

Chapter 6: Methane and Climate Change

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The start of the shale gas revolution coincided with the promotion of natural gas as a bridge fuel. According to those who promoted the bridge-fuel idea, natural gas (including shale gas) is a fuel that can replace coal and yet allow the continued use fossil fuels for a relatively short time until society can move to an economy powered entirely by renewable energy. While it is true that using natural gas instead of coal or oil lowers emissions of carbon dioxide, natural gas is composed mostly of a very powerful greenhouse gas in itself – methane -- which is inevitably emitted into the atmosphere from the production and use of natural gas.

The first peer-reviewed analysis of how methane emissions affect the greenhouse gas footprint of shale gas was published by my colleagues and I in 2011. We suggested that methane emissions from shale gas, as well as from conventional natural gas, were probably great enough to completely offset any climate advantage that might accrue from reducing carbon dioxide emissions from a switch from coal to natural gas. The paper has stimulated further investigation in the subsequent nine years, with a growing number of research papers on this topic, as reviewed here. The initial conclusion that methane emissions from both shale gas and conventional natural gas make these very poor bridge fuels continues to hold true. The greenhouse gas footprint of shale gas is worse than that of coal, when methane emissions are considered and compared to carbon dioxide over an integrated 20-year time period after emission.

Over the past decade, shale gas has come to dominate natural gas production in the United States, and this increase production of US shale gas has made up almost two thirds of the increased natural gas production globally. Coincident with this time frame, atmospheric methane concentrations have been increasing, after remaining level for the first decade of the 21st Century. Increased emissions from shale gas produc-

tion in North America alone have probably caused roughly 40% of total global increase in atmospheric methane from all sources. These increasing methane emissions make it substantially more difficult to reach the COP21 target of keeping the Earth well below 2° C compared to the pre-industrial baseline. Unless methane emissions can be drastically reduced, shale gas is not a viable option in a climate-smart future.

Keywords: shale gas, fossil gas, natural gas, methane, greenhouse gas emissions

6.1 Introduction

The beginning of the shale gas revolution coincided in time with the promotion of natural gas as a “bridge fuel.” Not only the oil and gas industry but political leaders, including both President G. W. Bush and President Obama, argued that society could substitute natural gas for coal, thereby continuing to use fossil fuels as a bridge while reducing greenhouse gas emissions for some period of time until the world could better rely on renewable energy. Part of this premise is true: to gain the same amount of energy, less carbon dioxide emissions are released from burning natural gas compared to either coal or oil (Hayhoe et al. 2002). However, the continued reliance on any fossil fuel, including shale gas or conventional natural gas, is an outdated concept. The atmosphere already contains so much carbon dioxide from the fossil fuels burned to date that even a few more years of carbon dioxide emissions at current rates will lock the world into a global average of warming 1.5 degrees Celsius (2.7 degrees Fahrenheit) above pre-industrial levels (Hausfather 2018). Beyond this, natural gas – including shale gas – is overwhelmingly composed of methane, and some of this methane is inevitably released to the atmosphere as the gas is developed and used. Methane is an incredibly powerful greenhouse gas, 120-fold more powerful than carbon dioxide compared mass-to-mass when both gases are in the atmosphere (IPCC 2013). Consequently, methane emissions from both shale gas

and conventional natural gas can more than counteract advantage of lower carbon dioxide emissions from using natural gas. Rather than serving as a bridge fuel, the use of gas may accelerate global warming in the next few decades.

Both methane and carbon dioxide are important drivers of global change. The radiative forcing of methane is approximately 1 watt per square meter when the indirect effects of methane are included, compared to approximately 1.66 watts per square meter for carbon dioxide, and methane has contributed roughly 25% of the warming seen over recent decades (IPCC 2013). However, the gases behave quite differently, and the climate system responds far more quickly to changes in emissions of methane compared to carbon dioxide (Shindell et al. 2012; IPCC 2018). Consequently, a reduction in methane emissions would significantly slow the rate of global warming almost immediately, while reducing carbon dioxide emissions would only slow global warming decades later.

