Comments on Clean Hydrogen Production Standard

by

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November 10, 2022

I have carefully reviewed the draft guidance posted by the DOE on the proposed Clean Hydrogen Production Standard and offer comments below. For context, I am an Earth systems scientist with a Ph.D. from MIT and more than 40 years of post-Ph.D. experience in research and policy related to human-accelerated global change. I have been a tenured faculty member at Cornell University since 1985, have published more than 200 peer-reviewed papers that have been cited in other peer-reviewed literature more than 75,000 times, and have served on and chaired many committees and panels for the National Academy of Sciences, the International Council of Science, and the US Environmental Protection Agency. I currently serve as one of 22 members of the New York State Climate Action Council, the agency charged by law with developing the implementation plan for New York's progressive climate law.

In August of 2021, I published together with Mark Jacobson one of the only assessments of the greenhouse gas footprint of blue hydrogen (Howarth RW & Jacobson M, 2021, How green is blue hydrogen? *Energy Science and Engineering* 9: 1676-1687, doi: 10.1002/ese3.956). There, we concluded that the emissions footprint of blue hydrogen under our base-case parameterization is 139 g CO_2-eq/MJ. Assuming 0.286 MJ per mole of hydrogen, this is equivalent to 19.9 kg CO_2-eq/kg H_2. We explored several sensitivity analyses, looking at a broad range of methane emission rates, carbon dioxide capture rates, and time frames for comparing methane and carbon dioxide (ie, GWP20 and GWP100). Our best-case scenario had a footprint of 57 g CO_2-eq/MJ and the worst-case scenario 182 g CO_2-eq/MJ, corresponding to a range of 8.2 to 26 kg CO_2-eq/kg H_2. That is, our most optimistic analysis demonstrates a greenhouse gas footprint for blue hydrogen that is more than twice as large as the DOE target of 4.0 kg CO_2-eq/kg H_2, our worst-case analysis gives a value that is 6.5-fold greater than the DOE target, and our most realistic scenario give a value that is 5-fold greater than the DOE target.

Given our Howarth & Jacobson (2021) paper, I am highly skeptical that blue hydrogen can be commercially produced in the US in such a manner as to meet the DOE target of 4.0 kg CO_2-eq/kg H_2. However, I am concerned that DOE may adopt an accounting LCA approach that understates emissions, and incorrectly indicates that industry can reach such a target. There are two critical aspects of the analysis that must be considered: 1) the emission rate for methane from the natural gas systems that provide gas to blue hydrogen facilities; and 2) the assumed global warming potential value. For both of these, I urge the DOE to rely on the preponderance of peer-reviewed literature. I note that the default values used in the DOE GREET model are not consistent with the preponderance of peer-reviewed literature, and are biased so as to severely underestimate the greenhouse gas footprint of blue hydrogen.

Methane emission rate:

Over the past decade, there has been an explosion of new, peer-reviewed studies on methane emissions associated with developing and using natural gas in the United States. Two general approaches have been used: bottom-up methodologies that look sum individual estimates for emissions from different processes and facilities, and top-down approaches that use integrated measures from tower monitoring stations, airplane flyovers, or satellite data to estimate total fluxes. In almost all cases, the top-down approaches provide methane emission estimates that are higher than those from bottom-up approaches. There are many reasons for this, including lack of consideration of all potential emission sources in the bottom-up studies. For a recent review on this issue, including citations to many peer-reviewed papers showing the advantages of the top-down studies, see: Howarth RW, 2022, Methane and climate change, in Stolz JF, Griffin WM, & Bain DJ (editors), *Environmental Impacts from Development of Unconventional Oil and Gas Reserves,* Cambridge University Press.

Building on my 2022 book chapter, I am author of an in-press peer-reviewed paper to be published December 2022 (Howarth RW, Methane Emissions from the Production and Use of Natural Gas, *EM Magazine*). A copy of the pre-print of this paper is appended at the end of my comments here. Using all peer-reviewed top-down studies on methane emissions from natural gas in the United States that had been published as of July 2022, I conclude that emissions are 4.8% of the rate of gas production. This includes both “downstream” distribution emissions (2.2%) and “upstream” and “midstream” emissions from the well sites, processing and storage facilities, and high-pressure transmission pipelines (2.6%). Arguably, this latter value of 2.6% is the best to apply for considering the greenhouse gas footprint of blue hydrogen.

