COMPENDIUM OF RECENT SCIENTIFIC STUDIES (2016-2019): METHANE AS A CLIMATE CHANGE AGENT; OIL AND GAS CONTRIBUTION TO METHANE EMISSIONS

Steiner, Irena & Schwartz, Brian. (2019). Environmental Health Concerns From Unconventional Natural Gas Development. 10.1093/acrefore/9780190632366.013.44.

- "Beyond its direct health impacts, UNGD [unconventional natural gas development] may be substantially contributing to climate change (due to fugitive emissions of methane, a powerful greenhouse gas), which has further health impacts."
- Emissions of methane result from pressurized UNGD equipment due to leaks during drilling, storage, and transport operations

FOURTH NATIONAL CLIMATE ASSESSEMENT

USGCRP, 2018: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. doi: 10.7930/NCA4.2018.

Chapter 1: Overview

- "Some of the other greenhouse gases released by human activities, such as methane, are removed from the atmosphere by natural processes more quickly than carbon dioxide; as a result, efforts to cut emissions of these gases could help reduce the rate of global temperature increases over the next few decades."

Chapter 13: Air Quality

- Figure 13.1: *Pathways by Which Climate Change Will Influence Air Pollution* "Climate change will alter chemical and physical interactions that create, remove and transport air pollution. Human activities and natural processes release precursors for ground-level ozone (O3)...including methane."
- "Future ozone levels in the United States will also be affected greatly by domestic emissions of ozone precursors as well as by international emissions of ozone precursors and global methane levels. Studies suggest that climate change will decrease the sensitivity of regional ozone air quality to intercontinental sources." (Doherty et al. 2013 linked here)
- "Many emissions sources of greenhouse gases also emit air pollutants that harm human health. Controlling these common emission sources would both mitigate climate change and have immediate benefits for air quality and human health. Because methane is both a greenhouse gas and an ozone precursor, reductions

of methane emissions have the potential to simultaneously mitigate climate change and improve air quality."

- "Methane is both a GHG and a slowly reactive ozone precursor that contributes to global background surface ozone concentrations. Some monitoring stations in remote parts of the western United States have recorded rising ozone concentrations, resulting in part from increased global methane levels." (Lin et al. 2017, linked here)
- "The magnitude of the human health benefit of lowering ozone levels via methane mitigation is substantial and is similar in value to the climate change benefits." (Sarofim et al. 2017, linked here; Shindell et al. 2017, linked here)

Chapter 22: Northern Great Plains

- “The energy sector is also a significant source of greenhouse gas emissions in the Northern Great Plains, … Methane is released during the production, processing, transmission, storage, and distribution of natural gas.”
- “Strategies being employed in the region to reduce greenhouse gas emissions from the energy sector include … conducting methane leak detection and repair programs using remote sensing technologies at natural gas operations; upgrading the equipment used to produce, store, and transport oil and gas ….”

Alvarez, Ramón A., Daniel Zavala-Araiza, David R. Lyon, David T. Allen, Zachary R. Barkley, Adam R. Brandt, Kenneth J. Davis, et al. 2018. “Assessment of Methane Emissions from the U.S. Oil and Gas Supply Chain.” *Science*, June, eaar7204. https://doi.org/10.1126/science.aar7204.

- Estimates methane emissions associated with U.S. oil and natural gas supply chain
- 2.3% of gross U.S. gas production, 60% higher than the U.S. EPA’s estimate
- This magnitude of emissions per unit natural gas consumed produces radiative forcing over a 20-year timescale comparable to the CO2 from natural gas combustion
    - However, substantial emissions reductions are feasible through rapid detection of the root causes of high emissions and deployment of less failure-prone systems

Collins, W. J., Webber, C. P., Cox, P. M., Huntingford, C., Lowe, J., Sitch, S., Chadburn, S. E., Comyn-Platt, E., Harper, A. B., Hayman, G., and Powell, T.: Increased importance of methane reduction for a 1.5 degree target, Environ. Res. Lett., 13, 054003, https://doi.org/10.1088/1748-9326/aab89c/, 2018.

