Natural Gas and Global Warming

A Review of Evidence Finds that Methane Leaks Undercut the Climate Benefits of Gas

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Table of Contents

Executive Summary

Natural gas has been touted as a "bridge fuel" that can help the United States and the world reduce emissions of global warming pollutants during the transition to truly clean sources of energy. The "bridge fuel" argument, however, hinges on a critical assumption: that the climate impacts of natural gas are modest.

In recent years, a number of studies have challenged that assumption, finding that **natural gas production, transportation and storage results in major leaks of methane to the atmosphere** that erode or nullify the climate benefits of shifting to natural gas. These findings should lead policymakers to reject natural gas as a "bridge fuel" and instead lead them to **redouble America's efforts to repower with truly clean energy from the sun, the wind and other renewable sources of energy**.

Methane is a powerful global warming pollutant.

- Methane, the primary component of natural gas, traps 86 to 105 times more heat in the atmosphere over 20 years than does the same amount of carbon dioxide. As a result, even small methane leaks during the production, processing, storage and transportation of natural gas negate its low emissions of carbon dioxide during combustion.

Multiple studies, summarized in Table ES-1 and in greater detail in this report, find high methane leakage rates from both unconventional sources of natural gas, such as shale gas produced through fracking, and from conventional sources of gas that we've tapped for decades.

- "Conventional gas" is produced from reservoirs trapped underground. "Unconventional gas" is trapped in porous rock such as shale or tight sands, which must be fractured to free the gas.
- Aircraft-based air sampling over Colorado's Front Range allowed researchers from the University of Colorado (CU) Boulder, the National Oceanic and Atmospheric Administration (NOAA), and the University of California, Davis to estimate that 4.1 percent of natural gas produced in the area escapes into the atmosphere.
- In southwestern Pennsylvania, an area with extensive fracking activity, researchers from Purdue, Cornell, CU Boulder, Penn State and NOAA estimate that 7 percent of natural gas produced in the region escapes to the atmosphere.
- High methane emissions don't occur just from natural gas obtained through fracking. A team at Carnegie Mellon has calculated that from 1985 to 1999—*before* the boom in high-volume hydraulic fracturing—global methane leakage rates could have been as high as 9.3 percent.

Several studies that have found a substantial global warming emission benefit from natural gas compared to other fossil fuels have used questionable assumptions or methodologies.

- A study conducted by a team from the University of Texas, Austin that found very low methane leakage rates relied on data from a small number of wells that had been selected by oil and gas companies with an incentive to minimize estimates of leakage.

- That same study drew from Environmental Protection Agency emissions estimates that have been found to greatly underestimate emissions.

- A number of analyses that show modest emissions from natural gas make overly optimistic assumptions about total lifetime gas production from each gas well, compared to data from two different federal agencies. Overestimating lifetime production lowers the calculated life-cycle emissions of electricity produced from natural gas.

The rising doubts about the climate benefits of natural gas raise the level of urgency for the United States to implement clean, renewable sources of energy—such as solar and wind power—with unambiguous benefits for the global climate. In addition, the United States should slow efforts to develop gas resources using dangerous technologies such as fracking that have major impacts on public health and the environment.

Table ES-1. Summary of Recent Studies Showing High Methane Emissions from Natural Gas (methane leakage as a percent of natural gas produced)

Lead Author	Publication Date	Conventional Gas	Unconventional Gas
Karion	2013		8.9%U
Caulton	2014		7%U
Howarth	2011	3.9%	5.8%
Howarth	2015		12%
Jeong	2014	5.3%	
Pétron	2014		4.1%
Pétron	2012		4.0%
Skone	2012	4.5%	3.9%
Hultman	2011	4.6%	2.8%
Peischl	2015		0.2%-2.8%
Burnham	2012	2.8%	2.0%
Schwietzke	2014	2-4%	
Jiang	2011	2.2%	
Laurenzi	2013		1.4%
Stephenson	2011		0.7%
Allen	2013		0.4%U
Zavala-Araisa	2015		0.4%

The table shows the percentage of produced natural gas that is lost to the atmosphere.

"U" indicates the methane leakage estimate is for "upstream" emissions from gas production and processing only. Therefore, total emissions—including "downstream" emissions from natural gas storage, transmission and distribution—are higher than listed here.

Does Burning Natural Gas Benefit the Climate?

Natural gas has been promoted as a "bridge fuel" that can help the U.S. reduce global warming pollution by replacing coal-fired electricity generation, curb its dependence on oil, and buy time for the country to develop more wind, solar and other clean energy sources. However, recent studies raise serious doubts about the degree to which natural gas is less damaging to the global climate than other fossil fuels.

The "Bridge Fuel" Argument: Gas Reduces Carbon Dioxide Emissions

The argument that natural gas could be a useful tool to lower global warming emissions gained some early prominence from a 2010 Massachusetts Institute of Technology study, funded in part by the natural gas industry, which modeled how gas might replace coal if the nation adopted policies to reduce global warming pollution.[1] In his 2014 State of the Union address, President Obama called natural gas "the bridge fuel that can power our economy with less of the carbon pollution that causes climate change."[2] Since then, the "bridge fuel" argument has persisted in the debate over natural gas' role in our energy system.[3]

The argument that natural gas can help us reduce climate impacts rests on the fact that combustion of natural gas releases less global warming pollution than other fossil fuels. Burning natural gas to generate electricity produces less than half as much carbon dioxide as generating the same amount of electricity by burning coal.[4] (In addition, natural gas-fired power plants produce less of the air pollution that threatens public health, such as nitrogen oxides, sulfur dioxide and mercury.) When used to power vehicles, natural gas releases 19 percent less carbon dioxide per mile than a gasoline-powered vehicle.[5]

However, comparing the carbon dioxide emissions from burning natural gas and coal tells only part of the story. To truly evaluate the global warming impact of various fuels and energy consumption pathways, one must conduct **life-cycle analysis** that totals **all forms** of global warming pollution (not just carbon dioxide) released during production, storage and transportation of the fuel from extraction to the ultimate point of use.

