a.m.	Presentation – Jim McCarthy, IES
11:30 a.m. – 12:30 p.m.	Lunch – on your own
12:30 p.m. – 1:30 p.m.	Presentation – Andrew Williams & David Lyon, EDF
1:30 p.m. – 2:45 p.m.	Group discussion
2:45 p.m.	Wrap up and next steps

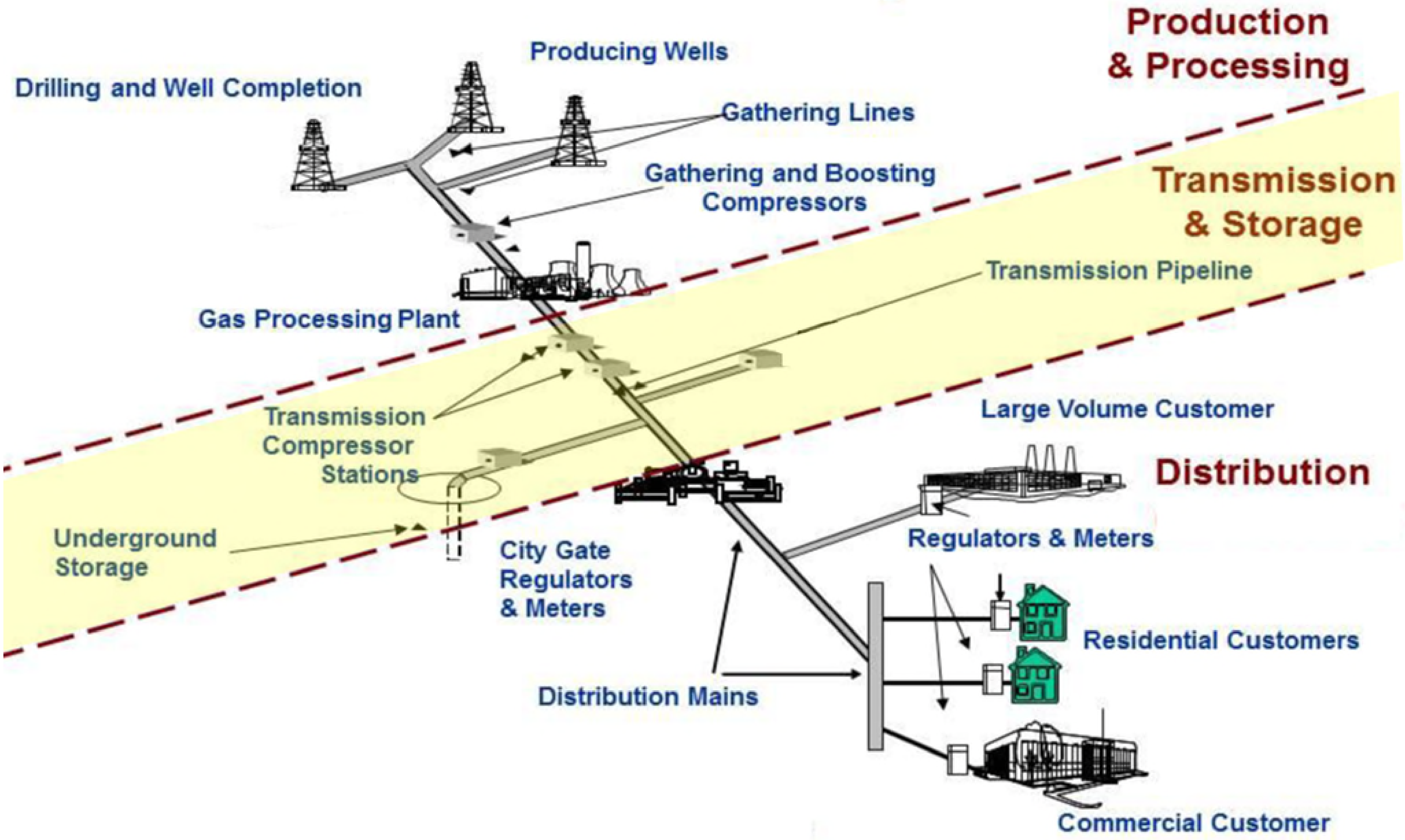
Stakeholder Discussion

- Turn off all electronic devices
- Be courteous; speak one at a time
- There is no public comment/open forum during this meeting
- Minutes and notes are being taken today
- To avoid confusion — after the meeting please speak for yourself not for the ad hoc group

Overview

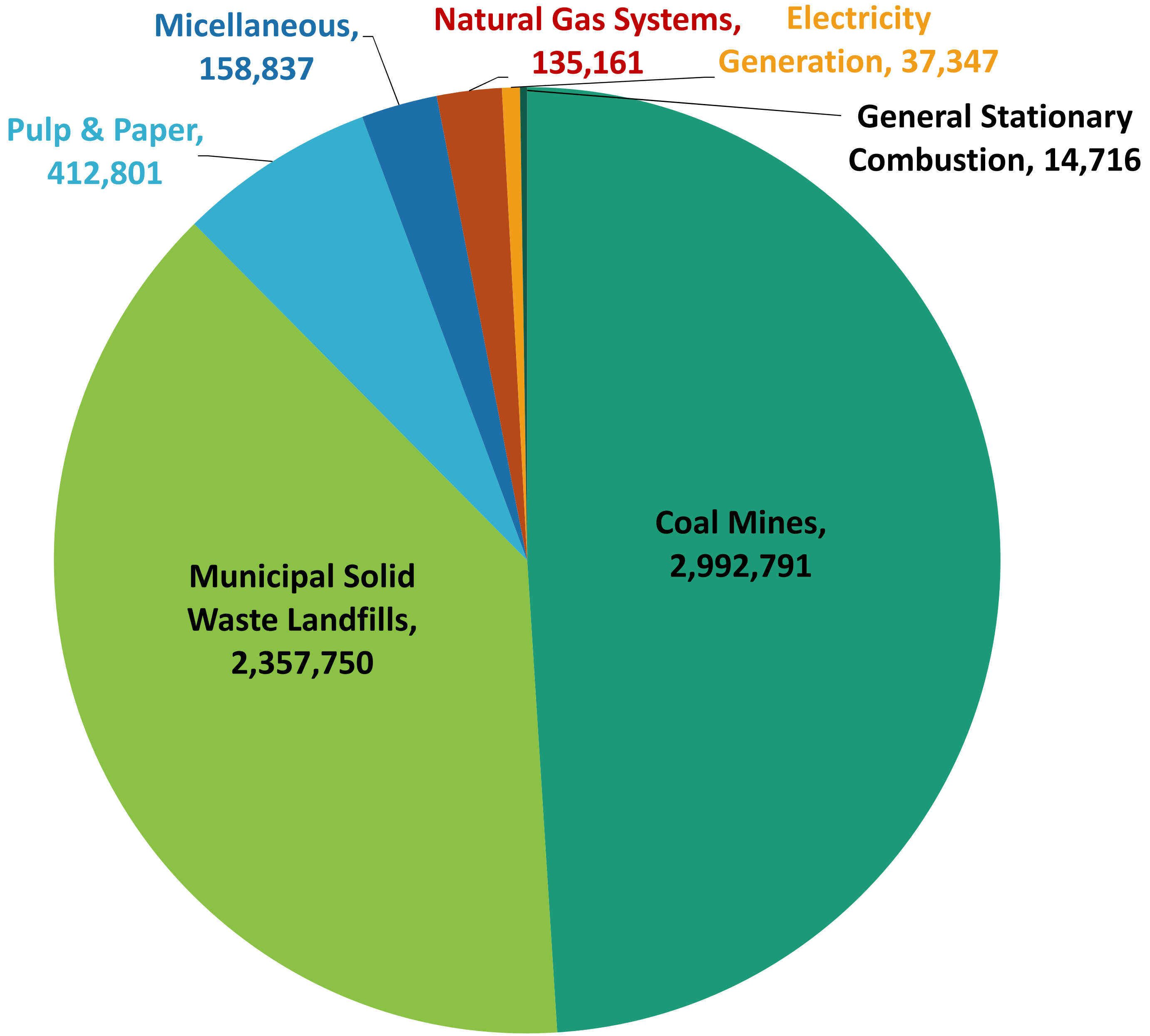
- Second most prevalent greenhouse gas emitted in the U.S.
  - About 10% of U.S. greenhouse gas emissions
- Per unit, at least 25x more potent at trapping heat in the atmosphere than CO_2 over 100 years; 72x more potent over 20 years





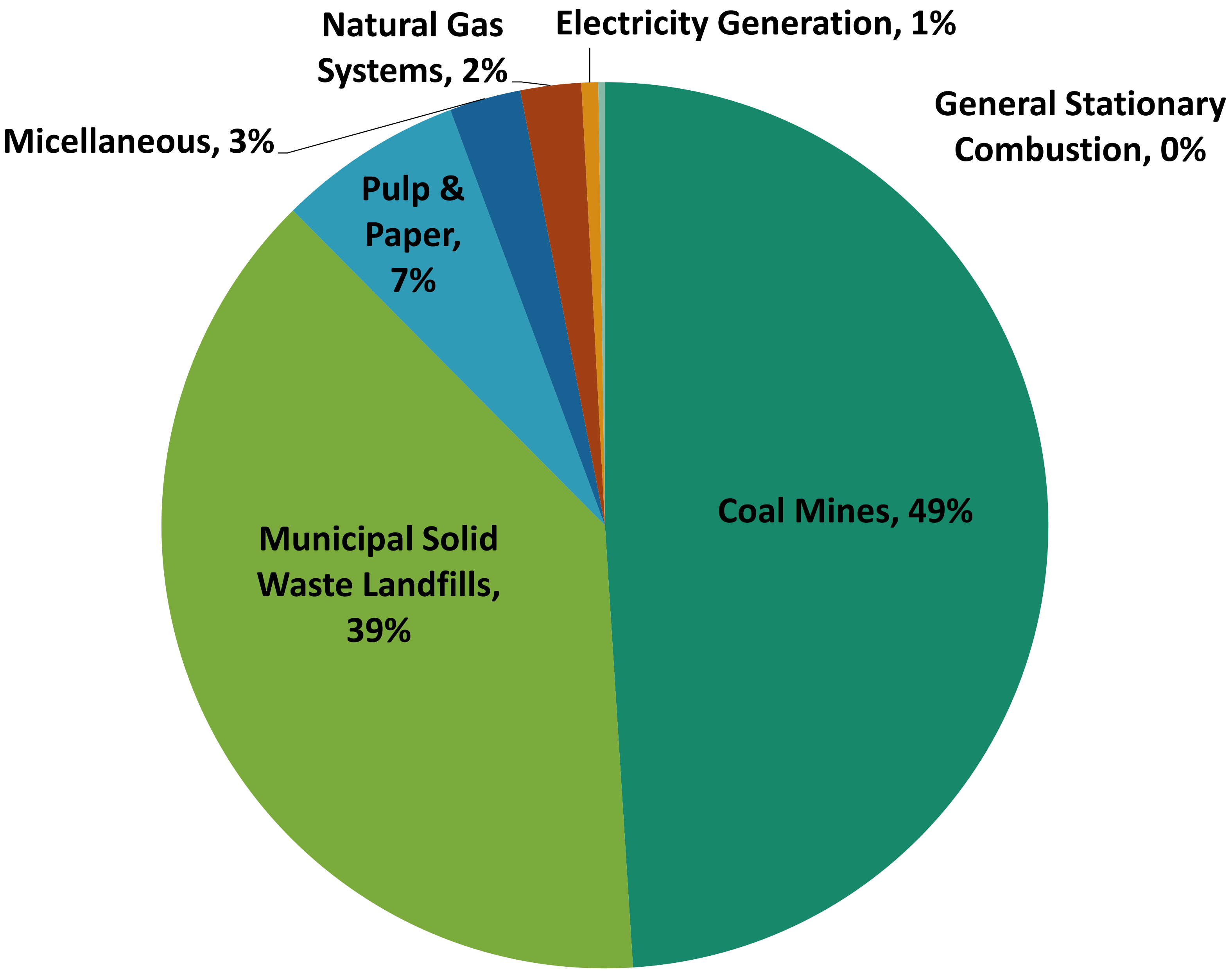
Production & Processing
Transmission & Storage
Distribution
Drilling and Well Completion
Producing Wells
Gathering Lines
Gathering and Boosting Compressors
Gas Processing Plant
Transmission Pipeline
Transmission Compressor Stations
Underground Storage
City Gate Regulators & Meters
Large Volume Customer
Regulators & Meters
Residential Customers
Distribution Mains
Commercial Customer