- early mitigation of CH_4 emissions would significantly increase the feasibility of stabilizing global warming below 1.5 °C, alongside having co-benefits for human and ecosystem health.

[$] Shindell, D. T., Fuglestvedt, J. S., and Collins, W. J. 2017. “The social cost of methane: theory and applications” *Faraday Discuss.* **200** 429–51

- The social cost of methane is approximately 50-100 times greater than the accepted social cost for carbon dioxide
    - This value takes into account the impacts “beyond those directly proportional to global mean temperature change and includes human and ecosystem impacts driven by emissions regardless of the process by which they occur”

J. A. Littlefield, J. Marriott, G. A. Schivley, T. J. Skone, Synthesis of recent ground-level methane emission measurements from the U.S. natural gas supply chain. J. Clean. Prod. **148**, 118–126 (2017). doi:10.1016/j.jclepro.2017.01.101

- “Since one quarter of total estimated U.S. anthropogenic CH_4 emissions is from natural gas systems (EPA, 2015), it is critical to understand the sources, magnitude, and variability of CH_4 emissions to prioritize opportunities for GHG emissions reductions.”
- “Natural gas gathering facilities are a significant and previously-overlooked emission source.”
- “1.7% of the CH4 in natural gas is emitted between extraction and delivery.”

[$] A. M. Robertson, R. Edie, D. Snare, J. Soltis, R. A. Field, M. D. Burkhart, C. S. Bell, D. Zimmerle, S. M. Murphy, Variation in methane emission rates from well pads in four oil and gas basins with contrasting production volumes and compositions. Environ. Sci. Technol. **51**, 8832–8840 (2017).

- Methane emissions from production sites were quantified in four major U.S. basins (Upper Green River, Denver-Julesburg, Uintah, Fayetteville
- Consolidation of operations onto single pads may reduce normalized emissions

D. Zavala-Araiza, R. A. Alvarez, D. R. Lyon, D. T. Allen, A. J. Marchese, D. J. Zimmerle, S. P. Hamburg, Super-emitters in natural gas infrastructure are caused by abnormal process conditions. Nat. Commun. **8**, 14012 (2017). doi:10.1038/ncomms14012pmid:28091528

- "Quantifying methane (CH_4) emissions from the natural gas supply chain is an active area of research [citing 21 recent studies from 2012-2015], with consistent findings that high-emitting sources disproportionately affect overall emissions."

S. Schwietzke, G. Pétron, S. Conley, C. Pickering, I. Mielke-Maday, E. J. Dlugokencky, P. P. Tans, T. Vaughn, C. Bell, D. Zimmerle, S. Wolter, C. W. King, A. B. White, T. Coleman, L. Bianco, R. C. Schnell, Improved mechanistic understanding of natural gas methane emissions from spatially resolved aircraft measurements. Environ. Sci. Technol. **51**, 7286–7294 (2017).
https://pubs.acs.org/doi/pdf/10.1021/acs.est.7b01810?rand=alcxym3z

- "Reducing the amount of leaked and vented natural gas (NG) during its production, processing, transport, and use has become a high priority in U.S. efforts to cut anthropogenic emissions of methane (CH4) and in some cases also of nonmethane hydrocarbons that can cause tropospheric ozone pollution or pose direct health risks."
- "Our paper is part of a comprehensive study to expand and improve the top-down vs bottom-up reconciliation effort by providing for the first time a spatially resolved aircraft-based midday CH4 emission estimate for comparison with a temporally and spatially consistent bottom-up inventory."

A. Gvakharia, E. A. Kort, A. Brandt, J. Peischl, T. B. Ryerson, J. P. Schwarz, M. L. Smith, C. Sweeney, Methane, black carbon, and ethane emissions from natural gas flares in the Bakken Shale, North Dakota. Environ. Sci. Technol. **51**, 5317–5325 (2017). doi:10.1021/acs.est.6b05183pmid:28401762

- "Incomplete combustion during flaring can lead to production of black carbon (BC) and loss of methane and other pollutants to the atmosphere, impacting climate and air quality."
- "We use airborne data of plume samples from 37 unique flares in the Bakken region of North Dakota in May 2014 to calculate emission factors for BC, methane, ethane, and combustion efficiency for methane and ethane."