By comparison, the DOE GREET model which is proposed to be used to estimate the greenhouse gas footprint of blue hydrogen under Clean Hydrogen Production Standard assumes a methane emission rate of only 1.1% (Burnham A, 2021, Updated Natural Gas Pathways in GREET2021, technical report from Argonne National Lab). This 1.1% is well under half of the best estimate of 2.6% from the preponderance of the peer-reviewed literature.

In my professional opinion, the standard assumption of a 1.1% methane emission used in the GREET model is simply wrong. The derivation of this estimate was explained to me by A. Burnham of the Argonne National Lab in a personal communication phone call on August 17, 2022. For estimates for 2015, the GREET model used the EPA inventory estimate for natural gas for that year of 1.4% for upstream and midstream emissions, but the Argonne team increased this, recognizing from the peer-reviewed literature that the official EPA estimate was clearly too low. Specifically, the Argonne team increased this value for 2015 from 1.4% to 2.0%, an increase of 1.4-fold. The 2.0% value is too low compared to the peer-reviewed literature (2.6%). Unfortunately, the Argonne team aggravated this low estimate when estimating emissions for 2019: the EPA reduced their official inventory estimate for 2019 from the 1.4% value for 2015 to 0.79%, and the Argonne team then used the same 1.4-fold correction to come up with a value for the GREET model of 1.1%. This remains the default methane emission estimate for the GREET model, and it simply not consistent with the peer-reviewed literature.

As explained in my 2022 in-press paper in EM Magazine (appended below, see Table 3), the EPA erred badly in reducing their methane estimate for upstream and midstream emissions from the 2015 value of 1.4% to a 2019 value of 1.9%. This reduction is based solely on unverified self-reporting by the natural gas industry, and is simply not supported by the peer-reviewed literature. The industry reported values went down not because of any real documented improvements in industry practice (there is no such documentation), but rather because it increasingly became clear to industry after 2015 that they would benefit from the public perception of lower methane emissions.

Note that I am not alone in my criticism of the EPA estimates. Multiple peer-reviewed papers have concluded that even the higher 2015 EPA estimates are far too low. And in February of 2022, the International Energy Agency pointed out that on average all nations in the world underestimate methane emissions in national inventories because of their reliance on unverified industry self reporting (International Energy Agency 2022. Global Methane Tracker. https://www.iea.org/reports/global-methane-tracker-2022). In fact, the IEA concluded that nations on average have been underestimating methane emissions by at least 1.7-fold. Applying this lower-limit 1.7-fold factor to the EPA estimate of 1.4% yields a corrected estimate of 2.4%, which is similar too albeit still a little lower than the 2.6% value supported by the preponderance of the peer-reviewed literature.

In summary, the DOE should not rely on EPA methane estimates – even when corrected – for estimating the greenhouse gas footprint of blue hydrogen. The best available peer-reviewed data should instead drive this analysis.

<u>Global warming potential</u>:

In addition to underestimating methane emissions, the DOE GREET model relies on the 100-year GWP as the default for comparing methane to carbon dioxide emissions. The model allows a user to instead substitute a 20-year GWP, and DOE should make this change when estimating the greenhouse gas footprint of blue hydrogen.

The latest synthesis report from the Intergovernmental Panel on Climate Change demonstrates that methane plays a far more important role in global warming than was recognized even a few years ago (IPCC. 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report_smaller.pdf). Specifically, over the time since 1900, methane has contributed 0.5° C of global warming, compared to 0.75° C for carbon dioxide. That is, over more than a century, methane has contributed 33% of the total warming from all greenhouse gases. Using a 100-year GWP dramatically underplays this level of warming, which is far better approximated by the 20-year GWP.