Virginia Methane Emissions (2017; CO2E)



DEQ

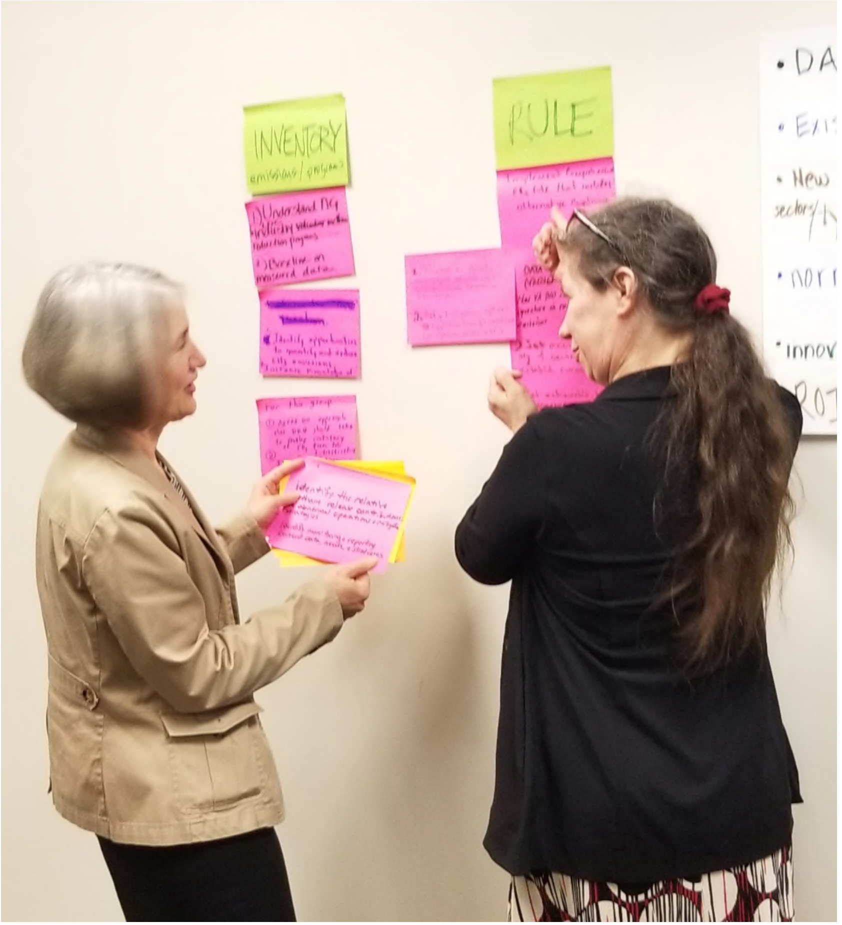
Virginia Methane Emissions (2017; CO2E)



DEQ

Needs identified

- Data: baseline emission factors
- Existing controls & programs
- New vs. existing structures/sources
- Normal vs. abnormal operations
- Innovation/alternative compliance
- Cost effective measures



Agenda

10:00 a.m. – 10:10 a.m.	Welcome
10:10 a.m. – 10:30 a.m.	Issues overview
10:30 a.m. – 11:30 a.m.	Presentation – Jim McCarthy, IES
11:30 a.m. – 12:30 p.m.	Lunch – on your own
12:30 p.m. – 1:30 p.m.	Presentation – Andrew Williams & David Lyon, EDF
1:30 p.m. – 2:45 p.m.	Group discussion
2:45 p.m.	Wrap up and next steps

ATTACHMENT C

Review of Methane Emissions and Sources from Natural Gas Operations

Virginia Department of Environmental Quality

Methane Leakage from Natural Gas Infrastructure Ad Hoc Workgroup Meeting

Presented by:

Jim McCarthy, Innovative Environmental Solutions, Inc.

Richmond, VA

May 29, 2019

Agenda

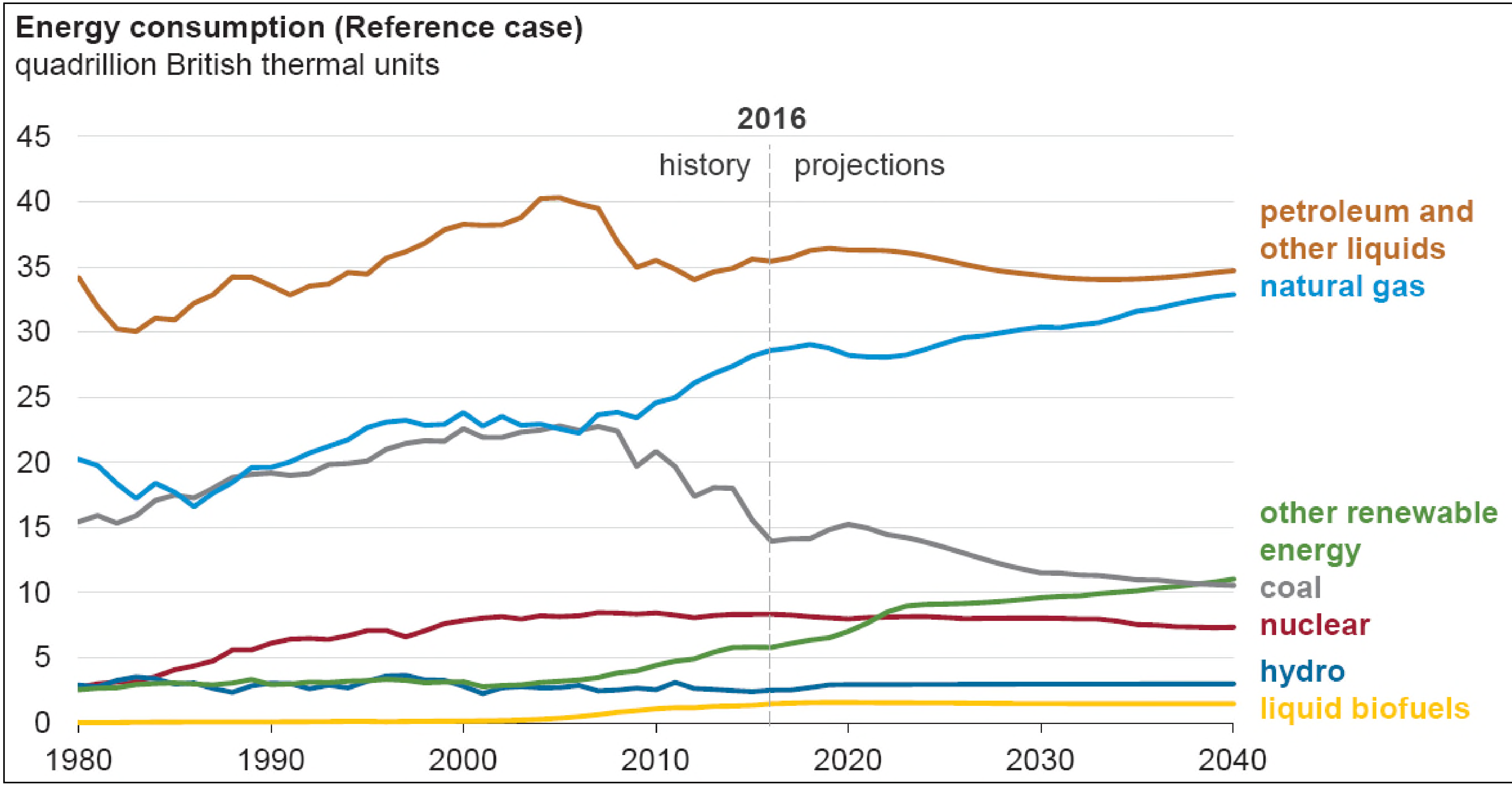
- Natural gas and U.S. energy use; VA implications
- Methane emission estimates from natural gas operations
  - » VA estimates from EPA GHG Reporting Program (GHGRP)
  - » Background on historical / other data sources
- Methane emission sources for transmission & storage (T&S) and distribution
- Overview of methane mitigation strategies for T&S and distribution
  - » Insights from GHGRP data
  - » EPA programs / regulations:
    - – NSPS (Subpart OOOOa) for compressor stations
    - – EPA Natural Gas STAR – e.g., Methane Challenge BMPs

Presentation Highlights

- **Natural gas use in U.S. and VA is growing and growth is projected to continue (e.g., supplant coal)**
  - **Although gas use has grown, methane emissions from natural gas systems have decreased**
- **There are relatively few natural gas facilities in VA, so methane emissions are relatively small from natural gas operations (Distribution systems, ~ 20 transmission compressor stations)**
- **Improved understanding of CH_4 sources & emissions in recent years – e.g., from GHGRP data, other studies**
  - **Sources and emissions by natural gas segment; GHGRP data is providing insight into emission priorities**
- **Voluntary efforts (e.g., Natural Gas STAR) and regulations have identified methane mitigation options**
- **For leak emissions, a few large leaks contribute most emissions**
  - **Technology advances (e.g., leak quantification) may be imminent**
  - **Convergence of emissions understanding and technology provide opportunities for smarter alternatives to reduce methane**

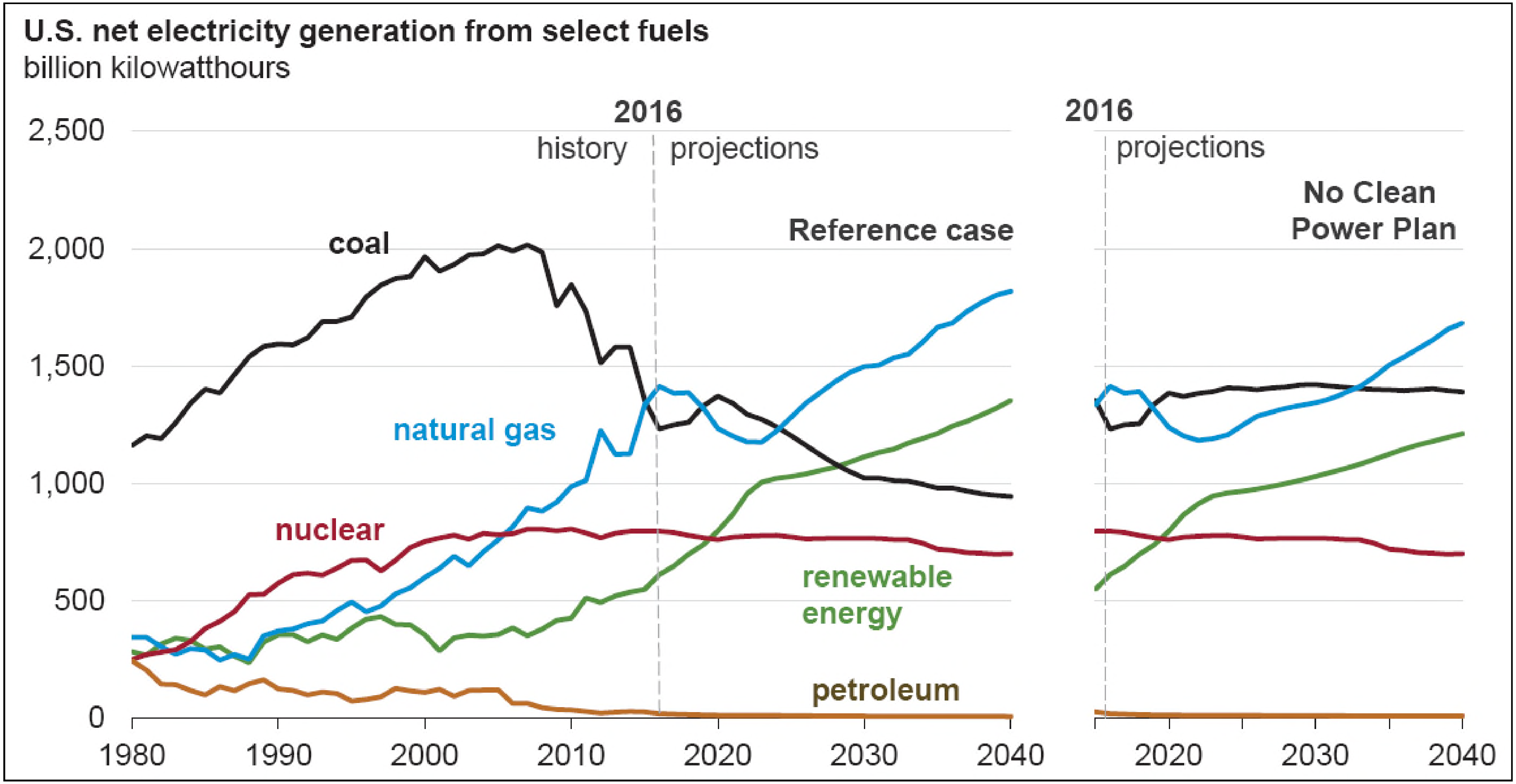
DOE EIA – U.S. Energy Consumption

- **DOE EIA projections – all uses (transportation, electricity, etc.)**



DOE EIA – U.S. Electricity Generation

- **DOE EIA projections for 2016 provided with and without Clean Power Plan**
- **2017 VA electricity: 11.9% coal, 49.2% gas, 33.8% nuclear**