In December 2015, the nations of the world came together in Paris under the COP21 agreement to pledge to try to keep the Earth well below 2° C from the pre-industrial baseline, with the clear acknowledgement that warming to even 1.5° poses significant risks. These risks include large social disruption caused by more extreme weather events and possible food and water shortages, as well as an increasing probability of fundamental changes in the climate system, leading to runaway catastrophic change over the long term as important thresholds are exceeded. These risks become more severe as the Earth's temperature rises above 1.5° C from the pre-industrial baseline, which is predicted to occur within 10 to 20 years from now, by 2030 or 2040 (Shindell et al. 2012; IPCC 2018). Again, because of the relatively fast response of the climate to methane, reducing methane emissions can help provide a pathway to reaching the COP21 climate goal (Collins et al. 2018).

6.2 Sources of methane

While some atmospheric methane comes from natural sources, 60% or more comes from human-controlled sources such as fossil fuels, agriculture, landfills, sewage treatment plants, and biomass burning (Kirschke et al. 2013; Begon et al. 2014). Atmospheric methane concentrations remained level for the first ten years of the 21st century, but over the past decade or so, methane concentrations have been rising rapidly. Evidence from changes in the carbon-13 stable isotopic composition of atmospheric methane suggests that emissions from the natural gas industry may be the largest driver of this recent increase in atmospheric methane (Howarth 2019). Other recently gained evidence—from carbon-14 radiocarbon dating of the methane content in glacial ice laid down before the Industrial Revolution—suggests that fossil fuel emissions of methane have historically been significantly underestimated. Specifically, the ice-core studies show virtually no fossil methane before the industrial revolution (Petrenko et al. 2017; Hmiel et al. 2020). This means that natural emissions of fossil methane from geological seeps have always

been small, far less than the 50 Tg per year assumed in many global budgets. Since we know from the carbon-14 content of atmospheric methane at the end of the 20th Century that approximately 30% of emissions were from fossil sources (fossil fuels plus natural seeps; Lassey et al. 2007), if the seep emissions are smaller, the fossil-fuel emissions must be correspondingly larger than previously assumed. This larger estimate for methane emissions from fossil fuels of 50 Tg per year means that fossil fuels contribute approximately 40% more to global methane emissions than assumed in most prior budgets (Begon et al. 2014).

Some methane emissions are associated with the extraction of any fossil fuel. But for coal and petroleum products, methane is a minor contaminant, while natural gas—including shale gas—is composed overwhelmingly of methane. It therefore should not come as a surprise that some of this methane is released into the atmosphere as natural gas is developed and used. These emissions come both from leaks and from purposeful release—such as what occurs, for instance, during the venting of natural gas pipelines before performing routine maintenance, or to control the pressure in storage tanks. Often when industry purposefully releases methane to the atmosphere, they will flare it, that is burn the methane to convert it to carbon dioxide. However, flares sometimes do not remain lit, and unburned methane is instead emitted. A very graphic visual article published in late 2019 by the New York Times well documents such events (Kessel and Tabouchi 2019).

6.3 Early estimates of methane from shale gas

The first analysis of how much methane is emitted from the development of both shale gas and conventional natural gas was published in 2011 (Howarth et al. 2011). Shale gas is also a form of natural gas, but composed of methane that has remained trapped in shale rock over geological time frames, while conventional natural gas is methane that has migrated from the shale or other source rock to reservoirs where further migration is prevented by an impermeable barrier. Note that some of the older geological literature refers to any gas that originated in shale as “shale gas,” whether or not it has migrated out of the shale to another reservoir. Here, and in all the literature and data on gas production, shale gas refers to the gas produced directly from a shale formation, that is the gas that had been trapped in the shale. Gas that has migrated from the shale over geological time is considered conventional natural gas. Shale gas was not commercially exploitable until quite recently when a combination of new technologies were employed to break the trapped gas free of the shale. These technologies include high-volume hydraulic stimulation (“fracking”), high-precision directional drilling, the invention of a new stimulation fluid (“slickwater”), and the introduction of injection equipment that could generate the very high downhole pressures required to permeate large volumes of fractured shale with this new stimulant. There was virtually no shale gas development until very late in the 20th Century, and as of 2005 global shale gas production was only

31 billion cubic meters per year (EIA 2016). Since then, the shale-gas revolution has accelerated tremendously, particularly in the United States. Global production in 2015 was 435 billion cubic meters, with 89% of this in the United States and 10% in western Canada (EIA 2016). By 2019, shale gas production in the United States alone had increased to 716 billion cubic meters (EIA 2020-a). Today, shale gas dominates natural gas production in the United States (approximately 75% of total production is from shale), and almost two-thirds of the total global increase in natural gas production between 2005 and 2015 came from shale gas in North America (Howarth 2019).