M. L. Smith, A. Gvakharia, E. A. Kort, C. Sweeney, S. A. Conley, I. Faloona, T. Newberger, R. Schnell, S. Schwietzke, S. Wolter, Airborne quantification of methane emissions over the Four Corners region. Environ. Sci. Technol. **51**, 5832–5837 (2017) doi:10.1021/acs.est.6b06107pmid:28418663

- "Methane (CH4) is a potent greenhouse gas and the primary component of natural gas. The San Juan Basin (SJB) is one of the largest coal-bed methane producing regions in North America and, including gas production from conventional and shale sources, contributed ~2% of U.S. natural gas production in 2015."

- "In this work, we quantify the CH4 flux from the SJB using continuous atmospheric sampling from aircraft collected during the TOPDOWN2015 field campaign in April 2015."

Z. R. Barkley, T. Lauvaux, K. J. Davis, A. Deng, N. L. Miles, S. J. Richardson, Y. Cao, C. Sweeney, A. Karion, M. K. Smith, E. A. Kort, S. Schwietzke, T. Murphy, G. Cervone, D. Martins, J. D. Maasakkers, Quantifying methane emissions from natural gas production in north-eastern Pennsylvania. Atmos. Chem. Phys. **17**, 13941–13966 (2017). doi:10.5194/acp-17-13941-2017

- "Natural gas infrastructure releases methane (CH4), a potent greenhouse gas, into the atmosphere. The estimated emission rate associated with the production and transportation of natural gas is uncertain, hindering our understanding of its greenhouse footprint. This study presents a new application of inverse methodology for estimating regional emission rates from natural gas production and gathering facilities in north-eastern Pennsylvania."

C. S. Foster, E. T. Crosman, L. Holland, D. V. Mallia, B. Fasoli, R. Bares, J. Horel, J. C. Lin, Confirmation of elevated methane emissions in Utah's Uintah Basin with ground-based observations and a high-resolution transport model: Methane emissions in Utah's Uintah Basin. J. Geophys. Res. D Atmospheres **122**, 13026–13044 (2017).

- "Large CH_4 leak rates have been observed in the Uintah Basin of eastern Utah, an area with over 10,000 active and producing natural gas and oil wells."
- "These findings corroborate emission estimates from the NOAA inventory, based on daytime mass balance estimates, and provide additional support for a suggested leak rate from the Uintah Basin that is higher than most other regions with natural gas and oil development."

T. N. Lavoie, P. B. Shepson, M. O. L. Cambaliza, B. H. Stirm, S. Conley, S. Mehrotra, I. C. Faloona, D. Lyon, Spatiotemporal variability of methane emissions at oil and natural gas operations in the Eagle Ford Basin. Environ. Sci. Technol. **51**, 8001–8009 (2017). doi:10.1021/acs.est.7b00814pmid:28678487

- Results indicate that understanding temporal emission variability will promote improved mitigation strategies and additional analysis is needed to fully characterize its causes.

J. D. Goetz *et al*., Analysis of local-scale background concentrations of methane and other gas-phase species in the Marcellus Shale. Elem. Sci. Anth. **5**, 1 (2017). doi:10.1525/elementa.182

- "…there has been growing concern about the emissions of greenhouse gases (largely methane), criteria pollutants, and air toxics from all stages of shale gas development."
- "…increased monitoring is needed to assess the air quality impact of shale gas activity."