Methane Emissions and Varying Time Scales of Global Warming

While carbon dioxide emissions are the leading cause of global warming, other air pollutants also contribute to climate change to varying degrees and over varying lengths of time.

Methane—the leading component of natural gas—is a global warming pollutant far more potent than carbon dioxide, but one that also does not last as long in the atmosphere. Over the course of 100 years, methane is 34 times more potent than carbon dioxide in its heat-trapping ability.[6] But over the course of 20 years, methane has 86 to 105 times the global warming potential of the same quantity of carbon dioxide.[7]

Typically, the 100-year timescale is used in assessments of the impact of various technologies and fuels on global warming. However, there are very good reasons to be equally concerned about the impacts of global warming pollution over shorter spans of time.

Temperature increases over the next few decades have the potential to push the climate past "tipping points"—such as the release of methane deposits frozen in the ocean or in Arctic permafrost—that could trigger further warming. According to a United Nations analysis, continuing emissions of methane and black carbon (another global warming pollutant) at the current rate—regardless of whether carbon dioxide emissions are controlled—will cause a 2.7°F (1.5°C) temperature increase by 2030 and a 3.6°F (2.0°C) increase by 2045 or 2050.[8] Warming of this magnitude could push the earth past climate tipping points.[9] One analysis suggests that the earth could reach such tipping points with 3.2°F (1.8°C) of warming.[10] (See Figure 1.) Keeping temperature increases below the level that could trigger additional warming can limit the amount of long-term warming that occurs.

A critical way to limit short-term warming is to control methane emissions. According to the Intergovernmental Panel on Climate Change, over the next 20 years, methane pollution will have nearly as much influence on the climate as will carbon dioxide.[12] That means that to avoid reaching climatic tipping points in the next few decades, methane emissions matter as much as carbon dioxide—and the decisions we make about natural gas in the next 20 years will influence what happens to the climate in 100 years.

Figure 1. Avoiding Climate Tipping Points Requires Immediate Reductions in Methane Emissions[11]

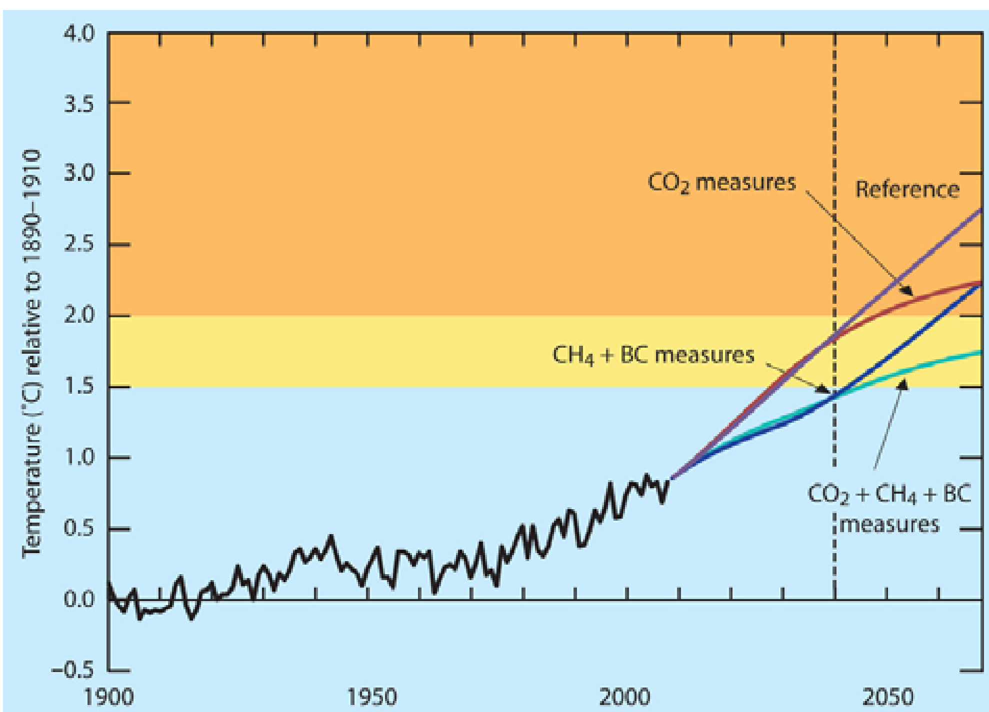

Figure 1 shows observed global temperatures through 2009 and projected temperatures under several scenarios. The threshold for key tipping points is shown with yellow shading. Immediate measures to reduce in methane (CH_4) and black carbon (BC) emissions are critical for slowing temperature increases in the next several decades (blue line). Curbing carbon dioxide (CO_2) emissions is critical for limiting longer term temperature rise, but will not produce changes quickly enough to avoid reaching tipping points before 2050 (red line).

Life-Cycle Emissions from Natural Gas Matter over All Time Scales

Producing, processing, storing, transporting and distributing natural gas can all contribute to methane pollution. Compared to a liquid like oil, a gas like methane can escape from a pipeline or a valve with relative ease. A minor crack or a pinprick hole creates an opportunity for gas to escape. Natural gas is colorless and odorless (until mercaptan, which has a sulfurous smell, is added) and therefore leaks are hard to detect without special equipment.

Table 1 shows the activities and equipment involved in handling gas, all of which present opportunities for methane to leak and contribute to the life-cycle emissions of natural gas. Emissions from the well site and from processing natural gas are often called "upstream" emissions, while leaks from storage, transmission and distribution are called "downstream" emissions.

For natural gas to be considered an unambiguous winner for the climate—and therefore, a useful "bridge fuel" —it should provide benefits in both the short term and the long term. Numerous studies, however, have cast doubt on whether natural gas use delivers climate benefits over a 20-year timeframe, while a few suggest that even the benefits over a 100-year timeframe may be minimal.