The IPCC (2021) specifically concluded that the continued reliance on a 100-year value is arbitrary, not a science-based decision. The decision by the US EPA to use 100-yr GWP was made in 1992, as part of Kyoto Protocol. At that time, the importance of methane as a driver of global warming was very poorly understood. As our scientific knowledge base on methane has improved, the logic for changing to a 20-year GWP grows stronger, and stronger. Please note that this has now been recognized by some states, and both New York and Maryland now require the use of a 20-year GWP rather than a

100-year value, through the NY Climate Leadership & Community Protection Act of 2019 and the MD Climate Solutions Now Act of 2022.

Methane Emissions from the Production and Use of Natural Gas

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In Press, EM Magazine, the peer-reviewed trade journal of the Air & Waste Management Association, for December 2022 issue.

Methane is a major driver of global warming and climate disruption, and scientists now recognize that human-controlled methane emissions are responsible for 0.5° C of the warming observed since the 1800s, compared to 0.75° C for carbon dioxide[1]. Reducing methane emissions is critical and is perhaps the easiest way to slow the rate of global warming[2]. Unfortunately, atmospheric methane has been rising rapidly over the past decade after emissions were steady at the start of the 20th Century[3]. Many studies suggest that much of this rise may have come from increased production of natural gas, and particularly shale gas development in North America[4].

Before this century, the technologies for developing shale gas did not exist, but since 2005 or so shale gas production has driven dramatically. Today, most natural gas production in the United States is from shale, and shale-gas production has accounted for most of the increase in all natural gas production globally since 2010[3]. I and others published the first analysis of how methane emissions contribute to the greenhouse gas footprint of shale gas in 2011. We used the best available data, but noted the urgent need for improved measurements on methane emissions made by independent scientists[5].

How large are methane emissions from natural gas?

Table 1. Top-down estimates for upstream and midstream emissions of methane from natural gas systems, including studies based on aircraft flyovers and satellite data, listed chronologically. Estimates are the percentage of the methane in natural gas that is produced. Reprinted from Howarth (2022)[4].

Aircraft data		
Peischl et al (2013)	Los Angeles Basin, CA	17.%
Karion et al. (2013)	Uintah shale, UT	9.0%
Caulton et al. (2014)	Marcellus shale, PA	10.%
Karion et al. (2015)	Barnett shale, TX	1.6%
Peischl et al. (2015)	Marcellus shale, PA	0.2%
Peischl et al. (2016)	Bakken shale, ND	6.3%
Barkley et al. (2017)	Marcellus shale, PA	0.4%
Peischl et al. (2018)	Bakken shale, ND	5.4%
	Eagle Ford shale, TX	3.2%
	Barnett shale, TX	1.5%
	Haynesville shale, LA	1.0%
Ren et al. (2019)	Marcellus shale, PA & WV	1.1%
Satellite data		
Schneising et al. (2014)	Eagle Ford shale, TX	20.%*
	Bakken shale, ND	40.%*
Zhang et al. (2020)	Permian Basin shale, NM	3.7%
Schneising et al. (2020)	Permian Basin shale, NM	3.7%
	Appalachia (Marcellus + Utica), PA	1.2%
	Eagle Ford shale, TX	3.5%
	Bakken shale, ND	5.2%
	Anadarko shale, OK	5.8%

*Schneising et al. (2014) reported emissions as percentage of combined production of oil and gas. Here these are converted to percentage of just gas production using data on relative production of oil and gas from Schneising et al. (2020).

Since our 2011 paper, there has been an explosion of new measurements on methane emissions, primarily in the United States. Table 1 summarizes the data collected from aircraft flyover and satellite studies that estimate emissions at the regional scale, so called "top-down" studies. These include emissions that occur at gas well sites plus those from the processing, storage, and transport of gas in high-pressure pipelines ("upstream and midstream" emissions). As a percentage of the natural gas produced, studies report between 0.2% and 40% released unburned to the atmosphere. Both spatial and temporal variation likely contribute to this rather large range. The median emission rate is 3.7% of the rate of gas production, and omitting the two highest satellite-based estimates as possible outliers, the mean weighted by the volume of production in the different gas fields is 2.6%[4]. These values are remarkably similar to what we estimated based on very preliminary data in our original 2011 paper: 3.2%[5].