P. Balcombe, K. Anderson, J. Speirs, N. Brandon, A. Hawkes, The natural gas supply chain: The importance of methane and carbon dioxide emissions. ACS Sustain. Chem.& Eng. **5**, 3–20 (January 2017). doi:10.1021/acssuschemeng.6b00144

- "While natural gas emits less CO2 when burned than other fossil fuels, its main constituent is methane, which has a much stronger climate forcing impact than CO2 in the short term."
- "This Perspective presents a comprehensive compilation of estimated CO2 and methane emissions across the global natural gas supply chain, with the aim of providing a balanced insight for academia, industry, and policy makers by summarizing the reported data, locating areas of major uncertainty, and identifying where further work is needed to reduce or remove this uncertainty."
- "The presence of "super emitters", a small number of facilities or equipment that cause extremely high emissions, is found across all supply chain stages creating a highly skewed emissions distribution. However, various new technologies, mitigation and maintenance approaches, and legislation are driving significant reductions in methane leakage across the natural gas supply chain."

M. Etminan, G. Myhre, E. J. Highwood, K. P. Shine, Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. Geophys. Res. Lett. **43**, 12614–12623 (2016). doi:10.1002/2016GL071930

- New calculations of methane's radiative forcing are presented (the difference between incoming and outgoing radiation, influencing how much the planet warms given a concentration of the gas) showing the 1750-2011 radiative forcing is about 25% higher compared to the value in the IPCC 2013 assessment; the 100-year global warming potential is 14% higher than the IPCC value

B. K. Lamb, M. O. L. Cambaliza, K. J. Davis, S. L. Edburg, T., W. Ferrara, C. Floerchinger, A. M. F. Heimburger, S. Herndon, T. Lauvaux, T. Lavoie, D. R. Lyon, N. Miles, K. R. Prasad, S. Richardson, J. R. Roscioli, O. E. Salmon, P. B. Shepson, B. H. Stirm, J. Whetstone, Direct and indirect measurements and modeling of methane

emissions in Indianapolis, Indiana. Environ. Sci. Technol. **50**, 8910–8917 (2016). doi:10.1021/acs.est.6b01198pmid:27487422

- "…methane (CH4), the main component of natural gas, is a powerful short-lived greenhouse gas, and the emission of CH4 associated with the natural gas supply chain can offset the climate benefits of reduced CO2 emissions relative to other fossil fuels."
- "…an accurate estimate of the CH4 lost to the atmosphere from the natural gas infrastructure and usage is needed to understand the climate impacts of using natural gas as an energy source and to identify viable opportunities for overall reductions in CH4 emissions."
- "This paper describes process-based estimation of CH4 emissions from sources in Indianapolis, IN and compares these with atmospheric inferences of whole city emissions."

D. Wunch, G. C. Toon, J. K. Hedelius, N. Vizenor, C. M. Roehl, K. M. Saad, J.-F. L. Blavier, D. R. Blake, P. O. Wennberg, Quantifying the loss of processed natural gas within California's South Coast Air Basin using long-term measurements of ethane and methane. Atmos. Chem. Phys. **16**, 14091–14105 (2016). doi:10.5194/acp-16-14091-2016

- "Anthropogenic sources of the potent greenhouse gas methane (CH4) constitute about 60 % of the global total CH4 emissions … Urban regions are thought to be an important contributor to this flux …"
- "…more than half of the excess methane in the SoCAB between 2012 and 2015 is attributable to losses from the natural gas infrastructure."

M. Omara, M. R. Sullivan, X. Li, R. Subramanian, A. L. Robinson, A. A. Presto, Methane emissions from conventional and unconventional natural gas production sites in the Marcellus Shale Basin. Environ. Sci. Technol. **50**, 2099–2107 (2016). doi:10.1021/acs.est.5b05503pmid:26824407

- "Methane (CH4) emissions from the natural gas (NG) supply chain have attracted significant interest in recent years because CH4, the principal component of NG (e.g., 76% to 92% CH4 in produced NG), produces 30 times more radiative forcing than CO2 over a 100-year time frame. These CH4 emissions may offset potential benefits of NG as a transition fuel between more carbon-intensive fossil fuels (e.g., coal) and renewable energy systems."
- The study data suggest that the recently instituted Pennsylvania CH4 emissions inventory substantially underestimates measured facility-level CH4 emissions by >10-40 times for five unconventional natural gas sites in this study.