VA Natural Gas Facts

- 1.3 million natural gas customers (1.2 million residential)
- Consumed ~552 BCF of natural gas in 2015 (~570 trillion Btu) with was 2.2% of U.S. consumption (AGA state gas facts)
  - » 14% residential
  - » 12% commercial
  - » 57% electric power generation
  - » 17% industrial / other
- VA natural gas market share for all electricity generation
  - » https://www.eia.gov/electricity/data/state/ (Sept 2018 update)
  - » 49.2% in 2017 (11.9% coal, 33.8% nuclear, 1.3% solar/biomass)
    - – 72% growth in VA electric generation from 1990 to 2017
  - » 23.3% in 2010 (34.9% coal, 36.4% nuclear , 1.1% solar/biomass)
  - » 6.0% in 2000 (51.5% coal, 36.7% nuclear , 0.6% biomass)
  - » 2.2% in 1990 (45.5% coal, 45.3% nuclear, 1.2% biomass)

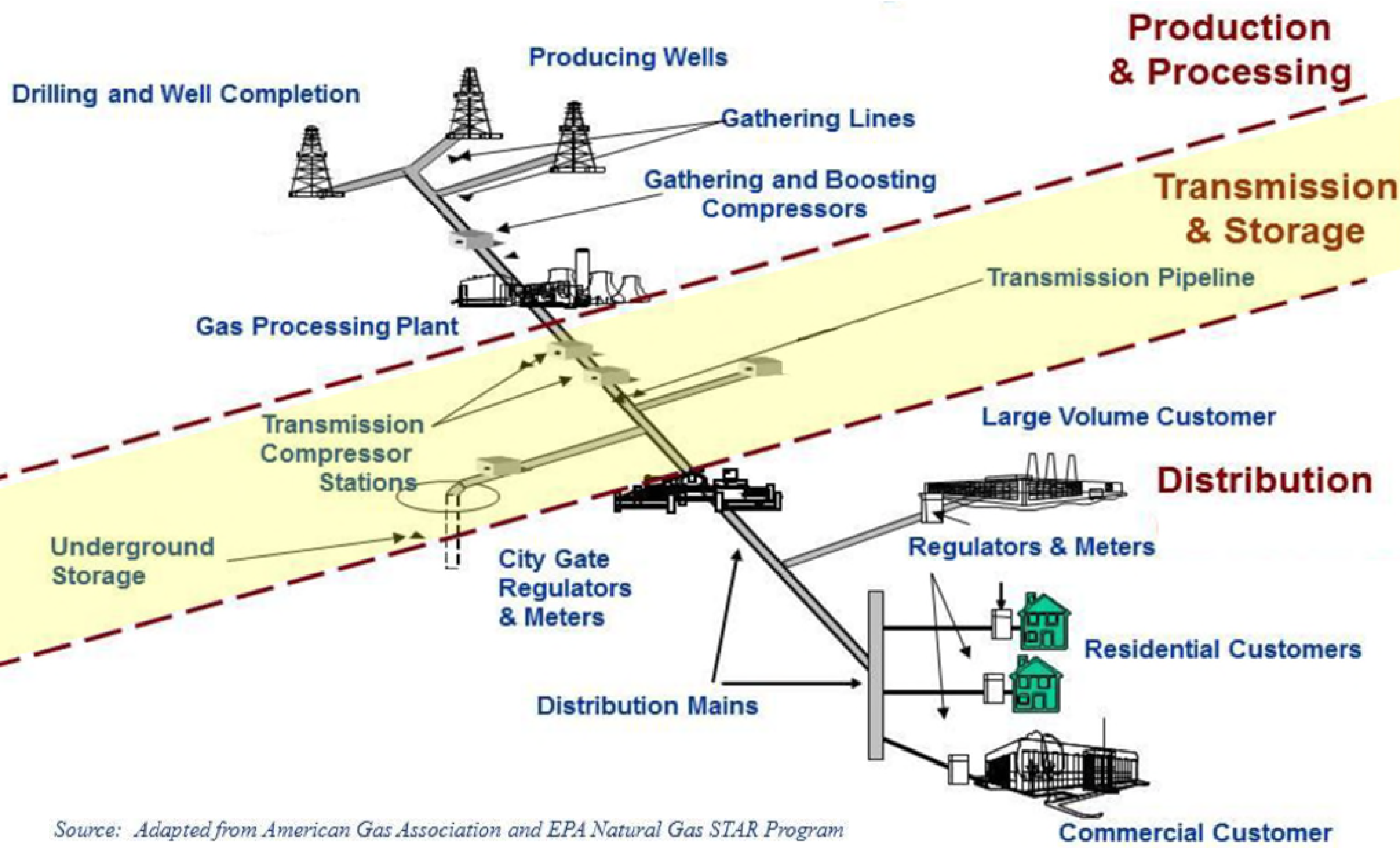
Natural Gas Operations: Methane Emissions Background

- Pipeline natural gas is typically 90 – 96% methane
  - » Balance is mainly ethane
  - » Relatively low VOC content
- Historical estimates of natural gas industry methane emissions (e.g., EPA annual GHG inventory (GHGi), estimation protocols) primarily based on 1996 EPA-GRI report
  - » For over 20 years, minimal new methane data was added
  - » EPA GHGRP, other new studies include new measurement data for T&S operations
- Voluntary Natural Gas STAR program demonstrated reductions – mitigation identified by industry operators
  - » STAR supplemented with Methane Challenge in 2016
  - » Mandatory rules now evolving at federal and state levels

Federal Programs: Chronology

- EPA-GRI report (15 vols) on NG industry methane emissions in 1996
- Annual U.S. GHGi has been prepared since 1997
  - » Time series of emissions by industry segment to 1990
- EPA Natural Gas STAR program: Voluntary reductions from natural gas systems since mid-1990s
  - » EPA introduced supplemental Methane Challenge program in 2016
- GHG Reporting Rule (GHGRP) since 2010 (combustion) and 2011 (add Subpart W methane leaks and vented emissions)
  - » Intent: Provide information to inform policy
  - » Most industries use emission factors or engineering estimates; T&S requires measurement of several key sources
- NSPS (Subpart OOOO) in 2012 affected oil and gas operations upstream of transmission: VOC rule with methane co-benefits
- Add methane to NSPS: Subpart OOOOa in June 2016 adds T&S

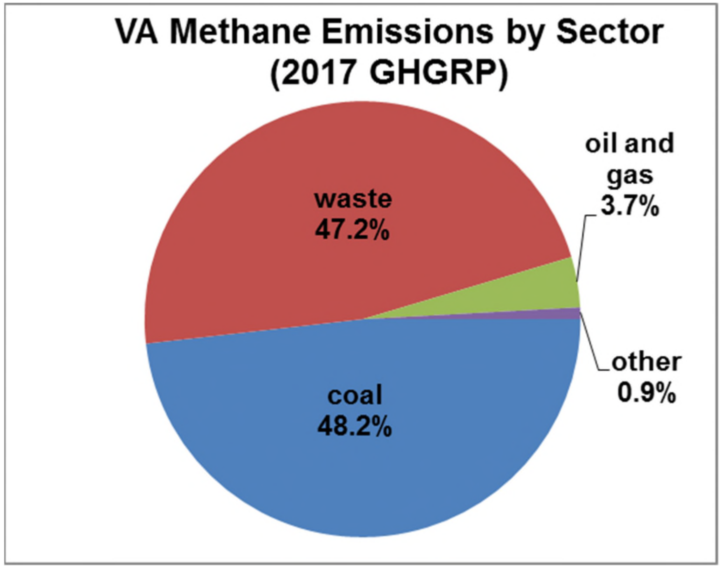
Natural Gas Operations: Industry Segments



Source: Adapted from American Gas Association and EPA Natural Gas STAR Program

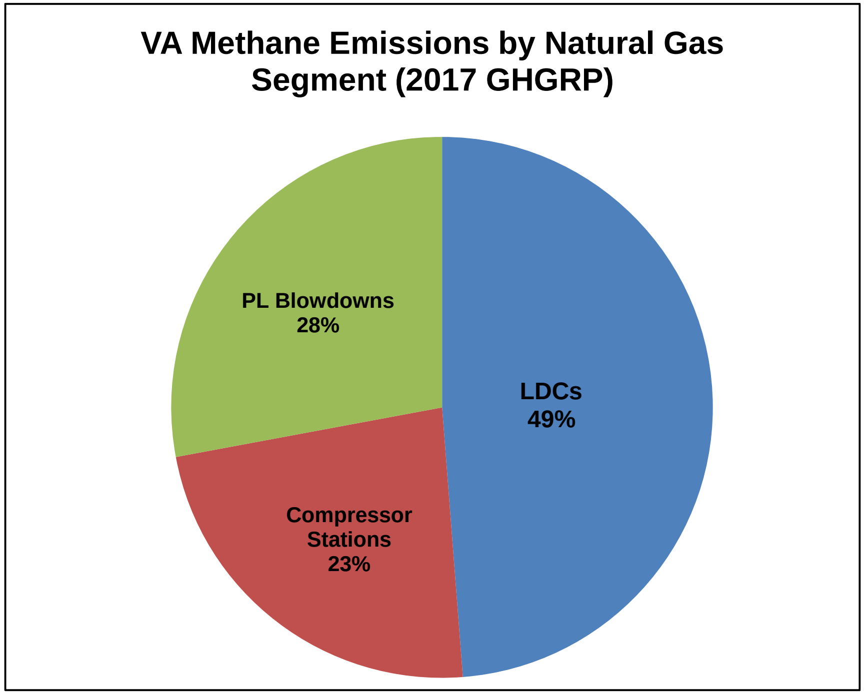
VA Methane Emissions and Natural Gas Operations

- Natural gas sector in VA (and thus emissions) is primarily comprised of transmission and storage (T&S), and distribution
  - » Minimal production (115 BCF in 2017, 0.3% of U.S. production)
- Approximately 20 T&S facilities in VA; EPA GHGRP (2017 data) includes 4 compressor stations, 4 LDCs
  - » Other compressor stations are smaller and/or low use so emissions did not exceed 25,000 metric ton reporting threshold
- Methane emissions are ~14% of VA GHG inventory (2017 GHGRP)
  - » 6 MM mt CO_2e CH_4 of 44 MM mt total
  - » VA methane mainly from coal and waste (landfills); 3.7% from gas ops
  - » In comparison, nationwide CH_4 ~10% of total; oil & gas is ~24% of methane



VA Methane Emissions by Natural Gas Segment

- Natural gas segment 2017 methane emissions in VA ~232,000 metric tons CO_2e
  - Roughly half of emissions from LDCs and half from T&S
  - LDCs have typically not been regulated – reductions primarily from replacing gas mains – e.g., see Methane Challenge Best Management Practices (BMPs)
  - Additional discussion follows on T&S emission sources and mitigation approaches