Our 2011 analysis was the first peer-reviewed effort to estimate methane emissions from shale gas (Howarth et al. 2011). We used a full-lifecycle approach, estimating emissions during hydraulic fracturing and production at the well sites,

during hydraulic fracturing and production at the well sites, during processing and storage, and from transportation of the gas to the consumer. We estimated that as a percentage of natural gas produced, emissions from conventional natural gas were likely in the range of 1.7% to 6.0%, and from shale gas 3.6% to 7.9%. Of this, we estimated that “downstream” emissions (during transport, storage, and distribution to the consumer) were likely in the range of 1.4% to 3.6% for both conventional and shale gas. We estimated “upstream” emissions (at the well site and from processing) as 0.3% to 2.4% for conventional gas and 2.2% to 4.3% for shale gas. We used the best available data, but noted that these data were often poorly documented, with very little information in published, peer-reviewed papers. We therefore called for more and better measurement of emissions.

In the ten years since our paper was published, there has

Table 6.1. Top-down estimates for upstream emissions of methane from natural gas systems, including studies based on aircraft flyovers and satellite remote-sensing data. Estimates are the percentage of the methane in natural gas that is produced.

Aircraft data		
Peischl et al. (2013)	Los Angeles Basin, CA	17.0%
Karion et al. (2013)	Uintah shale, UT	9.0%
Caulton et al. (2014)	Marcellus shale, PA	10.0%
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%
Ren et al. (2019)	Haynesville shale, LA	1.0%
	Marcellus shale, PA & WV	1.1%
Satellite data		
Schneising et al. (2014)	Eagle Ford shale, TX	20.0%*
	Bakken shale, ND	40.0%*
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).

been an explosion of new studies, leading to a much better understanding of methane emissions from natural gas systems. Perhaps somewhat surprisingly, our original conclusions have held up remarkably well.

6.4 Recent estimates of methane emissions

Table 6.1 synthesizes data from twelve recent studies that measured upstream methane emissions, with most of these from shale gas operations, from a total of nine different gas-producing geological basins, using either aircraft or satellite remote sensing data. Estimates range from 0.2% to 40% of production. All of these studies appear to have been well designed and executed, and the variation in observed emission rates probably reflects true variation in time and space: emission rates are probably higher in some shale-gas fields than in others, and emissions in any given field likely vary over time, for instance depending upon the amount of high-volume hy-

draulic fracturing occurring at the time. It is noteworthy that the highest values come from the earliest studies, suggesting industry may have improved their operations over time (Schneising et al. 2020).

In Table 6.2, I use data from the rate of shale-gas production during 2015 in individual fields (EIA 2020-b) and the rate of emissions reported for fields from Table 6.1 to estimate the actual mass of methane emitted from each field. I omit the very high values reported in the earlier studies shown in Table 6.1, assuming that those high emissions do not well represent emissions in more recent years. Quality data for both emissions and production in 2015 exist for only 6 shale-gas fields, but these represent a total production of 325 billion cubic meters per year (Table 6.2), or three-quarters of the total global production of shale gas that year (Howarth 2019). Comparing the total mass of methane emitted (5.6 Tg per year) with the production for these 6 fields (325 billion cubic

Table 6.2. Shale gas production and upstream methane emissions from various major shale-gas producing fields in 2015.

	Production (billion m ³ /yr)	% emitted upstream (with 90% CL)*	Mass emitted upstream (Tg/yr)**
Marcellus	155	2.58 % (+/- 4.2 %)	2.64
Eagle Ford	50	3.35 % (+/- 0.21 %)	1.11
Barnett	38	1.55 % (+/- 0.06 %)	0.39
Haynesville	36	1.0%	0.24
Permian	36	3.7 % (+/- 0.0 %)	0.88
Bakken	10	5.63% (+/- 0.59 %)	0.37
Total for above fields	325		5.63
Volume-weighted average		2.6 %***	
Global total	435		7.4****

*The values from Schneising et al. (2014) shown in Table 1 are considered outliers and are not included here.