[$] A. R. Brandt, G. A. Heath, D. Cooley, Methane leaks from natural gas systems follow extreme distributions. Environ. Sci. Technol. **50**, 12512–12520 (2016).

- "… leaking natural gas causes climate damage because methane (CH4) has a high global warming potential."
- "A unifying result is that the largest 5% of leaks typically contribute over 50% of the total leakage volume."

D. R. Lyon, R. A. Alvarez, D. Zavala-Araiza, A. R. Brandt, R. B. Jackson, S. P. Hamburg, Aerial surveys of elevated hydrocarbon emissions from oil and gas production sites. Environ. Sci. Technol. **50**, 4877–4886 (2016) doi:10.1021/acs.est.6b00705pmid:27045743

- "Methane, the primary constituent of natural gas, is a short-lived greenhouse gas with 28−34 and 84−86 times the cumulative radiative forcing of carbon dioxide on a mass basis over 100 and 20 years, respectively. Burning natural gas instead of other fossil fuels may increase net radiative forcing for some time, even if carbon dioxide emissions decline, depending on the loss rate of methane across the O&G supply chain."
- Tanks represent a key mitigation opportunity for reducing methane and VOC emissions.

J. D. Albertson, T. Harvey, G. Foderaro, P. Zhu, X. Zhou, S. Ferrari, M. S. Amin, M. Modrak, H. Brantley, E. D. Thoma, A mobile sensing approach for regional surveillance of fugitive methane emissions in oil and gas production. Environ. Sci. Technol. **50**, 2487–2497 (2016). doi:10.1021/acs.est.5b05059pmid:26807713

- "Leaks at [] well production and pipeline facilities release methane (CH4) directly to the atmosphere, thus reducing the potential greenhouse forcing advantage over competing fossil fuels such as coal. Significant debate surrounds the aggregate magnitude of these fugitive emissions. Much of the debate centers on whether the total losses are above or below the tipping point of 3.2%, beyond which natural gas is considered to be worse than coal from a greenhouse forcing perspective."
- This paper addresses the need for surveillance of fugitive methane emissions over broad geographical regions.

D.J. Jacob, A.J. Turner, J.D. Maasakkers, J. Sheng, K. Sun, X. Liu, K. Chance, I. Aben, J. McKeever, C. Frankenberg, Satellite observations of atmospheric methane and their value for quantifying methane emissions. Atmos. Chem. Phys. **16**, 14371–14396 (2016). doi:10.5194/acp-16-14371-2016

- "Methane is a greenhouse gas emitted by anthropogenic sources including livestock, oil–gas systems, landfills, coal mines, wastewater management, and rice cultivation. ... The atmospheric concentration of methane has risen from 720 to 1800 ppb since preindustrial times."
- "Here we review present, near-future, and proposed satellite observations of atmospheric methane and assess their value for quantifying emissions, from regional scales down to the scale of individual point sources."

A. Townsend-Small, T. W. Ferrara, D. R. Lyon, A. E. Fries, B. K. Lamb, Emissions of coalbed and natural gas methane from abandoned oil and gas wells in the United States. Geophys. Res. Lett. **43**, 2283–2290 (2016). doi:10.1002/2015GL067623

- "Recent work indicates that oil and gas methane (CH_4) inventories for the United States are underestimated. Here we present results from direct measurements of CH_4 emissions from 138 abandoned oil and gas wells, a source currently missing from inventories."

J. Peischl, A. Karion, C. Sweeney, E. A. Kort, M. L. Smith, A. R. Brandt, T. Yeskoo, K. C. Aikin, S. A. Conley, A. Gvakharia, M. Trainer, S. Wolter, T. B. Ryerson, Quantifying atmospheric methane emissions from oil and natural gas production in the Bakken shale region of North Dakota. J. Geophys. Res. D Atmospheres **121**, 6101–6111 (2016) doi:10.1002/2015JD024631

- "…studies that estimate CH_4 emissions from the oil and gas industry are necessary to constrain regional and national GHG emissions inventories and ultimately inform decisions based on the climate impacts of U.S. fuel choices."