Table 2. Top-down estimates for downstream emissions of methane from urban natural gas distribution systems, including estimates based on tower data and aircraft dates. Estimates are the percentage of methane in natural gas consumed.

Tower data		
McKain et al. (2015)[6]	Boston, MA	2.7 %
Wunch et al. (2016)[7]	Los Angeles, CA	1.7 %
Lamb et al. (2016)[8]	Indianapolis, IN	3.5 %[a]
Sargent et al. (2021)[9]	Boston, MA	2.5 %
Aircraft data		
Lamb et al. (2016)[8]	Indianapolis, IN	1.9 %[a]

a. Lamb et al. report gas consumption as 28 Gg/month in the summer and 140 Gg/month in the winter, which suggests annual gas consumption of 1,000 Gg/year. They report natural gas emissions from tower data as 34.8 Gg/year, or 3.5% of consumption, and from aircraft flyovers as 17.8 Gg/year, or 1.8% of consumption.

Unburned methane is also emitted from the distribution pipeline systems that run under virtually all streets in cities and towns, and even from within buildings. These "downstream" emissions are less studied, but recent top-down measurements in several studies[6,7,8,9] shows emissions of between 1.7% and 3.5% of natural gas consumption (Table 2), in addition to the upstream and midstream emissions shown in Table 1. The emissions for Boston (Figure 1)[10] are often attributed to the old cast-iron distribution pipelines still in use in much of that city, but of interest, emissions from Indianapolis are also high even though that city has a much more modern distribution system dominated by plastic piping with some steel[8]. The mean for the five downstream urban emission estimates shown in Table 2 is 2.5% of consumption. Note that gas consumption is always less than gas production, both because of the emission losses and due to some use of gas for powering the compressors in pipelines that deliver the gas to market. In the United States, consumption is approximately 12% less than production[11], so an emission rate of 2.5% of consumption is equivalent to 2.2% of production. Combining 2.2% of production for downstream emissions with the volume-weighted mean value of 2.6% emitted from upstream and midstream sources, overall average methane emissions in the United States are approximately 4.8% of natural gas production.

Figure 1. Methane concentrations along city streets in Boston, Massachusetts measured by a special instrument in a car that was driven along the streets by Prof. Nathaniel Phillips of Boston University.[10] The heights of the yellow bars are proportional to the concentrations. Methane leaks are widespread across much of the city.

Climate effects and systematic downplaying of emissions from natural gas:

Even though carbon dioxide emissions from burning natural gas are less than from burning coal and oil products, unburned methane emissions of 4.8% contribute to an overall greater greenhouse gas footprint for natural gas than for any other fossil fuel when the fuels are burned[4,12]. The details on how the fuels are used matter, so for example natural gas has no immediate climate advantage over coal for generating electricity if methane emissions are greater than 3.2%, or over diesel for powering large trucks if emissions are greater than 1%.[13] When used for heat energy, natural gas with methane emissions of 4.8% are far worse for the climate than either coal or oil for at least the first 20 years after the fuel is burned.[12] Note that while methane is also released from using coal and oil, methane is simply a contaminant of these fuels, while natural gas is composed overwhelmingly of methane. Methane emissions per unit of heat energy are far greater for natural gas than for coal or oil.[12]

Across the globe, governments have systematically underestimated methane emissions from the oil and gas industry for decades, on average by at least 1.7-fold according to a recent analysis by the International Energy Agency.[14] In the United States, a large number of independent scientific studies have concluded that the EPA has severely underestimated these methane emissions.[4, 12] Perhaps surprisingly, while the science showing high emissions has grown stronger in recent years, the official estimates from the EPA have gone down (Table 3). These official values show a decrease in total emissions of one third from 2015 to 2019, from 1.48% of production to 0.93%, driven by assumed decreases in upstream and midstream emissions only slightly countered by increased emissions downstream (Table 3). This decrease reflects the emissions estimates that the oil and gas industry report to EPA. These reported emissions are not independently verified, and are clearly too low when compared to objective, verifiable data from the peer-reviewed literature (Table 3). It seems unlikely that the emissions from the gas industry have actually decreased to any major extent in recent years.[4] What has changed is a growing awareness by the public and press that methane is dangerous to the climate, and therefore an increasing motivation by industry to downplay their contribution.