Table 1. Numerous Activities and Equipment Add to the Life-Cycle Global Warming Impact of Natural Gas. Table from Heath et al.[13]

Pre-production	Production	Processing	Transmission & Distribution
Drilling	Separators	Gathering lines	Pipeline leakage
Well construction	Engines	Pneumatic devices	Engines/turbines
Hydraulic fracturing*	Pneumatic devices	Fugitives	Meters
Completion flowback*	Liquids unloading	Engines/turbines	
Wastewater transport and reinjection or treatment	Refracturing/ recompletion*	Heaters	
	Chemical injection pumps	Gas treatment	
	Storage tanks (NG liquids, produced water, oil)	Storage tanks (NG liquids, produced water, oil)	
	Compressors and compressor blowdowns	Compressors and compressor blowdowns	
	Vessel and pipeline blowdowns		
	Heaters		
	Dehydrators		
	Flares		
	Fugitives		

* Indicates activities/equipment unique to fracking.

Recent Studies Show High Methane Leaks

When production of natural gas through the use of high-volume hydraulic fracturing expanded in the mid-2000s, little research had been conducted on the full impacts of this gas production method. As the practice spread to tens of thousands of wells across the United States, researchers began to look at the global warming impacts of natural gas produced through fracking—and to take a new look at gas production from conventional sources.

The first assessment of the life-cycle global warming impacts of unconventional gas production—gas trapped in shale, tight sands or coalbed methane—was published in 2011 by professors at Cornell University. That study's lead author, Robert Howarth, noted in a later journal article that, as of 2011, little research had been conducted on the life-cycle emissions of conventional natural gas, either.[14] In the years since, there have been numerous studies of life-cycle emissions of both unconventional and conventional natural gas, raising doubt about the degree to which natural gas, regardless of its source, provides a benefit for the climate.

Howarth and his colleagues estimated that 3.8 percent (with a range of 1.7 to 6 percent) of

Photo: Stephanie Gaswirth/USGS

Fugitive emissions released when a well is drilled are just one source of methane pollution from natural gas.

conventional natural gas is lost to the atmosphere and that 5.8 percent (with a range of 3.6 to 7.9 percent) of gas obtained from shale formations is lost.[15] Based on these rates, U.S. natural gas production would have leaked 1.5 trillion cubic feet of methane in 2014, resulting in 100-year global warming potential equivalent to 956 million metric tons (MMT) of carbon dioxide or 251 coal-fired power plants.[16] The 20-year global warming potential (for which methane is much more potent) of this quantity of leaked methane is equivalent to 2,418 MMT of carbon dioxide, or more than the amount of carbon dioxide released by all U.S. electricity generation in 2014.[17] In a paper revisiting his 2011 study and evaluating its findings against more recent research, Howarth concludes that "both shale gas and conventional natural gas have a larger GHG [footprint] than do coal or oil, for any possible use of natural gas."[18]

A number of researchers have subsequently undertaken extensive data collection efforts to document methane leaks and to better substantiate estimates of life-cycle emissions from natural gas. Many studies have found high methane leakage rates:

- Data from an air sampling tower operated by the National Oceanic and Atmospheric Administration (NOAA) and air samples collected throughout an oil and gas field in Colorado's Front Range showed methane emissions equal to 4 percent (with a range of 2.3 to 7.7 percent) of the natural gas produced in the region in 2008.[19]
- Aircraft-based air sampling in May 2012 over the same region allowed researchers from the University of Colorado (CU) Boulder, NOAA and the University of California (UC), Davis to estimate a very similar leakage rate of 4.1 percent (with a range of to 2.6 to 5.6 percent).[20]
- Flights over Uintah County, Utah, in February 2012 to collect data on methane leakage from natural gas fields allowed researchers from CU Boulder, NOAA and UC Davis to estimate that 8.9 percent (with a range of 6.2 to 11.7 percent) of gas produced in the region is lost to the atmosphere.[21] The study did not estimate downstream emissions.
- Researchers from Purdue, Cornell, CU Boulder, Penn State and NOAA measured upstream methane leakage in June 2012 over southwestern Pennsylvania, an area with extensive fracking activity. By combining their observations with industry-reported production data and an estimate of how much methane comes specifically from oil and gas production (in addition to livestock), the researchers estimated that 7 percent (with a range of 2.8 to 17.3 percent) of natural gas produced in the region escapes to the atmosphere.[22]
- In a 2015 study, Howarth estimated that 12 percent of shale gas production is lost to the atmosphere, based on a 2014 study by Oliver Schneising that relied on satellite data to estimate methane leakage from North American shale formations.[23] Schneising's study found that atmospheric methane concentrations in major shale-producing regions grew dramatically after 2008, a period of heavy shale oil and gas well development. In his 2015 study, Howarth notes that "satellite data provide the most robust estimates for upstream methane emissions from shale gas operations" because the variability of drilling site leakage rates limits the accuracy of short term analyses, both bottom-up and top-down.
- Another study using satellite-based measurements documented a 30 percent increase methane emissions in the past decade, particularly in the central U.S. where oil and gas production has increased.[24]

These studies have not been without their critics. Regarding the 2008 estimate from Colorado's Front Range, concern has been raised that the estimated leakage rate is not adjusted for background levels of naturally occurring methane in the atmosphere. In

Photo: Jeff Foster/Flickr/CC BY 2.0

Researchers are able to adjust atmospheric methane measurements to account for emissions from oil and gas production versus methane from livestock.

reality, the critics argue, methane from oil and gas production is likely closer to 2 percent than 4 percent.[25] The authors themselves acknowledged that their study relied on "unverifiable assumptions" and revised their approach in their more recent study of the same area, producing results comparable to those of the initial study.[26]

Though the results from Uintah County have generally been accepted as accurate, they have been criticized as being unrepresentative of emissions nationally.[27] The Pennsylvania findings have been questioned as possibly showing emissions from unused coal mines rather than active oil and gas wells, though the authors disagree.[28]