J. D. Maasakkers, D. J. Jacob, M. P. Sulprizio, A. J. Turner, M. Weitz, T. Wirth C. Hight, M. DeFigueiredo, M. Desai, R. Schmeltz, L. Hockstad, A. A. Bloom, K. W. Bowman, S. Jeong, M. L. Fischer, Gridded national inventory of U.S. methane emissions. Environ. Sci. Technol. **50**, 13123–13133 (2016). doi:10.1021/acs.est.6b02878pmid:27934278

- "Here we present a spatially disaggregated version of the GHGI at 0.1° × 0.1° spatial resolution and monthly temporal resolution, including detailed information and error characterization for individual emission types. Our goal is to enable the use of the GHGI as an a priori estimate for inversions of atmospheric methane that may guide improvements in the inventory."
- "Total US anthropogenic emission is 29.0 Tg a^{-1} , including major contributions from natural gas systems (24%), enteric fermentation (23%), landfills (20%), coal mining (9%), manure management (9%), and petroleum (or equivalently oil) systems (8%)."

C. Frankenberg, A. K. Thorpe, D. R. Thompson, G. Hulley, E. A. Kort, N. Vance, J. Borchardt, T. Krings, K. Gerilowski, C. Sweeney, S. Conley, B. D. Bue, A. D. Aubrey, S. Hook, R. O. Green, Airborne methane remote measurements reveal heavy-tail flux distribution in Four Corners region. Proc. Natl. Acad. Sci. U.S.A. **113**, 9734–9739 (2016). doi:10.1073/pnas.1605617113pmid:27528660

- "Methane (CH_4) impacts climate as the second strongest anthropogenic greenhouse gas and air quality by influencing tropospheric ozone levels. Space-based observations have identified the Four Corners region in the Southwest United States as an area of large CH_4 enhancements."
- "We conducted an airborne campaign in Four Corners during April 2015 with the next-generation Airborne Visible/Infrared Imaging Spectrometer (near-infrared) and Hyperspectral Thermal Emission Spectrometer (thermal infrared) imaging spectrometers to better understand the source of methane by measuring methane plumes at 1- to 3-m spatial resolution. Our analysis detected more than 250 individual methane plumes from fossil fuel harvesting, processing, and distributing infrastructures, spanning an emission range from the detection limit ∼ 2 kg/h to 5 kg/h through ∼ 5,000 kg/h."

A. Townsend-Small, E. C. Botner, K. L. Jimenez, J. R. Schroeder, N. J. Blake, S. Meinardi, D. R. Blake, B. C. Sive, D. Bon, J. H. Crawford, G. Pfister, F. M. Flocke, Using stable isotopes of hydrogen to quantify biogenic and thermogenic atmospheric methane sources: A case study from the Colorado Front Range. Geophys. Res. Lett. **43**, 11462–11471 (2016). doi:10.1002/2016GL071438

- "Global atmospheric concentrations of methane (CH_4), a powerful greenhouse gas, are increasing, but because there are many natural and anthropogenic sources of CH_4, it is difficult to assess which sources may be increasing in magnitude."
- "…at least 50% of CH_4 emitted in the region is biogenic, perhaps because regulatory restrictions on leaking oil and natural gas wells are helping to reduce this source of CH_4."

M. F. Hendrick, R. Ackley, B. Sanaie-Movahed, X. Tang, N. G. Phillips, Fugitive methane emissions from leak-prone natural gas distribution infrastructure in urban environments. Environ. Pollut. **213**, 710–716 (2016). doi:10.1016/j.envpol.2016.01.094pmid:27023280

- "Fugitive emissions from natural gas systems are the largest anthropogenic source of the greenhouse gas methane (CH_4) in the U.S. …"
- "Fixing 'superemitter' leaks will disproportionately stem greenhouse gas emissions."