Table 3. Comparison of estimates for average methane emissions in the United States from the natural gas industry based on the preponderance of top-down studies in the peer-reviewed literature and values assumed by the US EPA for 2015 and for 2019 (as a percentage of the methane in natural gas that is produced).

	Average from peer-reviewed literature	EPA for 2015	EPA for 2019
Upstream & midstream emissions[a]	2.6 %[c]	1.4 %[e]	0.79 %[g]
Downstream emissions[b]	2.2 %[d]	0.08 %[f]	0.14 %[h]
Total emissions	4.8 %	1.48 %	0.93 %

a. Upstream & midstream emissions include those from production, processing, storing, and transmission of gas.
b. Downstream emissions include those from distribution gas pipelines as well as emissions that occur within buildings from leaks and incomplete combustion.
c. Volume-weighted mean from 18 top-down studies, excluding two other very high estimates from satellites which may be outliers, as presented in Table 1.[4]
d. Mean from 5 studies for US cities presented in Table 2.
e. Based on emissions of 7.64 Tg/year[15], assuming natural gas production of 28.8 trillion cubic feet for 2015[16], and assuming gas is 93% methane.[17]
f. Based on emissions of 0.44 Tg/year[15], assuming natural gas production of 28.8 trillion cubic feet for 2015[16], and assuming gas is 93% methane.[17]
g. Calculated from the mean estimate for shale and conventional gas of 152 g methane per million BTU reported.[18]
h. Calculated from the value for distribution of 26.8 g methane per million BTU.[18]

How much can emissions be reduced?

Can methane emissions from natural gas be reduced? Absolutely, although there are limits as how great these reductions can be. Importantly, methane emissions are not simply a result of unintended leaks and accidents: some emissions are the result of routine, purposeful release of methane to the atmosphere, for instance to control pressure in tanks and pipelines for safety and for maintenance of pipelines. Methane is a colorless, invisible gas so routine emissions cannot be observed without special equipment, but the use of special FLIR cameras tuned to the infra-red absorption spectrum of methane allows visualization. Figure 2 compares what the naked eye and a FLIR camera see when looking at a storage tank for natural gas, with the “smoke” seen in the infra-red imagery actually methane vented from the tank. In 2019, the New York Times ran a great interactive visual highlighting FLIR imagery of methane emissions from natural gas facilities.[19] For maintenance on pipelines, the methane in the pipeline is generally released to the atmosphere, to reduce the explosion risk when welding the pipeline. This “blow-down” of gas, when it occurs rapidly, causes cooling of the air around

Figure 2. Natural gas storage tanks at the Haynseville, Texas, shale fields. Picture on left taken with a normal camera. Picture on right was taken with forward-looking infrared (FLIR) camera tuned to the infrared spectrum of methane, which allows visualization of methane emissions. Photo courtesy of Sharon Wilson. Reprinted from Howarth (2019).[3]

the release, which can condense water vapor and make the release highly visible, even though the methane itself remains invisible (Figure 3).

Particularly important emissions upstream and midstream include those during the initial drilling of gas wells, leaks from the “gathering lines” that connect wells to storage and processing centers, emissions from incomplete combustion of flared gas, release from blow-downs for pipeline maintenance, and emissions from incomplete combustion of natural gas used to power compressors that drive gas through pipelines.[15,20,21] The methane that is released during drilling apparently occurs when drillers encounter old gas wells or coal mines. When drilling in regions with a lot of prior fossil-fuel history, drillers use “under balanced” techniques for safety reasons, and this apparently results in methane releases to the air. There is no known technology for reducing these emissions if wells are to be safely drilling in areas with large numbers of old gas wells or coal mines.[4,20] With regard to flaring, this purposeful burning of released gas is required in many regions, rather than venting unburned methane. However, combustion of methane in the flares is never 100% effective, and flares go out, with the unlit flares then venting completely unburned methane. Enforcement of flaring requirements by federal and state authorities is often poor, and a recent study documents that methane emissions from flares are on average five-fold greater than has previously been estimated by EPA.[21]