Researchers at Carnegie Mellon University and the National Oceanic and Atmospheric Administration published new findings in June 2014 using a different approach. The four authors used global methane and ethane measurements over three decades to estimate methane emissions from natural gas production and use. Their conclusion is that methane emissions from the natural gas production life-cycle since 2000 have ranged from 2 to 4 percent globally, though they may have been as high as 5 percent from 2006 to 2011.[29]

High methane emissions don't occur just from natural gas obtained through fracking. The global data analyzed by the Carnegie Mellon team suggest that all natural gas production and use is problematic. From 1985 to 1999—*before* the boom in high-volume hydraulic fracturing—the researchers estimate that methane emissions from the natural gas life-cycle could have been as high as 9.3 percent.[30]

A separate study of methane emissions in California—where, the authors contend, the "oil and gas infrastructure is arguably subject to the most comprehensive emissions control regulations in the U.S."—also found high emissions from conventional gas production. The authors estimated an upstream leakage rate of 5.3 percent for natural gas produced using conventional methods at wells containing both oil and gas in 2010.[31] (Note that they included storage in their estimate of upstream emissions, even though storage typically is included as an element of downstream emissions.) The Lawrence Berkeley National Laboratory-based researchers obtained the best available data regarding production, processing and transmission activities, and infrastructure in California, and applied a mix of state and national emissions factors to each stage of natural gas handling to arrive at their estimate.

The results of these studies suggest that, on either a 20-year or 100-year timescale, the life-cycle emissions of natural gas used for electricity production are significant enough to preclude natural gas as a useful tool to prevent the worst impacts of global warming. With even a relatively low leakage rate of 2 percent, annual methane leaked in the U.S. from natural gas production would have the 100-year global warming pollution equivalent of 86 million cars.[32]

Studies Showing Low Methane Leaks Have Important Limitations

Studies showing natural gas is bad for the climate due to high methane leakage rates have been contradicted by other studies showing more modest methane emissions from natural gas.[33] However, studies showing low methane leakage rates have serious limitations that raise questions about their conclusions.

In 2013, for example, a team led by Professor David Allen and other researchers from the University of Texas, Austin worked in collaboration with the Environmental Defense Fund and oil and gas companies to measure methane emissions from selected drilling sites. The study reported very low average leakage rates and, when coupled with EPA estimates for methane emissions from other stages of natural gas production, led the researchers to conclude that methane leaks account for just 0.42 percent of gas production.[34] This 0.42 percent leakage rate is just for production; once leaks from processing, transmission, storage, and distribution are accounted for the leakage rate is marginally higher, although still under 2 percent. There are several important concerns with this study:

- First, the emissions estimates were based on a small sample size (just 190 well locations or activities) and were carried out at facilities approved for study by oil and gas companies with an incentive to minimize estimates of leakage. Other research has suggested that a large share of fugitive emissions may come from a small number of faulty pieces of equipment—precisely the kinds of equipment likely to be screened out of a small, industry-approved group of wells.[35] One study measured leaks from 75,000 individual components used at natural gas well sites, compressor stations and gas processing plants, revealing that 0.06 percent of the devices were responsible for 58 percent of the documented pollution. And a 2015 study of Texas' Barnett Shale found that 19 percent of methane emissions come from just 2 percent of sites.[36] In other words, even if more than 99 percent of components operate perfectly, emissions still can be high because of the failure of a handful of devices.[37] As a result, Professor Allen's study may document how low emissions could be in a best case scenario, not what emissions are in standard practice or on average.

- Second, the EPA data from which downstream emissions were calculated after the gas left drilling sites likely underestimates emissions. A separate analysis by researchers from Stanford, the National Renewable Energy Laboratory (NREL), the University of Michigan and other institutions that compared measured emissions in multiple studies to EPA's national greenhouse gas inventory found that actual emissions were 50 percent greater than reported in the inventory.[38]

- Third, the emission estimates could be missing other leak sources—for example, from abandoned wells. A 2014 study led by Mary Kang from Princeton University measured methane flows from abandoned oil and gas wells in Pennsylvania.[39] If leakage from these Pennsylvania wells is assumed to be representative of leakage from the approximately 3 million abandoned wells in the U.S., methane from abandoned wells could increase Allen's estimate by more than 10 percent.[40] Allen's study and other studies that base emission estimates on short-term analyses of specific gas well components likely miss emissions that can only be found using broader and longer-term methodologies.

Another study attempted to overcome the limitations of individual research papers by standardizing and aggregating the results of many different analyses. The meta-analysis, conducted by researchers at NREL and an institute founded by NREL, CU Boulder and other prominent universities, includes eight diverse peer-reviewed studies plus one previous meta-analysis.[41] The researchers harmonized the results of the studies by applying consistent power plant efficiency estimates, standardizing the estimated global warming potential of methane, converting all results to the same units, presenting the results based on 100-year impacts, and making other changes to enable full comparison of the studies. Of the eight studies included, the researchers found methane leakage rates of between 0.66 and 6.2 percent.

Photo: Bill Cunningham/USGS

Every pipe joint, whether at a conventionally or unconventionally drilled well, has the potential to leak methane.

The results of the NREL study are dependent upon the assumptions made in the source studies about the likely total production from each gas well, and those studies may have overestimated lifetime production. Bringing a new well into production releases methane into the atmosphere. If a well produces copious amounts of natural gas over its lifetime, then the initial surge in emissions is spread over a large amount of electricity generation or other uses of natural gas, and the life-cycle emissions attributed to each unit of final energy consumption are relatively low. But if a well doesn't produce much gas, then those initial methane releases result in higher life-cycle emissions.