**Assumes 93% of produced gas is methane (Schneising et al. 2020).

*** Calculated from total production and methane mass emission for six shale-gas fields listed.

**** Calculated from volume-weighted average percent methane emitted.

meters per year), the volume-weighted average rate of upstream emissions is 2.6% (Table 6.2). This is in the range of 2.2% to 4.3% we had estimated for upstream emissions from shale gas in our original paper (Howarth et al. 2011), and again note that this does not include the very high emissions reported by Peischl et al. (2013) and Schneising et al. (2014). Applied to the global increase in shale gas production over the period 2005-2015, this 2.6% upstream emission rate leads to an estimated increase in global methane emissions of 7.4 Tg per year (Table 6.2), or a little over 30% of the entire global increase in methane over that time period (Howarth 2019). This does not include the downstream emissions, and again, it does not include the highest emission rates shown in Table 6.1.

Fewer studies have attempted to characterize downstream emissions. Perhaps the most comprehensive effort that used top-down airplane flyovers is a study by Plant et al. (2019) that reported emissions for the urban, northeastern US seaboard from Boston south to Washington, DC. Their data indicate an emission rate of 0.8% of the natural gas consumption in that region (Howarth 2020). Other top-down estimates in Boston, Los Angeles, and Indianapolis give estimates that are at least this high, and up to 2.5% in the case of Boston (McKain et al. 2015; Lamb et al. 2016; Wunch et al. 2016). The available data suggest that we may have overestimated the downstream emissions in our 2011 study (1.4 to 3.6%), but not greatly so.

Combining an upstream emission estimate of 2.6% (volume-weighted mean from Table 6.2) with the downstream estimate of 0.8% derived from Plant et al. in 2019 yields an overall emission estimate for shale gas of 3.4%, somewhat lower than our original study estimate: 3.6 to 7.9% for shale gas (Howarth et al. 2011). This 3.4% emission rate corresponds to an increase of 10 Tg per year from shale gas development between 2005 and 2015, or 40% of the entire global increase in methane emissions from all sources over that time period (Howarth 2019).

Numerous studies have used “bottom-up” approaches for estimating methane emissions from natural gas systems; that is, estimates based on evaluating individual emission sources on the ground and summing these up to get a total emission. In general, this approach gives lower emission estimates than do top-down studies such as those shown in Table 6.1 (Miller et al. 2013; Howarth 2014; Vaugn et al. 2018). There are many reasons why this might be the case. One is that the bottom-up approaches tend to not include all possible emission sources—for example, by leaving out emissions during initial well drilling, which can be high (Caulton et al. 2014). Another reason is that bottom-up measurements often require researchers to get permission to access sites controlled by natural gas operators, so that the researchers can make measurements near their operations. It seems likely that companies that are more willing to allow such access are also more careful in their operations, and perhaps emit less methane. There is always the possibility that if natural-gas operators know

when the emission measurements will be made, they may take particular care to reduce emissions at those times.

Alvarez et al. (2018) synthesized data from a large number of bottom-up studies of shale and conventional gas operations coordinated by the Environmental Defense Fund, and came up with estimates of 1.9% of production for upstream emissions (production, gathering-line leaks, and processing), 0.4% for downstream emissions (transmission, storage, and local distribution), and 2.3% overall. From the bottom-up data, they concluded that emissions from shale gas are no higher than from conventional gas. The US Environmental Protection Agency in its official greenhouse gas reporting relies exclusively on bottom-up estimates, and at that often uses old and outdated non-peer-reviewed studies, resulting in estimates that are even lower than these from the Environmental Defense Fund (Miller et al. 2013; Howarth 2014; Alvarez et al. 2018; Ren et al. 2019). The EPA too assume no difference in emissions from shale gas and conventional gas operations. As discussed below, the bottom-up studies may not adequately characterize differences in emissions between shale and conventional natural gas operations.