Figure 3. Blowdown for maintenance of a natural gas pipeline in Yates County, New York. Methane is an invisible gas, but the cooling from the rapid blowdown condenses water vapor, leading to the obvious cloud. Phot courtesy of Jack Ossont. Reprinted from Howarth (2019).[3]

Should we just let urban distribution systems leak methane?

As noted above, roughly half of the total methane emissions from producing and using natural gas occur downstream. These emissions include leaks from medium and low-pressure pipelines that occur under the streets of most cities and towns, as well as leaks within homes and buildings and incomplete combustion of the gas burned in furnaces, water heaters, and stoves. Gas delivery systems are managed to keep leaks below levels likely to lead to explosions, but leaks below this level are expensive to fix and are generally ignored by gas utilities. These leaks could presumably be reduced by replacing the gas distribution system, but this is both expensive and disruptive, requiring widespread ripping up of pavement. I believe that rather than spending funds to reduce these distribution-pipeline leaks, society should move as quickly as possible away from using natural gas in building and homes. A climate law passed by the State of New York in 2019 requires that all greenhouse gas emissions from all economic sectors in the State be reduced by 40% by 2030 and by at least 85% by 2050.[22] The use of fossil fuels in homes and commercial buildings is the single largest source of greenhouse emissions in New York, and the implementation plan for the State to reach its climate goals calls for reducing the use of natural gas by 25% by 2030, by 50% by 2035, and completely by 2050.[22] Given this, the priority for funding for energy should be on moving away from fossil fuels rather than on rebuilding the gas infrastructure.

References:

1. IPCC. 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report_smaller.pdf

2. United Nations Environment Programme and Climate and Clean Air Coalition. 2021. Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions. Nairobi: United Nations Environment Programme. https://www.unep.org/resources/report/global-methane-assessment-benefits-and-costs-mitigating-methane-emissions

3. Howarth, R.W. 2019. Ideas and perspectives: Is shale gas a major driver of recent increase in global atmospheric methane? *Biogeosciences* 16: 3033- 3046. https://doi.org/10.5194/bg-16-3033-2019

4. Howarth, R.W. 2022. Methane and climate change. In: JF Stolz, WM Griffin, DJ Bain, editors. Environmental Impacts from Development of Unconventional Oil and Gas Reserves. Cambridge, UK: Cambridge University Press. http://www.eeb.cornell.edu/howarth/documents/Howarth_2021_Methane_and_Climate.pdf

5. Howarth, R.W., Santoro, R., and Ingraffea, A. 2011. Methane and the greenhouse gas footprint of natural gas from shale formations. *Climatic Change Letters* 106: 679–690, doi:10.1007/s10584-011-0061-5

6. McKain, K., Down, A., Raciti, S., Budney, J., Hutyram, L.R., Floerchinger, C., Herndon, S.C., Nehrkorn, T., Zahniser, M., Jackson, R., Phillips, N., and Wofsy, S. 2015. Methane emissions from natural gas infrastructure and use in the urban region of Boston, Massachusetts. *Proceedings of the National Academy of Sciences*. 112:1941-1946, doi:10.1073/pnas.1416261112

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

8. Lamb, B.K., Cambaliza, M., Davis, K., Edburg, S., Ferrara, T., Floerchinger, C., Heimburger, A., Herndon, S., Lauvaux, T., Lavoie, T., Lyon, D., Miles, N., Prasad, K., Richardson, S., Roscioli, J., Salmon, O., Shepson, P., Stirm, B., and Whetstone, J. 2016. Direct and indirect measurements and modeling of methane emissions in Indianapolis, Indiana. *Environ. Sci. Technol.,* 50: 8910-8917, doi:10.1021/acs.est.6b01198