Multiple studies analyzed by the NREL researchers agree that the estimate of the total amount of gas likely to be produced from a well is one of the key assumptions in an analysis of life-cycle emissions from natural gas. Ian Laurenzi and Gilbert Jersey at ExxonMobil Research determined that projected total production per well was an influential factor in the outcome of their analysis, while Trevor Stephenson and his co-authors from Shell Global Solutions concluded that "emissions intensity is strongly affected by the ultimate recovery from a well."[42] Researchers at Argonne National Laboratory came to a similar conclusion.[43]

Many of the studies included in the NREL-led study assume greater gas production per well than is estimated by the U.S. Energy Information Administration (EIA) or the U.S. Geological Survey (USGS). For example, based on data for 222 Marcellus wells, Laurenzi and Jersey estimate the average Marcellus well will produce 1.8 billion cubic feet of gas. In contrast, an analysis of EIA and USGS data by J. David Hughes, a geoscientist who worked with the Geological Survey of Canada for decades, shows that total recoverable gas from Marcellus wells may be lower. EIA estimates production from Marcellus wells at 1.56 billion cubic feet per well, while USGS data provide a range of 0.129 to 1.16 billion cubic feet, 15 to 90 percent less than Laurenzi and Jersey's estimate.[44] Table 2 shows the gap between estimated gas production per well assumed in selected studies included in the NREL analysis, and the EIA and USGS estimates for those same shale plays.

If shale wells are less productive than assumed in the studies used in the NREL analysis, the climate benefits of natural gas would be much reduced.

The EPA Likely Underestimates Methane Emissions

Even the U.S. Environmental Protection Agency, which might be expected to have solid data, likely underestimates methane leakage. EPA's 2013 greenhouse gas inventory shows fugitive emissions equal to 1.3 percent of natural gas production.[48] There are several reasons why EPA's figures may be low.

First, the EPA relies on a bottom-up approach to measuring emissions, in which emissions estimates are based on measurements taken from specific instruments at well sites, rather than ambient methane concentrations around well sites.[49] Researchers have found flaws in the tools used to measure bottom-up emissions. One recent study published in *Energy Science & Engineering* found that one of the primary EPA-approved tools for measuring methane releases, the Bacharach Hi-Flow Sampler, significantly underestimates methane emissions in a variety of circumstances.[50] Also, as noted before in this paper's discussion of Allen et al., bottom-up approaches like the EPA's are likely to underrepresent the emission impact of the small number of high-emitting components, or "super-emitters."[51] Top-down studies, in which methane is measured from towers or plane flyovers, are able to capture emissions from unexpected sources such as venting or faulty equipment that wouldn't typically leak at all. One 2013 top-down study estimated that the EPA's inventory underestimates total methane emissions nationally by a factor of 1.5 to 1.7.[52]

Second, many of EPA's assumptions about emission rates and activities undertaken in the natural gas industry are from the early 1990s, when natural gas infrastructure and activities were quite different.[53] The EPA has been self-critical for basing its methodology on a nearly 20 year old study, which the agency says "has a high level of uncertainty."[54] One recent study estimated that emissions from the gathering and processing of natural gas are nearly double those contained in the EPA's Greenhouse Gas Inventory.[55]

Finally, the EPA approach relies on industry-supplied activity data, which is not independently verified, and could lead to underreporting of emissions.[56]

In short, while some studies show modest methane leakage rates from natural gas, the weaknesses and limitations of those studies do not provide the confidence necessary to embrace the "bridge fuel" strategy as a tool for addressing global warming.

Table 2. Comparison of Estimated Gas per Well in NREL-led Study versus Federal Estimates

Selected studies included in Heath et al.	Shale play(s)	Estimated gas per well (billion cubic feet/well)			Notes
		Researchers' estimate[45]	EIA estimate[46]	USGS estimate[47]	
Jiang et al.	Marcellus	2.7	1.56	1.158	USGS estimate shown is high end of range.
Laurenzi & Jersey	Marcellus	1.8	1.56	1.158	USGS estimate shown is high end of range.
Skone et al.	Barnett	3.0	0.30	2.034	USGS estimate is mean potential from sweet spots.
Heath et al. (2012)	Barnett	1.4	0.30	2.034	USGS estimate is mean potential from sweet spots.
Burnham et al.	Weighted average of Marcellus, Barnett, Haynesville and Fayetteville	3.5	2.67	2.617	EIA and USGS estimate shown is for Haynesville. Marcellus and Fayetteville are less productive per well.
Stephenson et al.	US shale gas	2.0	1.6	1.2	Unweighted average of productivity from 10 shale plays listed in PCI.

The Future Is Here: Truly Clean Energy

To avoid the worst impacts of global warming—and to keep global temperatures below critical tipping points—we must cut emissions from all sources swiftly. Unfortunately, the emission-reduction potential of natural gas is undermined by methane leaks and therefore it cannot serve as a reliable "bridge fuel" to help us curb fossil fuel emissions as other, less polluting sources are developed. That raises the urgency for the U.S. and the world to implement truly clean technologies (e.g., wind, solar, geothermal and energy efficiency) that can help us slash global warming pollution now and in the years to come.

The good news is that clean energy sources are widely available:

- The U.S. has the potential to generate up to 10 times more electricity from wind than is consumed in a year.[57]
- America has enough solar energy potential to power the nation several times over. Every one of the 50 states has the technical potential to generate more electricity from the sun than it uses.[58]
- Geothermal energy is also available across the nation.[59]

Use of these clean energy sources is growing rapidly.

- American wind capacity quadrupled from December 2007 to December 2015.[60]
- American solar capacity grew by 50 times over the same period.[61]

With the right mix of policies to curb global warming pollution, thereby reducing fossil fuel use, and promote renewable energy technologies, the U.S. can take full advantage of its clean energy resources and slash global warming pollution.

Notes

1. Joel Kirkland and ClimateWire, "Natural Gas Could Serve as a 'Bridge' Fuel to Low-Carbon Future," *Scientific American*, 24 June 2010, archived at web.archive.org/web/20160329233347/http://www.scientificamerican.com/article/natural-gas-could-serve-as-bridge-fuel-to-low-carbon-future.

2. President Obama, *State of the Union Address*, 28 January 2014, archived at web.archive.org/web/20160329233635/https://www.whitehouse.gov/the-press-office/2014/01/28/president-barack-obamas-state-union-address.