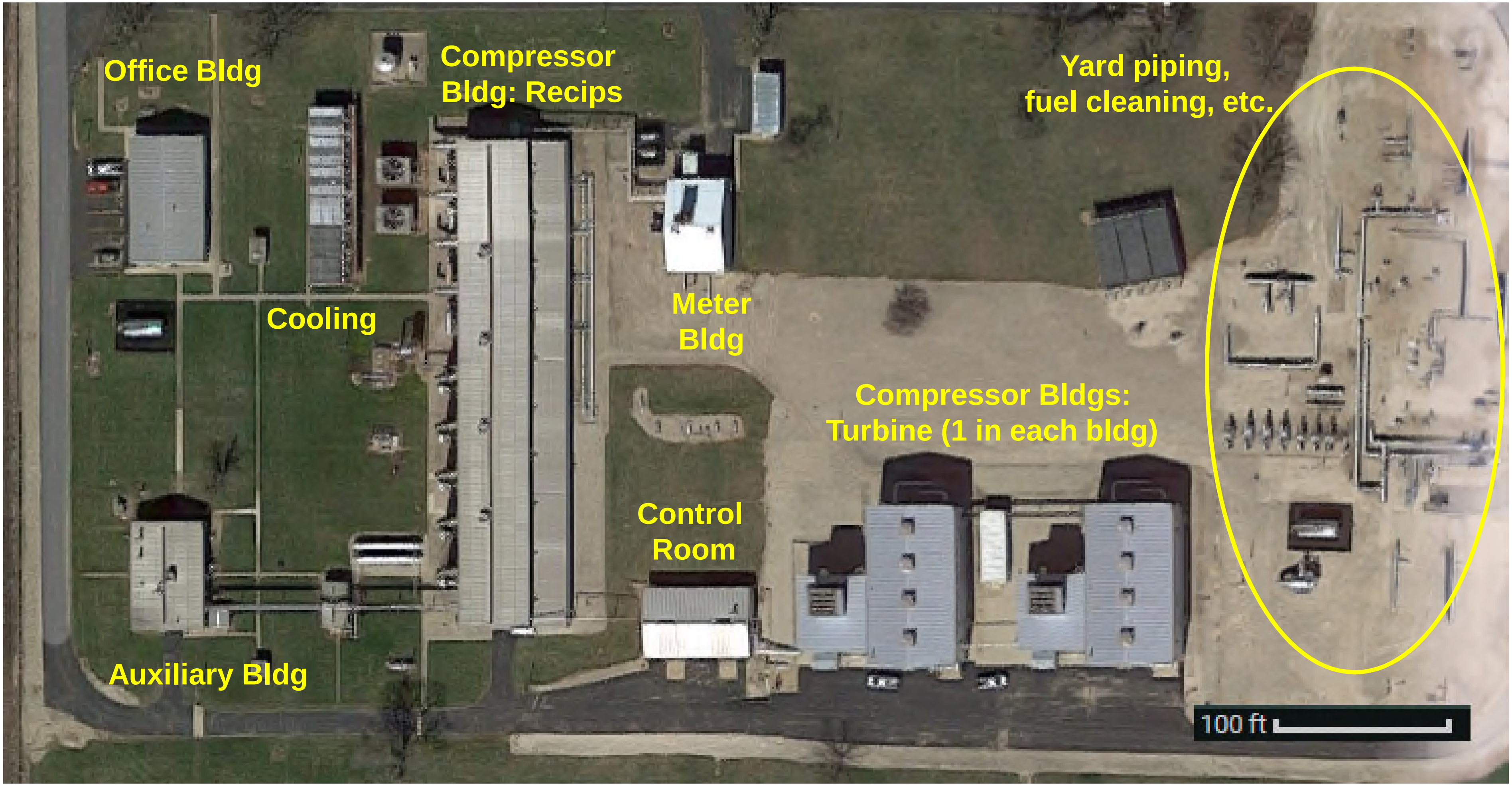


U.S. EPA GHG Reporting Program: Primary Methane Emission Sources

- Onshore production segment reports 16 methane sources
  - » Well-related venting (completions, recompletions, etc.)
  - » Initial processing (e.g., remove H_2O) and compression at well
  - » Storage tanks, pneumatic devices, leaks
- Gathering and boosting segment reports 10 sources
  - » Pneumatics, processing, blowdowns, compressors, leaks
- Processing segment reports 6 sources
  - » Processing, compressors, blowdowns, leaks
- Transmission compressor stations report 6 sources
  - » Pneumatics, blowdowns, compressors, leaks (details upcoming)
  - » Underground storage facilities report 4 of the 6
  - » Pipeline blowdown reporting added in 2016
- Distribution – 6 sources (leaks from mains, services, M&R)

Transmission Compressor Station

- Overhead view of example compressor station (Recips & Turbines)



Subpart W Methane Emission Sources

- **GHGRP: Reporting is required for six methane emission sources for "onshore natural gas transmission compression" sector (*four of six apply to underground storage facilities*):**
  - ***(1) Reciprocating compressor venting*** [A]
  - ***(2) Centrifugal compressor venting*** [A]
  - **(3) Transmission storage tanks (leaking valve)** [A]
  - **(4) Blowdown vent stacks**
  - ***(5) Natural gas pneumatic device venting***
  - ***(6) Equipment leaks from valves, connectors, open ended lines, pressure relief valves and meters*** [B]

  [A] **Subpart W requires direct measurement of emissions for T&S**

  [B] **Subpart W requires Leak Survey for T&S segments; emission estimates based on leak counts & "leaker" emission factors**

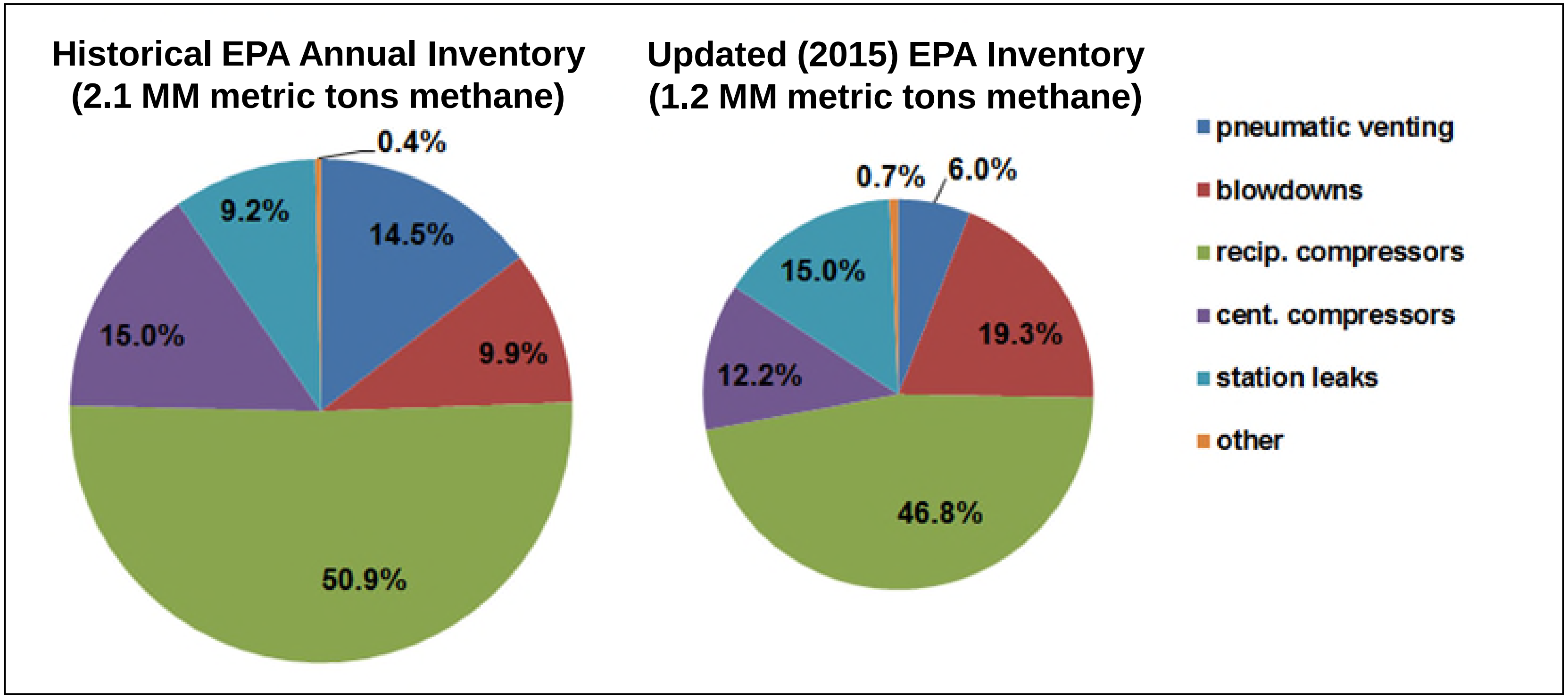
- **Transmission pipeline blowdown reporting added in 2016**

Subpart W Estimation Methods for Natural Gas Transmission

Emission Source	Monitoring Method / Data	Emission Quantification Method
Natural Gas Pneumatic Devices: Low (≤ 6cfh), High (>6 scfh) or intermittent bleed devices	Component Count for (1) Low Bleed, (2) High Bleed and (3) Intermittent Bleed Devices	Population EF (scfh) x device count x 8,760 hr/yr (three emission factors)
Blowdown Vent Stacks	Engineering Estimation (calculation)	Volume calculation; track by event type
Condensate Tanks (leaking dump valve)	Leak Detection & Direct Flow Measurement	For leaks; Measured emission rate x operating hours
Centrifugal Compressors: Blowdown Valve Leaks, Unit Isolation Valve Leaks, and Wet Seal Oil Degassing Vent	Direct Measurement of Vented Gas Emissions in TWO Modes: Operating and Not operating – depressurized	Measured emission rate (or Emission Factor if mode not measured) x operating hrs (by operating mode)
Reciprocating Compressors: Rod Packing Leakage, Blowdown Valve Leaks, and Unit Isolation Valve Leaks	Direct Measurement of Vented Gas Emissions THREE Operating Modes: -Operating, Standby pressurized, Not operating – depressurized	Measured emission rate (or Emission Factor if mode not measured) x operating hrs (by operating mode)
Equipment Leaks (other)	Leak Survey to identify & count leaking components OR Component count (population – for storage wellheads)	Leaking components count x Leaker EF x operating hours OR, Population by component type x EF (storage wellheads)

T&S *Compressor Station* Methane Emissions from Leaks and Vents

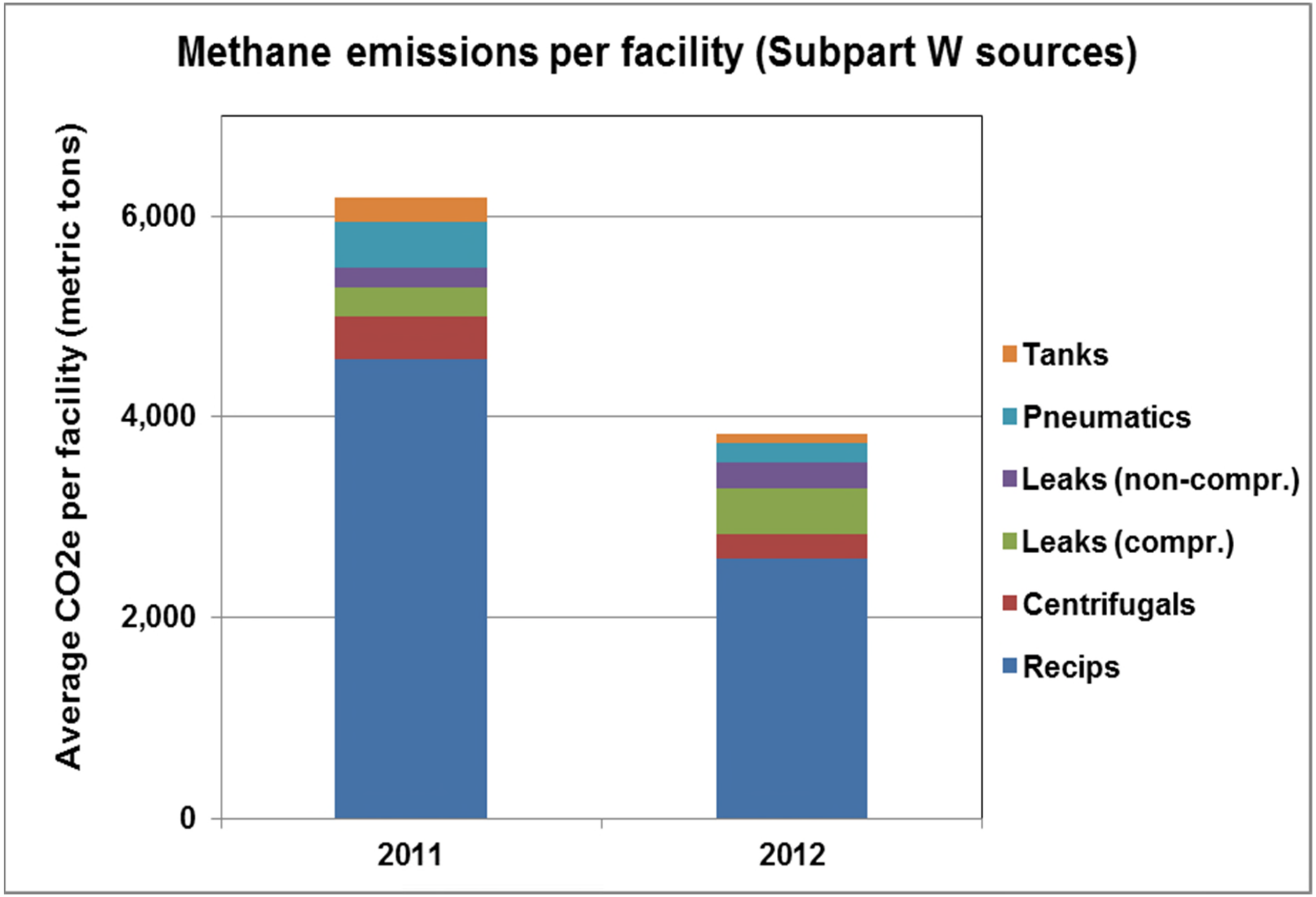
- **EPA updated GHGi methods in 2016 – T&S CH_4 emissions *decreased* using more recent data (e.g., emissions factors from EDF-Industry study)**
  - » **The updated estimates did *not* incorporate Subpart W data**
- **Relative % of station emissions from leaks & vents by source type:**
  - » **Compressor leaks and rod packing are the primary source**