9. Sargent, M.R., Floerchinger, C., McKain, K., Budney, J., Gottlieb, E.W., Hutyra, L.R., Rudek, J., and Wofsy, S.C. 2021. Majority of US urban natural gas emission unaccounted for in inventories. *Proceedings of the National Academy of Sciences* 118 (44) e2105804118 https://doi.org/10.1073/pnas.2105804118

10. Gellerman, B. 2012. Living on Earth, National Public Radio. http://www.loe.org/shows/segments.html?programID=12-P13-00002&segmentID=3

11. Howarth, R.W. 2020. Methane emissions from fossil fuels: Exploring recent changes in greenhouse-gas reporting requirements for the State of New York. *Journal of Integrative Environmental Sciences,* doi: 10.1080/1943815X.2020.1789666.

12. Howarth, R.W. 2014. A bridge to nowhere: Methane emissions and the greenhouse gas footprint of natural gas. *Energy Sci Eng*. 2: 47- 60. https://doi.org/10.1002/ese3.35

13. Alvarez, R.A., Pacala, S.W., Winebrake, J.J., Chameides, W.L., and Hamburg, S.P. 2012. Greater focus needed on methane leakage from natural gas infrastructure. *Proceedings of the National Academy of Sciences.* 109: 6435–6440, doi:10.1073/pnas.1202407109

14. International Energy Agency 2022. Global Methane Tracker. https://www.iea.org/reports/global-methane-tracker-2022

15. Alvarez, R.A., Zavalao-Araiza, D., Lyon, D.R., Allen, D.T., Barkley, Z.R., Brandt, A.R., Davis, K.J/, Herndon, S.C., Jacob, D.J., Karion, A., Korts, E.A., Lamb, B.K., Lauvaux, T., Maasakkers, J.D., Marchese, A.J., Omara, M., Pacala, J.W., Peischl, .J, Robinson, A.,J, Shepson, P.B., Sweeney, C.,Townsend-Small, A., Wofsy, S.C,, and Hamburg, S.P. 2018. Assessment of methane emissions from the U.S. oil and gas supplychain. *Science* 361:186-188, doi:10.1126/science.aar7204

16. Energy Information Administration. 2022. Today in energy, December 16, 2016. Energy Information Administration, U.S. Department of Energy. https://www.eia.gov/todayinenergy/detail.php?id=29192

17. Schneising, O., Burrows, J.P., Dickerson, R.R., Buchwitz, M., Reuter, M., and Bovensmann, H. 2014. Remote sensing of fugitive emissions from oil and gas production in North American tight geological formations. *Earth's Future* 2: 548–558, doi:10.1002/2014EF000265

18. Burnham, A. 2021. Updated natural gas pathways in GREET 2021. Argonne National Lab, U.S. Department of Energy. https://greet.es.anl.gov/publication-update_ng_2021

19. Kessel, J.M., and Tabuchi ,H. 2019. It's a vast, invisible climate menace: we made it visible. New York Times, December 12, 2019, https://www.nytimes.com/interactive/2019/12/12/climate/texas-methane-superemitters.html

20. Caulton, D.R., Shepson, P.D., Santoro, R.L., Sparks, J.P., Howarth, R.W., Ingraffea, A., Camaliza, M.O., Sweeney, C., Karion, A., Davis, K.J., Stirm, B.H., Montzka, S.A., and Miller, B. 2014. Toward a better understanding and quantification of methane emissions from shale gas development. *Proceedings of the National Academy of Sciences* 111: 6237-6242, doi:10.1073/pnas.1316546111

21. Plant, G., Kort, E.A., Brandt, A.R., Chen, Y., Fordice, G., Negron, A.M.G., Schwietzke, S., Smith, M., and Zavala-Araiza, D. 2022. Inefficient and unlit natural gas flares both emit large quantities of methane. *Science* 377: 1566-1571, doi:10.1126/science.abq0385

22. Climate Action Council. 2021. Draft scoping plan, New York State Climate Action Council. https://climate.ny.gov/Our-Climate-Act/Draft-Scoping-Plan