3. For example, in this October 2015 opinion piece by the former Massachusetts energy secretary: Rick Sullivan, "Natural Gas Is Crucial to Mass. Energy Grid," *Boston Globe*, 6 October 2015.

4. Based on 2012 generation and emissions data, per U.S. Department of Energy, Energy Information Administration, *United States Electricity Profile 2012*, 1 May 2014, archived at web.archive.org/web/20160329233918/https://www.eia.gov/electricity/state/unitedstates.

5. Based on a comparison of a 2014 Honda Civic natural gas car and its gasoline-powered counterpart. U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, *www.fueleconomy.gov*, accessed at www.fueleconomy.gov, 25 July 2014.

6. Gunnar Myhre et al., "Anthropogenic and Natural Radiative Forcing," in T.F. Stocker et al. (eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2013), 714.

7. 86: Ibid., 714; 105: Drew Shindell et al., "Improved Attribution of Climate Forcing to Emissions," *Science* 326: 716-718, doi: 10.1126/science.1174760, 2009.

8. As cited in Robert Howarth, "A Bridge to Nowhere: Methane Emissions and the Greenhouse Gas Footprint of Natural Gas," *Energy Science & Engineering* 2(2): 47-60, doi:10.1002/ese3.35, 22 April 2014.

9. James Hansen and Makiko Sato, "Greenhouse Gas Growth Rates," *Proceedings of the National Academy of Sciences*, 101(46): 16109-16114, doi: 10.1073/pnas.0406982101, 16 November 2014, and James Hansen et al., "Climate Change and Trace Gases," *Philosophical Transactions of the Royal Society*, 365(1856): 1925-1954, doi: 10.1098/rsta.2007.2052, 15 July 2007, as cited in Robert Howarth, "A Bridge to Nowhere: Methane Emissions and the Greenhouse Gas Footprint of Natural Gas," *Energy Science & Engineering* 2(2): 47-60, doi:10.1002/ese3.35, 22 April 2014, 54.

10. Ibid.

11. Robert Howarth, "A Bridge to Nowhere: Methane Emissions and the Greenhouse Gas Footprint of Natural Gas," *Energy Science & Engineering* 2(2): 47-60, doi:10.1002/ese3.35, 22 April 2014.

12. Intergovernmental Panel on Climate Change, *Climate Change 2013: The Physical Science Basis*, available at ipcc.ch/report/ar5/wg1/, 2013; as cited in Robert Howarth, "A Bridge to Nowhere: Methane Emissions and the Greenhouse Gas Footprint of Natural Gas," *Energy Science & Engineering* 2(2): 47-60, doi:10.1002/ese3.35, 22 April 2014, 54.

13. Garvin Heath et al., "Harmonization of Initial Estimates of Shale Gas Life Cycle Greenhouse Gas Emissions for Electric Power Generation," *Proceedings of the National Academy of Sciences*, 111(31): E3167-E3176, doi: 10.1073/pnas.1309334111, 21 April 2014.

14. See note 11, 47-48.

15. Ibid., 49. Professor Howarth and his colleagues analyzed the life-cycle emissions of natural gas from both conventional and unconventional sources. Their assessment includes methane from deliberate venting and accidental leaks during production, storage, processing and delivery of natural gas, and carbon dioxide emissions from burning gas and from equipment associated with gas production and use (such as construction equipment used to build pipelines). Data for the study came from information provided by the oil and gas industry to the Environmental Protection Agency and a Government Accountability Office report about methane losses from wells on public lands.

16. To calculate total methane leakage, U.S. 2014 natural gas production in cubic feet was multiplied by respective leakage rates (5.8 percent for shale, 3.8 percent for all other natural gas) and the products were converted to carbon dioxide equivalent using conversion factors from the EPA; to put this potential in terms of coal plants, global warming potential was divided by annual carbon dioxide emissions of a typical U.S. coal plant: Total natural gas production found in: U.S. Energy Information Administration, *Natural Gas Annual - Table 1. Summary statistics for Natural Gas in the United States, 2010-2014*, archived at web.archive.org/web/20160329234741/http://www.eia.gov/naturalgas/annual/pdf/table_001.pdf; methane cf conversion calculations: U.S. Environmental Protection Agency, *Methane Emissions Reductions Calculator Conversion Factors*, accessed 6 January 2016, archived at web.archive.org/web/20160330000451/https://www3.epa.gov/gasstar/tools/calculations.html; U.S. coal plant annual emissions: U.S. Environmental Protection Agency, *GHG Equivalencies Calculator - Calculations and References*, accessed 6 January 2016, archived at web.archive.org/web/20160330000447/https://www.epa.gov/energy/ghg-equivalencies-calculator-calculations-and-references; assuming methane has GWP of 34 for 100-year time frame and 86 for 20-year time frame: see notes 6 and 7.

17. Total carbon dioxide emissions from electricity generation in 2014 was 2046 MMT: U.S. Energy Information Administration, *Monthly Energy Review December 2015*, December 2015.

18. See note 11.

19. Gabrielle Pétron et al., "Hydrocarbon Emissions Characterization in the Colorado Front Range: A Pilot Study," *Journal of Geophysical Research*, 117(D4): D04304, doi: 10.1029/2011JD016360, 27 February 2012.

20. Gabrielle Pétron et al., "A New Look at Methane and Nonmethane Hydrocarbon Emissions from Oil and Natural Gas Operations in the Colorado Denver-Julesburg Basin," *Journal of Geophysical Research: Atmospheres* 119(11): 6836-6852, doi: 10.1002/2013JD021272, 3 June 2014.

21. Anna Karion et al., "Methane Emissions Estimate from Airborne Measurements over a Western United States Natural Gas Field," *Geophysical Research Letters*, 40(16): 4393-4397, doi: 10.1002/grl.50811, 28 August 2013.

22. Dana Caulton et al., "Toward a Better Understanding and Quantification of Methane Emissions from Shale Gas Development," *Proceedings of the National Academy of Sciences* 111(17): 6237-6242, doi: 10.1073/pnas.1316546111, 14 April 2014.