T & S Methane Emissions: Subpart W Implications

- **For many years, estimates in EPA annual GHGi were primarily based on data from mid-1990s EPA/GRI study**
  - » **Updates in 2016 report (for 2014 inventory) integrated some results from EDF-Industry study (~45 T&S facilities)**
  - » **Compressor emissions are a key source**
  - » **Compressor "emission factor" (EF) includes leaks from blowdown valves, isolation valves, rod packing (reciprocating compressor) and seals (centrifugal compressor)**
    - – **These emissions are *measured* for Subpart W of GHGRP**
    - – **EDF-Industry study provided EF updates for compressors**
    - – **Subpart W compressor measurement data provides the opportunity for further review and update of compressor EFs**
    - – **A Pipeline Research Council International (PRCI) report (April 2018) compiled and analyzed Subpart W compressor measurements**
- **2nd PRCI report in 2019 will present other Subpart W data**

Station Emissions: Subpart W Results for Leaks and Pneumatic Controller Venting



- **Bar charts from PRCI GHGRP data compilation**

Initial Overview of Emissions Mitigation (and Subpart OOOOa Sources)

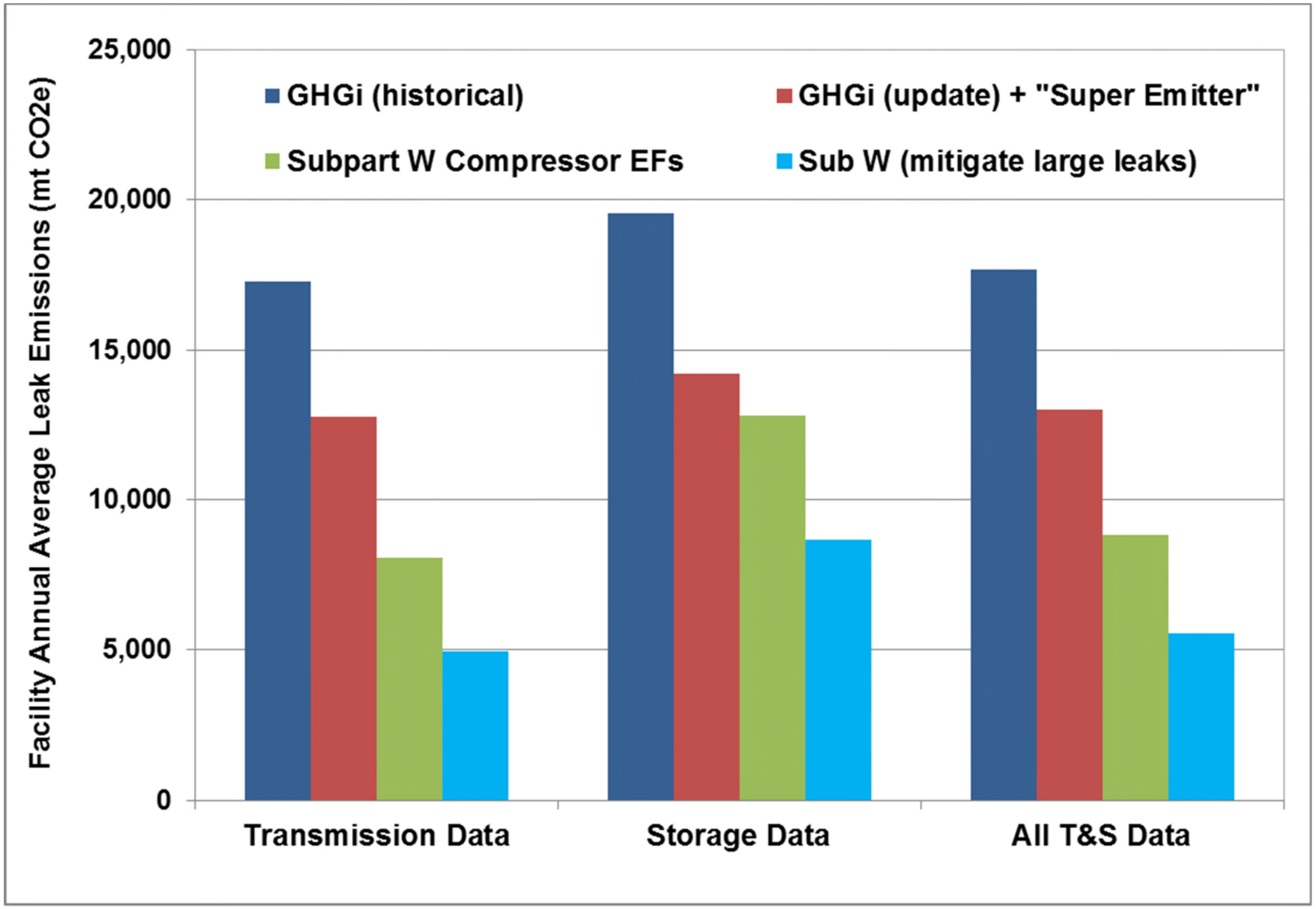
- **EPA National Inventory and Natural Gas STAR reports provided background for 2014 EPA "White Papers" on mitigation of methane from natural gas leaks and venting**
- **T&S sources and mitigation in Subpart OOOOa include:**
  - » **Reciprocating compressor rod packing (replacement every 26,000 operating hours or 36 months)**
  - » **Centrifugal compressors wet seals oil degassing vents (reduce VOC emissions)**
  - » **High bleed pneumatic devices (low / no bleed or air driven devices)**
  - » **Equipment leaks (LDAR)**
  - » **Storage tanks with VOC emissions >6 TPY (reduce VOC emissions)**

Subpart W Measurement / Survey Data

- PRCI project compiled Subpart W data from members and developed report that presents compressor emission factors
  - PRCI Report, “GHG Emission Factor (EF) Development for Natural Gas Compressors” (based on over 14,000 measurements)
  - Report presents 2011–2016 data for different leak source – e.g., unit isolation valves, rod packing, wet seals, etc. and resulting implications for compressor EFs
  - PRCI White Paper in Spring 2019 will include significant additional details on compressor EFs based on Subpart W data
- PRCI companion report will be available in Spring 2019 that presents other Subpart W data on facility leak surveys, pneumatics, facility and pipeline blowdowns
- These Subpart W results can be compared to historical data (e.g., facility emission estimates based on EPA GHGi)

Updated Compressor EFs: Facility Level GHG Inventory Implications

- **Emission factors can be used to assess the implications for "average" facility leak emissions based on EPA GHGi EFs versus Subpart W-based Compressor EFs**
  - » **Historical GHGi**
  - » **Recent GHGi updates w/ EFs from industry-EDF study**
  - » **Subpart W Compressor EFs**
  - » **Subpart W Compressor EFs commensurate with mitigating larger compressor-related leaks (~3% of leaks)**



Theme from Literature: Large Leaks are Responsible for Most Leak Emissions

- **INGAA Foundation study summarized literature in response to influx of papers**
  http://www.ingaa.org/Foundation/Foundation-Reports/ComparativeMethaneStudies.aspx

Study	Measurement Technique	% of Leak Sources Contribute to...	...% of emissions
Allen (2013)	Direct Measurement of Well Liquids Unloading	44 percent	90 percent
Alvarez (2012)	Analysis of Reported Emissions	10 percent	70 percent
Kang (2014)	Direct Measurement	16 percent	3 orders of magnitude larger than median flow rate
Subramanian (2015)	Direct measurement Site level and concurrent downwind tracer-flux (T&S)	10 percent	50 percent
Mitchell (2015)	Direct measurement at G&P site level; concurrent downwind tracer-flux	30 percent	80 percent
Clearstone (2002)*	Direct measurement w/ Hi-Flow™ sampler	Up to 10 leaks in each facility	36 – 65 percent
NGML, Clearstone, IES (2006)*	Direct measurement w/ Hi-Flow™ sampler and optical methods	0.6 percent	58 percent
Picard (2005)*	Sampling via various methods	Top 10 leaks	80 percent
Shorter (1997)*	Remote sampling via tracer methods	Top emitters	2 – 4 orders of magnitude larger than small emitters
Trefiak (2006)*	Optical measurement and Hi-Flow™	23 percent	77 percent

* Cited in Brandt (2014), which provided a synopsis of studies and data gaps

Technology Solutions – Status: Methane Monitoring or Measurement

- **Technology continues to advance – e.g., leak *rate* algorithms may become available for optical gas imaging (OGI)**
- **DOE ARPA-E "MONITOR" program is developing and testing several low cost technologies**
  - **e.g., lower cost OGI / IR technology and operating platforms such as miniature sensors and use on drones**
  - **See https://arpa-e.energy.gov/?q=arpa-e-programs/monitor**
- **OGI / IR camera manufacturers are developing leak rate *quantification* capability using advanced computational algorithms from plume visual; commercial products anticipated**
  - **Even qualitative binning into leak size ranges could support leak repair decisions**
- **While not yet feasible, flexibility to integrate new technologies is desired (e.g., streamlined path for alternative methods)**

Pipeline Blowdown Mitigation

- Pipeline blowdown mitigation from "pump down" is a common practice, but application is limited
- Pipeline blowdown mitigation practices may include:
  - » Divert to low pressure line: Transfer gas to a parallel line
  - » In-Line compression: Operate downstream compression after upstream valve is closed
  - » Mobile compression: Use additional compressors to move gas or pull line down to lower pressure (e.g., incremental gain)
  - » Flaring: Rarely used
- Practice is limited by:
  - » Availability of parallel line
  - » Pressures of lines
  - » Economics (e.g., for mobile compression)

Summary and Conclusions

- T&S and Distribution segment methane emissions are a relatively minor contributor to VA methane emissions
  - » And, some emissions sources are minor for T&S facilities
  - » Recent data, including Subpart W measurements, show T&S emissions are lower than historical levels
- EPA voluntary programs, NSPS, and state actions have focused on similar sources and mitigation approaches
  - » Voluntary reductions have occurred and will continue
- New data and technologies provide the opportunity for program evolution and efficiency gains
  - » Flexibility / access to alternative methods / technologies
  - » Addressing large leaks is key – and new technologies may facilitate development of improved approaches

Questions and Discussion

ATTACHMENT D

Methane Synthesis Study: Quantifying CH_4 Emissions from the U.S. Oil and Gas Supply Chain