23. Robert Howarth et al., "Methane Emissions and Climatic Warming Risk from Hydraulic Fracturing and Shale Gas Development: Implications for Policy," *Energy and Emission Control Technologies*, doi: dx.doi.org/10.2147/

EECT.S61539, 1 July 2015; Oliver Schneising et al., “Remote Sensing of Fugitive Methane Emissions from Oil and Gas Production in North American Tight Geologic Formations,” *Earth’s Future*, doi: 10.1002/2014EF000265, 6 October 2014.

24. Alexander Turner et al., “A Large Increase in U.S. Methane Emissions over the Past Decade Inferred from Satellite Data and Surface Observations,” *American Geophysical Union*, doi: 10.1002/2016GL067987, 6 February 2016.

25. Michael Levi, “Comment on ‘Hydrocarbon Emissions Characterization in the Colorado Front Range: A Pilot Study’ by Gabrielle Pétron et al.,” *Journal of Geophysical Research*, 117(D21): 16, doi: 10.1029/2012JD017686, 16 November 2012, and Lawrence Cathles, *Comments on Petron et al.’s (2012) Inference of Methane Emissions from the Denver-Julesburg Basin from Air Measurements at the Boulder Atmospheric Observatory Tower*, 6 March 2012. Available at http://www.geo.cornell.edu/eas/PeoplePlaces/Faculty/cathles/Gas%20Blog%20PDFs/0.3%20Comments%20on%20Petron%20et%20al.pdf.

26. See note 20.

27. Lawrence Cathles, *The 8% vs 2% Debate: Comments on Selected Papers*, accessed at http://www.geo.cornell.edu/eas/PeoplePlaces/Faculty/cathles/Gas%20Blog%20PDFs/9_lit_rev%20Comments%20on%20selected%20Papers.pdf, 1 August 2014; Lawrence Cathles, *Letter and Reply re Brandt et al, 2014*, accessed at http://www.geo.cornell.edu/eas/PeoplePlaces/Faculty/cathles/Gas%20Blog%20PDFs/Brandt%20et%20al%20Science%20Exchange.pdf, 1 August 2014.

28. Andrew Revkin, “A Deeper Look at a Study Finding High Leak Rates from Gas Drilling,” *New York Times Dot Earth* (blog), 23 April 2014.

29. Stefan Schwietzke et al., “Natural Gas Fugitive Emissions Rates Constrained by Global Atmospheric Methane and Ethane,” *Environmental Science & Technology* 48(14): 7714-7722, doi: 10.1021/es501204c, 19 June 2014.

30. Ibid.

31. Seongeun Jeong, Dev Millstein and Marc Fischer, “Spatially Explicit Methane Emissions from Petroleum Production and the Natural Gas System in California,” *Environmental Science & Technology*, 48: 5982-5990, doi: 10.1021/es4046692, 23 April 2014.

32. For calculation methodology see note 16; same methodology was used, except assuming a 2 percent leakage rate for all natural gas production.

33. Daniel Zavala-Araisa et al., “Allocating Methane Emissions to Natural Gas and Oil Production from Shale Formations,” *SCA Sustainable Chemistry & Engineering*, doi: 10.1021/sc500730x, 28 January 2015; Nathan Hultman et al., “The Greenhouse Gas Impact of Unconventional Gas for Electricity Generation,” *Environmental Research Letters*, doi: 10.1088/1748-9326/6/4/044008, 25 October 2011; J. Pesichl et al., “Quantifying Atmospheric Methane Emissions from the Haynesville, Fayetteville, and Northeastern Marcellus Shale Gas Production Regions,” *Journal of Geophysical Research: Atmospheres*, doi: 10.1002/2014JD022697, 13 March 2015.

34. David Allen et al., “Measurements of Methane Emissions at Natural Gas Production Sites in the United States,” *Proceedings of the National Academy of Sciences*, 110(44): 17768-17773, doi: 10.1073/pnas.1304880110, September 2013.

35. Daniel Zimmerle et al., “Methane Emissions from the Natural Gas Transmission and Storage System in the United States,” *Environmental Science & Technology*, doi: 10.1021/acs.est.5b01669, 21 July 2015.

36. David Lyon et al., “Constructing a Spatially Resolved Methane Emission Inventory for the Barnett Shale Region,” *Environmental Science and Technology*, doi: 10.1021/es506359c, 7 July 2015.

37. National Gas Machinery Laboratory, Clearstone Engineering and Innovative Environmental Solutions, *Technical Report: EPA Phase II Aggregate Site Report: Cost-*

Effective Directed Inspection and Maintenance Control Opportunities at Five Gas Processing Plants and Upstream Gathering Compressor Stations and Well Sites, for U.S. Environmental Protection Agency, March 2006, as cited in Adam Brandt et al., "Methane Leaks from North American Natural Gas Systems," *Science*, 343: 733-735, doi: 10.1126/science.1247045, 14 February 2014.

38. Adam Brandt et al., "Methane Leaks from North American Natural Gas Systems," *Science*, 343: 733-735, doi: 10.1126/science.1247045, 14 February 2014.

39. Mary Kang et al., "Direct Measurements of Methane Emissions from Abandoned Oil and Gas Wells in Pennsylvania," *Proceedings of the National Academy of Sciences*, 111(51): 18173-18177, doi: 10.1073/pnas.1408315111, 8 December 2014.

40. 3 million abandoned wells: Adam Brandt et al., "Methane Leaks from North American Natural Gas Systems – Supplementary Materials," *Science* 343(6172): 733-735, doi: 10.1126/science.1247045, 14 February 2014.

41. See note 13.

42. Ian Laurenzi and Gilbert Jersey, "Life Cycle Greenhouse Gas Emissions and Freshwater Consumption of Marcellus Shale Gas," *Environmental Science & Technology*, 47(9): 4896-4903, doi: 10.1021/es305162w, 2 April 2013; and Trevor Stephenson et al., "Modeling the Relative GHG Emissions of Conventional and Shale Gas Production," *Environmental Science & Technology*, 45(24): 10757–10764, doi: 10.1021/es2024115, 15 November 2011.