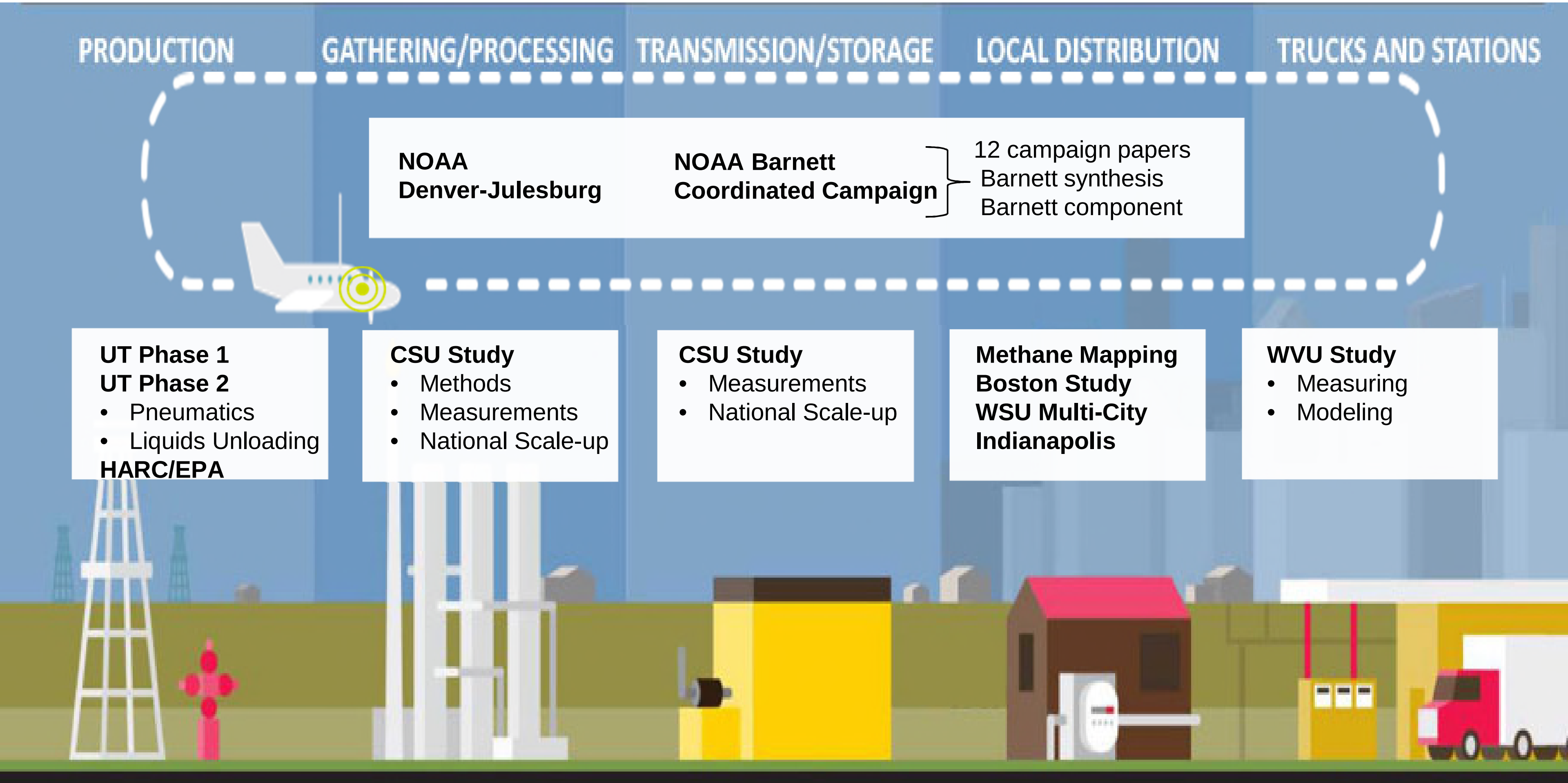
David Lyon

Scientist

EDF ENVIRONMENTAL DEFENSE FUND®

Finding the ways that work

EDF U.S. Oil and Gas Methane Studies



Pilot Projects

Gap Filling
- Abandoned wells
- Helicopter IR Survey

Synthesis Projects
- NETL LCA
- **Synthesis**

EDF's Methane Research

Science
Studies employ independent experts and use multiple methods to measure methane emissions

Collaboration
More than 130 co-authors from 50 research institutions and 50 O/NG companies

Results
Published in peer-reviewed journals with publically available data

Science REPORTS

Cite as: R. A. Alvarez *et al.*, *Science* 10.1126/science.aar7204 (2018).

Assessment of methane emissions from the U.S. oil and gas supply chain

Ramón A. Alvarez[1]*, Daniel Zavala-Araiza[1], David R. Lyon[1], David T. Allen[2], Zachary R. Barkley[3], Adam R. Brandt[4], Kenneth J. Davis[3], Scott C. Herndon[5], Daniel J. Jacob[6], Anna Karion[7], Eric A. Kort[8], Brian K. Lamb[9], Thomas Lauvaux[3], Joannes D. Maasakkers[6], Anthony J. Marchese[10], Mark Omara[1], Stephen W. Pacala[11], Jeff Peischl[12,13], Allen L. Robinson[14], Paul B. Shepson[15], Colm Sweeney[13], Amy Townsend-Small[16], Steven C. Wofsy[6], Steven P. Hamburg[1]

[1]Environmental Defense Fund, Austin, TX, USA. [2]University of Texas at Austin, Austin, TX, USA. [3]The Pennsylvania State University, University Park, PA, USA. [4]Stanford University, Stanford, CA, USA. [5]Aerodyne Research Inc., Billerica, MA, USA. [6]Harvard University, Cambridge, MA, USA. [7]National Institute of Standards and Technology, Gaithersburg, MD, USA. [8]University of Michigan, Ann Arbor, MI, USA. [9]Washington State University, Pullman, WA, USA. [10]Colorado State University, Fort Collins, CO, USA. [11]Princeton University, Princeton, NJ, USA. [12]University of Colorado, CIRES, Boulder, CO, USA. [13]NOAA Earth System Research Laboratory, Boulder, CO, USA. [14]Carnegie Mellon University, Pittsburgh, PA, USA. [15]Purdue University, West Lafayette, IN, USA. [16]University of Cincinnati, Cincinnati, OH, USA.

*Corresponding author. E-mail: ralvarez@edf.org

Manuscript and supplementary materials published June 2018 in *Science*
DOI: 10.1126/science.aar7204

Scope of Synthesis Study

- Quantify methane emissions from the U.S. oil and gas supply chain
- Integrates several recently published datasets
  - Production segment emissions based on site-level measurements from 6 U.S. basins
  - Emissions compared to aircraft-based estimates in 9 basins

Drilling & Production

Gathering & Processing

Transmission & Storage

Local Distribution

Regional Research

Synthesis Collaborators

Aerodyne Research
Scott C Herndon

Carnegie Mellon University
Allen L. Robinson

Colorado State University
Anthony J. Marchese

EDF
Ramon A. Alvarez
David R. Lyon
Daniel Zavala–Araiza
Mark Omara
Steven P. Hamburg

Harvard University
Daniel J. Jacob
Joannes D. Maasakkers
Steven C. Wofsy

National Institute of Standards and Technology
Anna Karion

National Oceanic and Atmospheric Administration
Earth System Research Laboratory
Jeff Peischl (University of Colorado)
Colm Sweeney

Pennsylvania State University
Zachary R. Barkley
Kenneth J. Davis
Thomas Lauvaux

Princeton University
Stephen W. Pacala

Purdue University
Paul B. Shepson

Stanford University
Adam R. Brandt

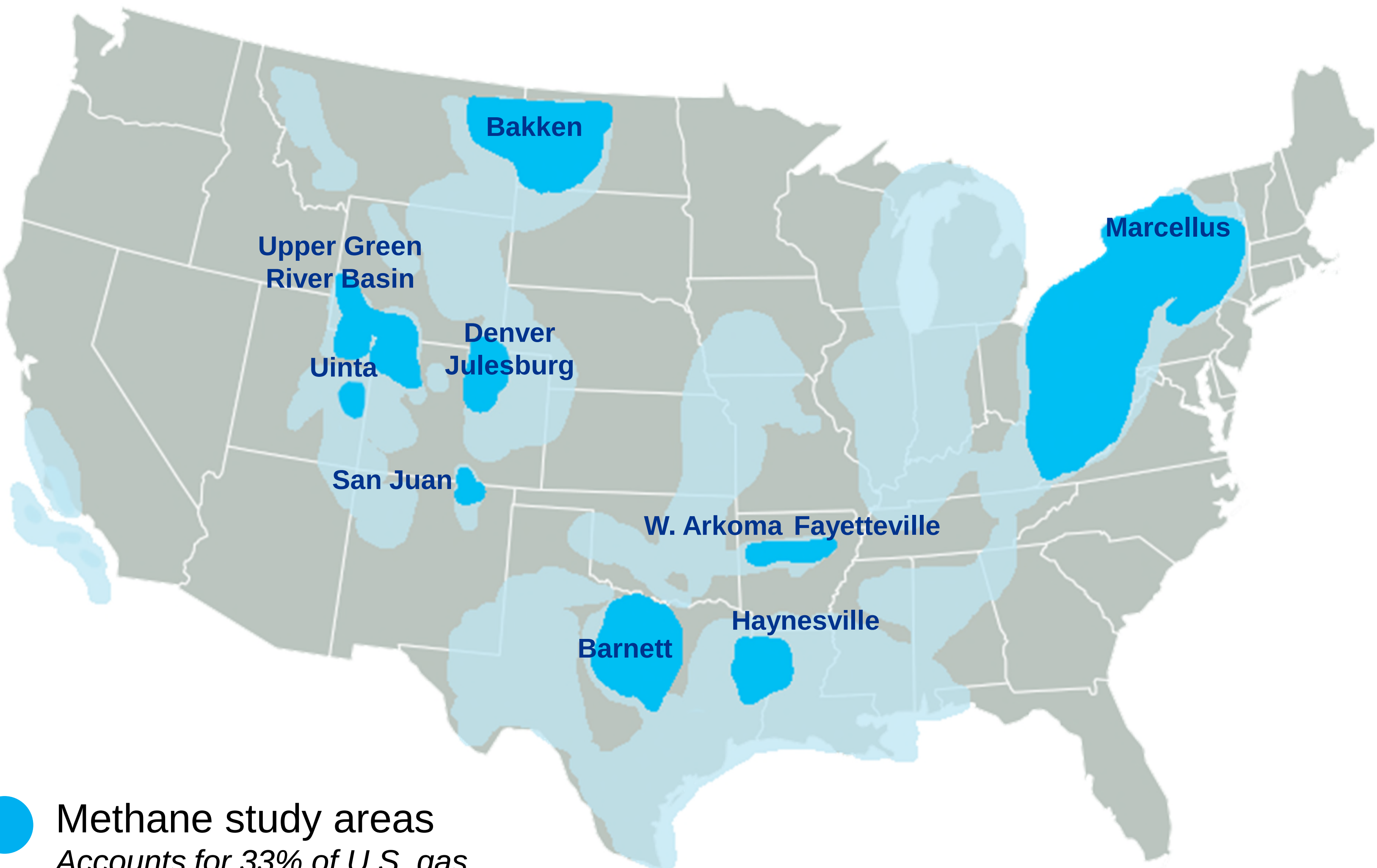
University of Cincinnati
Amy Townsend-Small

University of Michigan
Eric A. Kort

University of Texas
David T. Allen

Washington State University
Brian K. Lamb

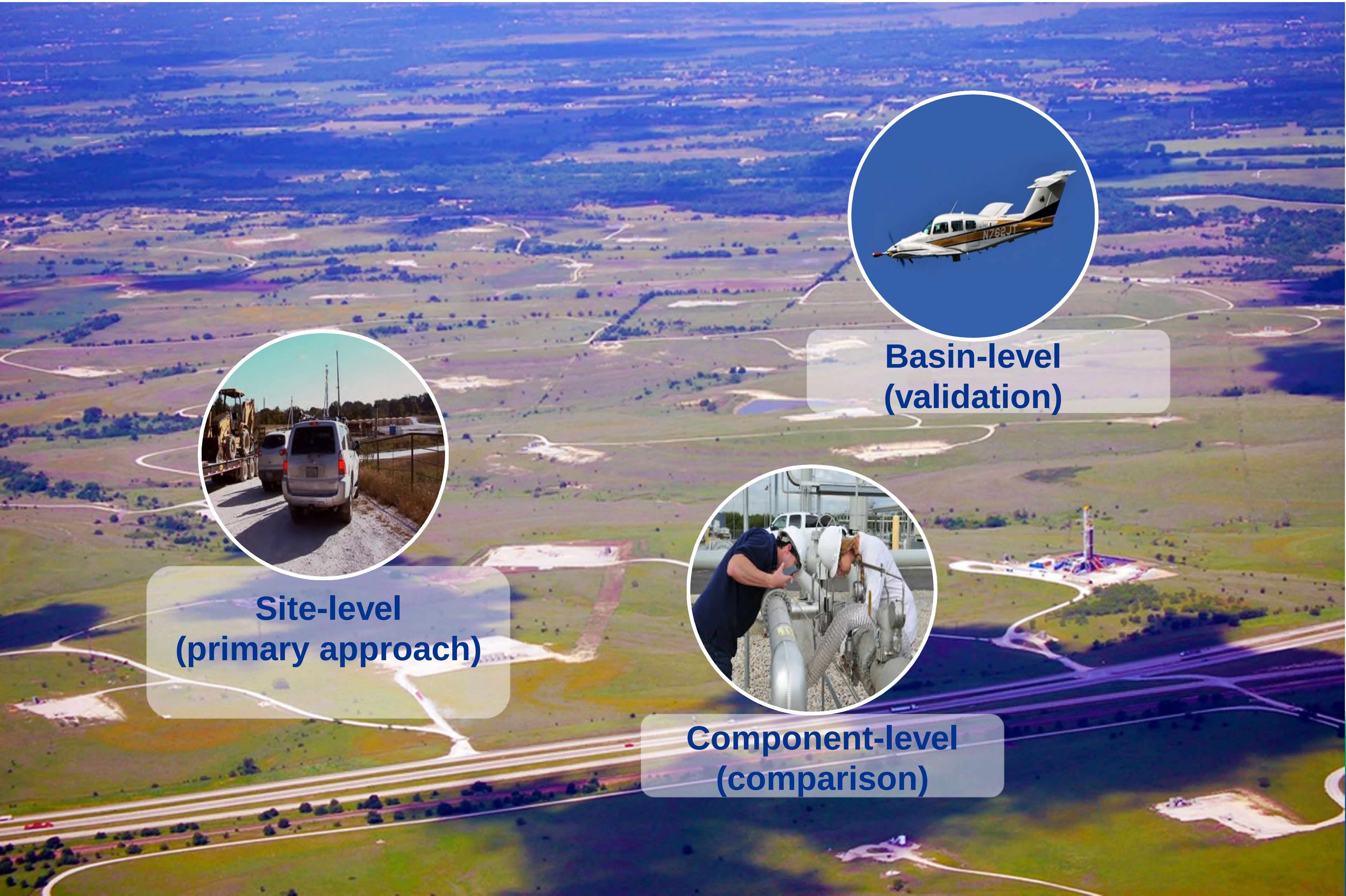
Sources of Regional Synthesis Data



Methane study areas

Accounts for 33% of U.S. gas production; 24% of oil production

Emissions Quantified at Different Spatial Scales

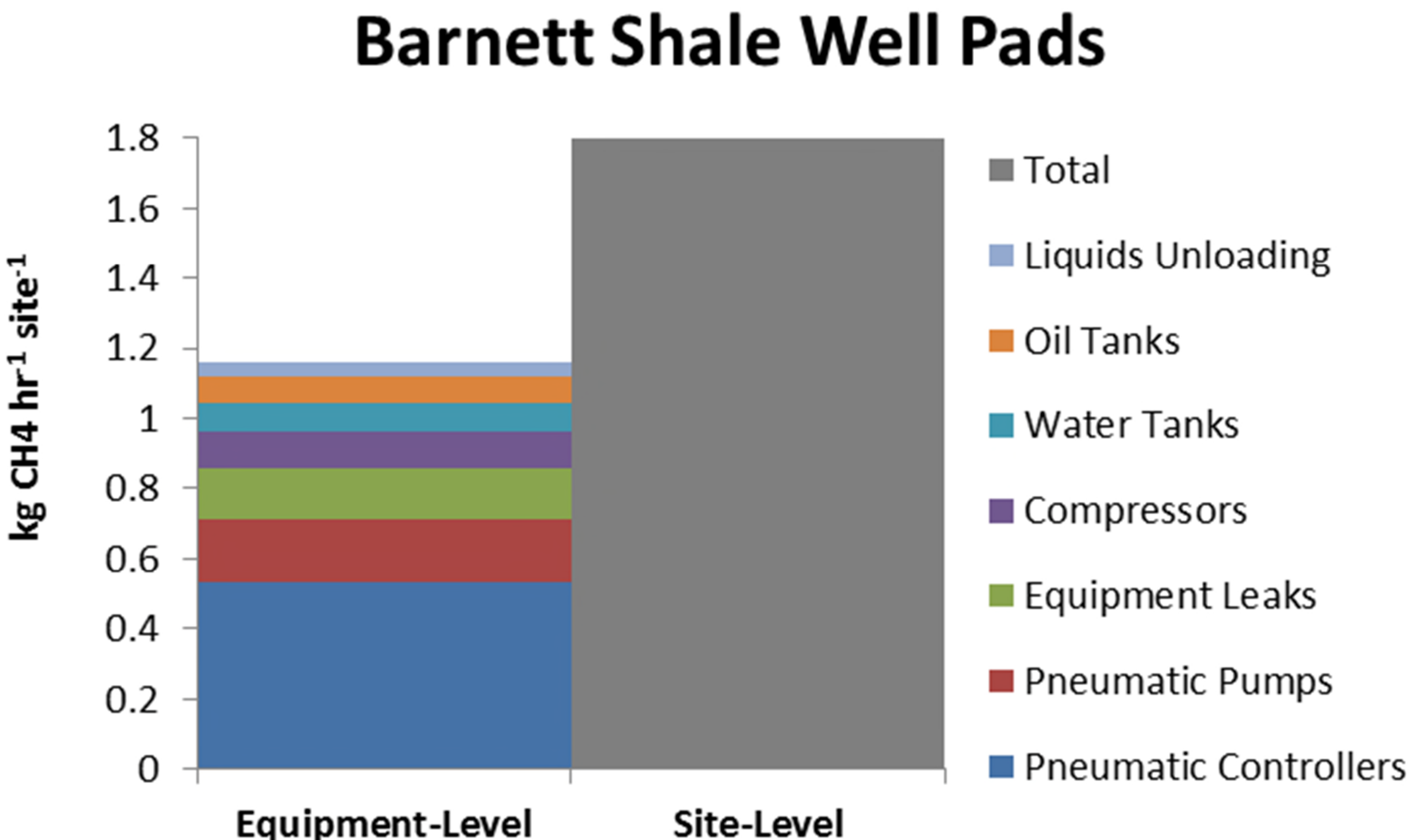




Comprehensive site measurements reveal higher emissions than inventories

Basin- and site-level quantification methods can find emissions that are overlooked by equipment-level measurements.

For example, site-level measurements find 50% more emissions in the Barnett Shale than estimated by traditional methods

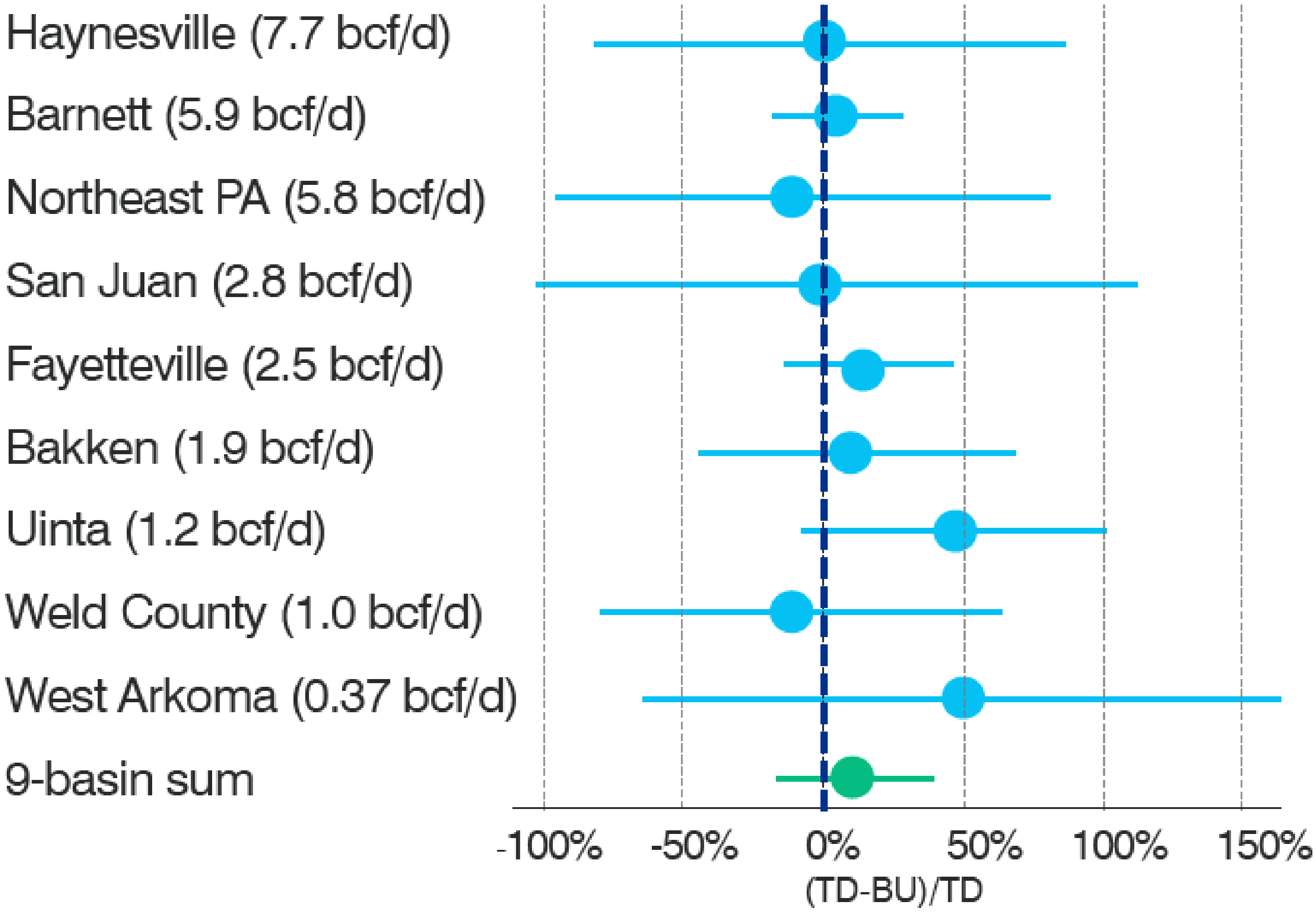


https://www.nature.com/articles/ncomms14012

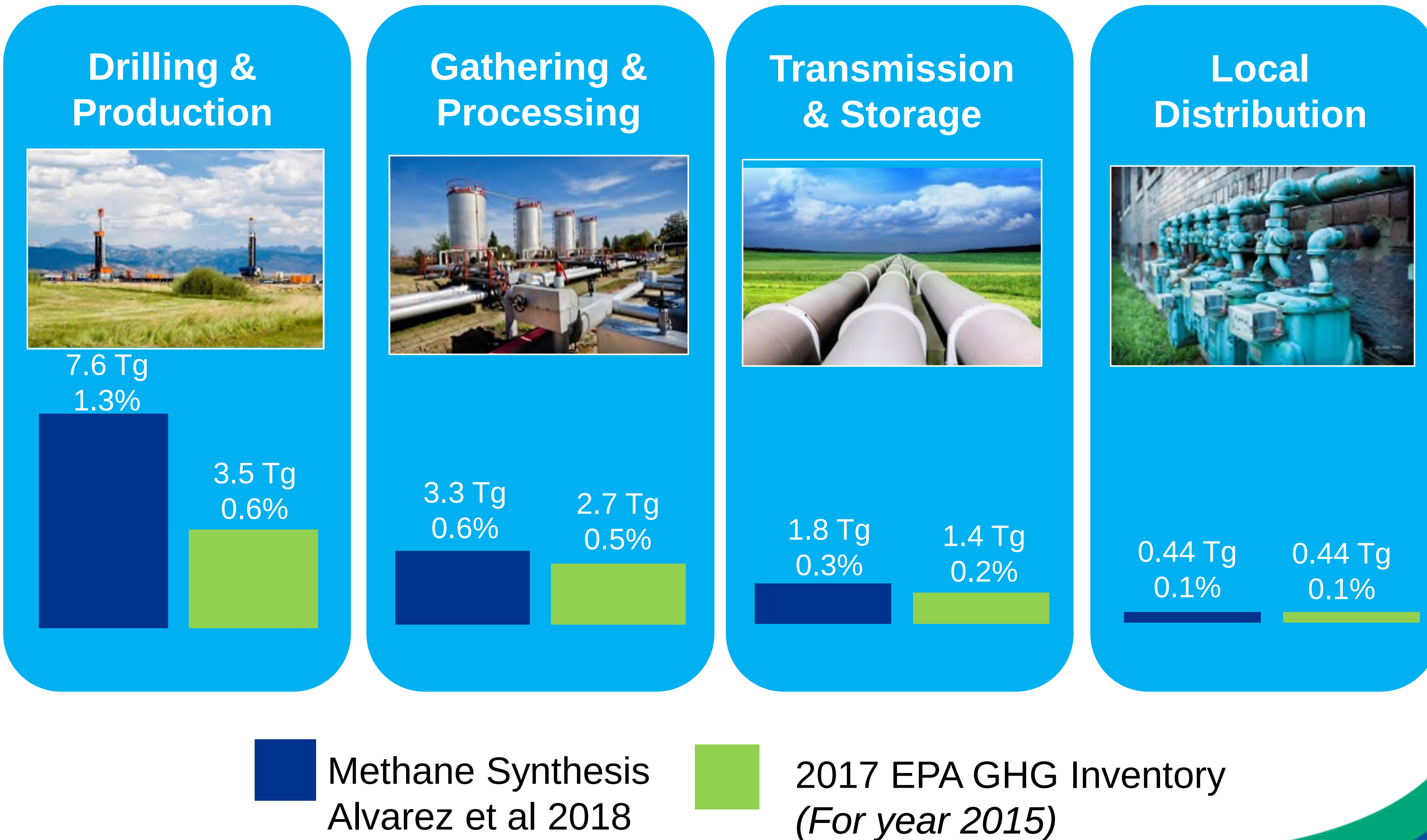
Synthesis Methods

- Multiple, previously published datasets integrated to estimate 2015 U.S. O&G CH_4 emissions by segment
  - **Production**: >400 site-level measurements from 6 basins
    - Basins: Barnett, DJ, Fayetteville, Uintah, Upper Green River, Marcellus
    - Methods: Dual tracer, mobile flux plane, inverse Gaussian, OTM 33A
  - **Gathering & Processing**: Marchese et al 2015
  - **Transmission & Storage**: Zimmerle et al 2015
  - **Local distribution**: Lamb et al 2015
- Basin-level, site-based estimates validated with aerial mass balance data from 9 basins
    - Basins: Haynesville, Barnett, Marcellus, San Juan, Fayetteville, Bakken, Uintah, Weld, West Arkoma
- Synthesis estimate compared to U.S. EPA GHG Inventory and custom component-based inventory