43. Heath et al. cite A. Burnham et al., "Life-cycle Greenhouse Gas Emissions of Shale Gas, Natural Gas, Coal and Petroleum," *Environmental Science & Technology*, 46(2): 619-627, 2012. That same group of authors published a fuller explanation of their work, which we relied upon here, in C.E. Clark et al., Argonne National Laboratory, *Life-cycle Analysis of Shale Gas and Natural Gas,* December 2011.

44. J. David Hughes, *Drill, Baby, Drill: Can Unconventional Fuels Usher in a New Era of Energy Abundance* (Santa Rosa, CA: Post Carbon Institute, February 2013), 76.

45. Data on studies from Garvin Heath et al., "Harmonization of Initial Estimates of Shale Gas Life Cycle Greenhouse Gas Emissions for Electric Power Generation," *Proceedings of the National Academy of Sciences*, 111(31): E3167-E3176, doi: 10.1073/pnas.1309334111, 21 April 2014.

46. EIA estimates for all plays except Barnett are from J. David Hughes, *Drill, Baby, Drill: Can Unconventional Fuels Usher in a New Era of Energy Abundance* (Santa Rosa, CA: Post Carbon Institute, February 2013), 76. EIA data for Barnett from U.S. Energy Information Administration, *Assumptions to the Annual Energy Outlook 2015*, September 2015, 133. Archived at web.archive.org/web/20160226224515/https://www.eia.gov/forecasts/aeo/assumptions/pdf/oilgas.pdf.

47. USGS estimates for all plays except Barnett are from J. David Hughes, *Drill, Baby, Drill: Can Unconventional Fuels Usher in a New Era of Energy Abundance* (Santa Rosa, CA: Post Carbon Institute, February 2013), 76. USGS data for Barnett from U.S. Geological Survey, *National and Global Petroleum Assessment: Assessment of Undiscovered Shale Gas and Shale Oil Resources in the Mississippian Barnett Shale, Bend Arch–Fort Worth Basin Province, North-Central Texas*, dx.doi.org/10.3133/fs20153078, December 2015. EUR is mean for wells located in the play's sweet spot. EUR for wells outside the sweet spot is 0.956 bcf.

48. According to the EPA's inventory of U.S. emissions and sinks, there were 6.3 MMT of methane leaks in 2013; according to the Energy Information Administration, there were 25,562,232 million cubic feet of marketed natural gas production in 2013, which is roughly equivalent to 493 MMT. Emissions inventory: EPA, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2013*, 15 April 2015, archived at web.archive.org/web/20160330002040/https://www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2015-Main-Text.pdf; methane volume to weight conversion: EPA, *Coalbed Methane Outreach Program: Interactive Units Converter*, archived at

web.archive.org/web/20160330004709/https://www3.epa.gov/cmop/resources/converter.html; natural gas production: EIA, *U.S. Natural Gas Marketed Production*, archived at web.archive.org/web/20160330005235/http://www.eia.gov/dnav/ng/hist/n9050us2a.htm. Our calculation here of leakage in 2013 is the same as the 2012 leakage rate reported in Daniel Zimmerle et al., "Methane Emissions from the Natural Gas Transmission and Storage System in the United States," *Environmental Science & Technology*, doi: 10.1021/acs.est.5b01669, 21 July 2015.

49. Technical document with methodology is available here: EPA, *Methane Emissions from the Natural Gas Industry*, June 1996, archived at web.archive.org/web/20160330005334/https://www3.epa.gov/gasstar/documents/emissions_report/2_technicalreport.pdf.

50. Touché Howard et al., "Sensor Transition Failure in the High Flow Sampler: Implications for Methane Emission Inventories of Natural Gas Infrastructure," *Journal of the Air & Waste Management Association*, doi: 10.1080/10962247.2015.1025925, 2015.

51. A.R. Brandt et al., "Methane Leaks from North American Natural Gas Systems," *Science*, doi: 10.1126/science.1247045, 14 February 2014.

52. Scot Miller, "Anthropogenic Emissions of Methane in the United States," *PNAS*, doi: 10.1073/pnas.1314392110, 10 December 2013.

53. See note 35.

54. Rick Beusse et al., EPA Office of Inspector General, *Improvements Needed in EPA Efforts to Address Methane Emissions From Natural Gas Distribution Pipelines*, 25 July 2014, archived at web.archive.org/web/20160330005545/https://www.epa.gov/sites/production/files/2015-09/documents/20140725-14-p-0324_0.pdf.

55. Anthony Marchese et al., "Methane Emissions from United States Natural Gas Gathering and Processing," *Environmental Science & Technology*, doi: 10.1021/acs.est.5b02275, 18 August 2015.

56. Bobby Magill, "EPA Moves to Count Methane Emissions from Fracking," *Scientific American,* 8 January 2015, archived at web.archive.org/web/20160330005637/http://www.scientificamerican.com/article/epa-moves-to-count-methane-emissions-from-fracking/.

57. American Wind Energy Association, *Get the Facts*, accessed 30 July 2014, archived at web.archive.org/web/20160330005736/http://www.awea.org/Resources/Content.aspx?ItemNumber=900.

58. Anthony Lopez et al., National Renewable Energy Laboratory, *U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis*, July 2012, archived at web.archive.org/web/20160330005850/http://www.nrel.gov/docs/fy12osti/51946.pdf.

59. Ibid.

60. U.S. Department of Energy, *Installed Wind Capacity*, accessed 21 January 2016, archived at web.archive.org/web/20160330005938/http://apps2.eere.energy.gov/wind/windexchange/wind_installed_capacity.asp.

61. SEIA, *U.S. Solar Market Insight: U.S. Installs 1.3 GW in Q3, Headed Toward Record-Breaking 2015*, accessed at seia.org/research-resources/us-solar-market-insight on 21 January 2016.