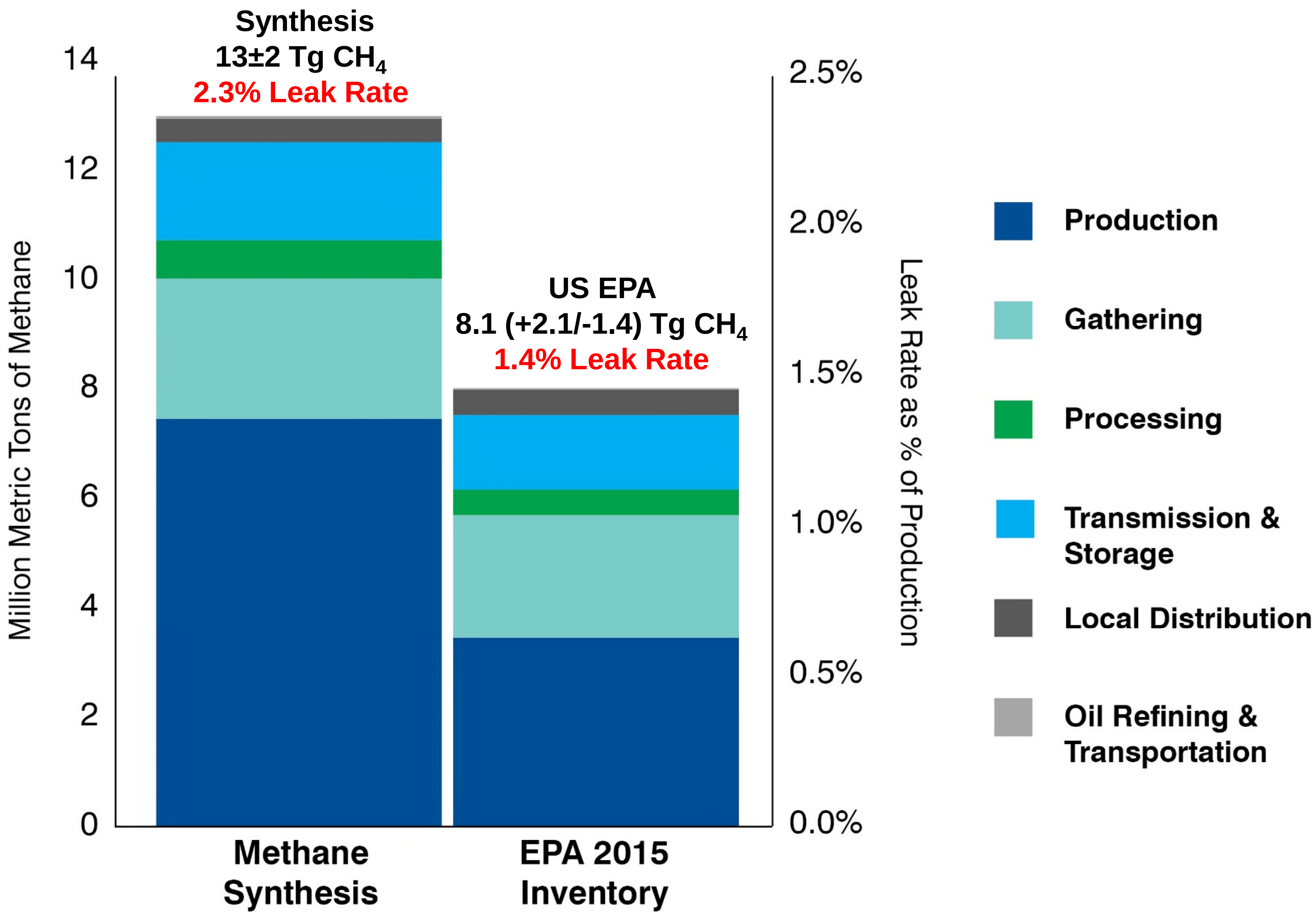
Aircraft- and site-based emission estimates are statistically similar



U.S. O&G Supply Chain
2015 Methane Emissions

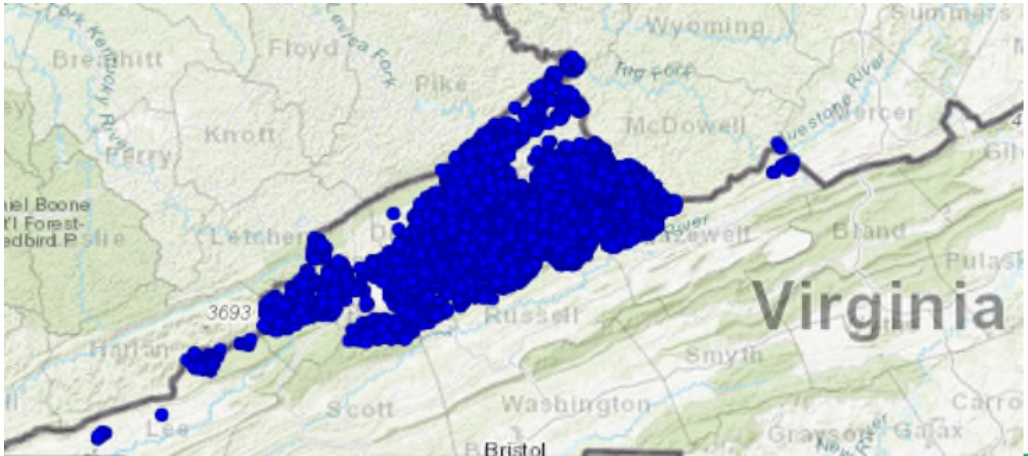


O&G CH_4 emissions 60% higher than EPA GHGI



Implications for Virginia

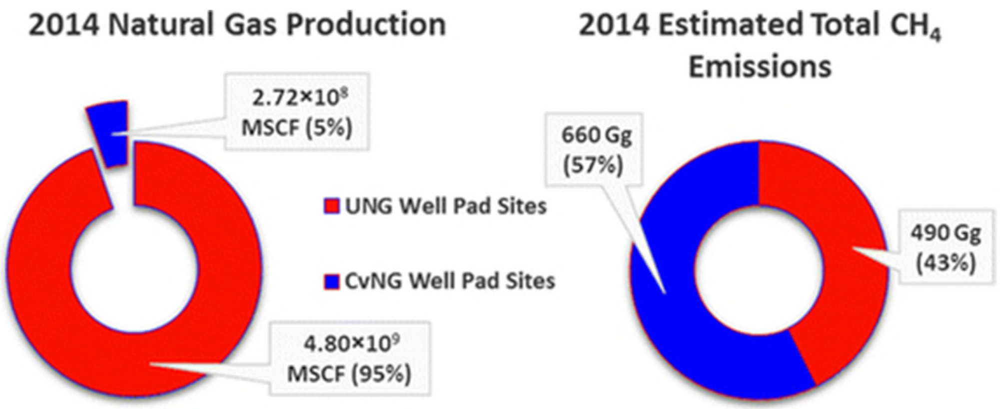
- The state includes approximately:
  - 8,000 active O&G wells
  - 3,000 inactive/plugged wells
  - 25 compressor stations
  - 2 storage fields
- Active wells are almost exclusively marginal gas wells with 94% producing less than 15 barrel of oil equivalents per day.



Drillinginfo

Implications for Virginia

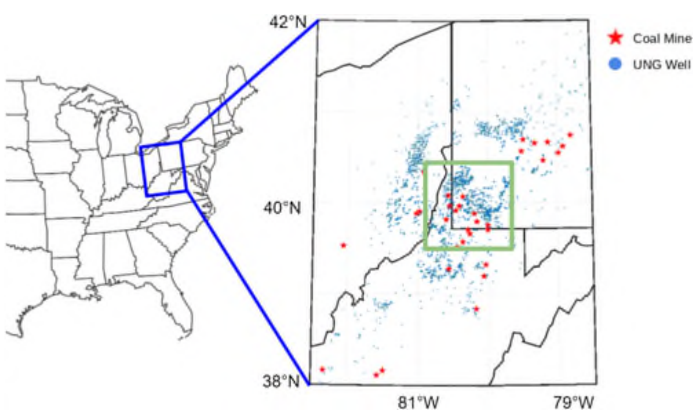
- Measurement data from the state are not available, but studies from a similar production area in southwest Pennsylvania provide insights.
- Marginal conventional wells have relatively low absolute emission rates but very high loss rates:
  - Mean emission factor = 0.8 kg CH_4/hr (7.8 tons per year)
  - Median loss rate = 11% gas production



https://pubs.acs.org/doi/abs/10.1021/acs.est.5b05503

Implications for Virginia

- Another study in SW PA used aircraft data to estimate emissions from O&G and coal mines.
  - Both coal and O&G were important methane sources.
  - EPA estimates were accurate for coal but 5X too low for O&G.
  - Production and gathering loss rate of 0.5±0.3% is in agreement with other regional studies.



https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019GL082131

Preliminary Emission Estimates for Virginia wells and compressor stations

- 8,000 active wells * 7.8 TPY = 62,400 TPY CH_4
  - https://pubs.acs.org/doi/abs/10.1021/acs.est.5b05503
- 3,000 abandoned wells * 0.14 TPY = 400 TPY
  - https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015GL067623
- 25 compressor stations * 739 TPY = 18,500 TPY
  - https://pubs.acs.org/doi/abs/10.1021/acs.est.5b01669

Summary

- **O&G CH_4 emissions are higher than estimated by official inventories like the EPA GHGI**
  - Upstream sources responsible for ~80% of total emissions
  - Site-based estimates validated with basin-level data
- **Abnormal conditions cause large emissions often excluded from traditional inventories**
  - Avoidable issues such as malfunctions, human error, and poor site design can lead to very high emission rates
  - Abnormal conditions account for about 50% of production segment and 33% of total supply chain emissions
- **Regulatory and voluntary actions can reduce emissions**
  - Effective monitoring to quickly detect high emissions
  - Root cause analysis and better site design to minimize the recurrence of abnormal conditions
  - Improved reporting to more accurately understand emissions

Additional Slides

Alternative, source-based estimate is substantially lower than site-based estimate. This traditional approach underestimates emissions by failing to account for uncategorized abnormal emissions.

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)

Over 30% of emissions are from very marginal (<10 Mcf/d) sites responsible for <1% of U.S. gas production.

Table S4. Distribution of the activity data of U.S. oil and natural gas wells in 2015. The last row shows the percent of emissions from production sites calculated with the model described in this section. The production cohorts in this table were selected based on breakpoints evident in the dataset of production site emission measurements (Fig. S2 and Section S1.9), and 0.68 Mcf/d is the minimum production of the sampled population. The measurement dataset predominantly contains sites with gas production within the bolded gas production cohorts.

	% of US 2015 Activity Data by Gas Production Cohort				
Natural Gas Production Cohorts (Mcf d^{-1})	0	>0–0.68	**0.68–10**	**10–5,000**	>5,000
Sites*	15% (0%)	7.6% (8.9%)	29% (34%)	48% (57%)	0.38% (0.45%)
Wells	19%	5.1%	20%	53%	3.3%
Gas Production	0%	0.015%	0.84%	59%	40%
Oil Production	7.3%	0.49%	3.0%	74%	15%
Emissions*	6.4% (0%)	5.1% (5.5%)	20% (21%)	64% (68%)	4.8% (5.1%)

*The main value includes oil wells with zero reported gas production; the value in parentheses excludes them.