6.5 Comparing methane emissions from shale and conventional gas

Some methane is emitted during each step of developing, processing, transporting, storing, and distributing shale gas to consumers. Many of these emission sources are similar for both conventional natural gas and shale gas, but some are greater for shale and other unconventional gas such as tight-sand formations. The most obvious differences between shale gas and conventional gas development are the higher volume of stimulation fluid that is central to developing shale gas and the much larger number of shale gas wells that are completed per unit area. A substantial amount of methane can be emitted to the atmosphere during the flowback of this fluid that immediately follows the stimulation. In Howarth et al. (2011), we summarized data indicating that two shale gas wells emitted 1.1% and 3.6% of their lifetime production of gas during the short flow-back period, while two unconventional tight sand wells emitted 0.6% and 1.3% of their lifetime production total during flow-back. The technology exists for industry to capture this gas and sell it to market, but to do so is expensive and slows the whole process of well completion; consequently, little of this gas was being captured, at least as of 2011 (EPA 2011; Howarth et al. 2012; Howarth 2014). As of 2015, the EPA regulated methane emissions during well completion, in general requiring the gas to be captured if technically possible, and flaring (burning) the gas otherwise, although with many exceptions (EPA 2016). However, effectiveness of this regulation has not been independently determined, and as noted above, qualitative evidence suggests unlit flares that vent unburned methane may be common (Kessel and Tabouchi 2019). Further, under the Trump administration, the EPA repeatedly took steps to end these regulations (Lavelle 2019).

Another difference in methane emissions between conventional gas and shale gas operations is less obvious. Caulton et al. (2014) observed substantial emissions of methane while wells were being drilled in the Marcellus shale region in southwestern Pennsylvania even before the drillers reached the shale. This area has a long history of fossil-fuel exploitation, with development of oil, conventional gas, and coal dating back to the 1800s. The emissions during shale-gas well drilling may be the result of hitting pockets of trapped methane from these earlier fossil-fuel operations, which must be drilled through to reach the shale, which is much deeper underground. In such an environment, the gas industry sometimes employs “underbalanced” or negative-pressure drilling to reduce the chance of blowouts, and this could increase the emission of methane from any pockets that are encountered while drilling (Caulton et al. 2014).

The Alvarez et al. (2018) synthesis of the studies coordinated by the Environmental Defense Fund do not refer to emissions during flowback, to emissions during well drilling, or to higher emissions from producing shale gas wells (Ingraffea et al., 2020). Since they are not including these shale-specific emissions, it may have misled them to conclude that overall shale emissions are no higher than for conventional natural gas. Further, unintended emissions can occur during well completions. The well blowout at Powhatan Point, OH in March of 2018 released over a period of 20 days methane equivalent to 25% of the states total annual natural gas emissions (Pandey et al. 2019).

6.6 Evidence from change in carbon-13 content of atmospheric methane

Another, completely independent approach has been used to estimate the full lifecycle (upstream plus downstream) of methane emissions from shale gas: an analysis of the change in the carbon isotopic composition of atmospheric methane globally over time (Howarth, 2019).

After remaining constant for the first decade of the 21st century (when methane concentrations in the atmosphere were constant), the carbon-13 content of methane has been decreasing since 2007 or so, coinciding with the increase in atmospheric methane concentrations. Some studies interpreted this to mean that there had been an increase in methane emissions from biogenic sources, such as animal agriculture, rather than an increase from fossil fuels (Schaefer et al. 2016; Schwietzke et al. 2016). There are many reasons to doubt this conclusion. One reason is that satellite data indicated that 30% to 60% of the global increase in methane emissions over the past decade came from the United States (Turner et al. 2016), yet the number of cows and cattle in the United States decreased by 5% to 10% over this time (USDA 2020).

The work of Schaefer et al. (2016) and Schwietzke et al. (2016) had assumed that methane emissions from biomass burning had remained constant over time. Worden et al. (2017) noted that this is not true: biomass burning had actually decreased globally as a source of methane over the past

decade. Biomass burning is a relatively small contribution to global methane emissions, but the methane from this source is quite enriched in carbon-13 compared to most other emissions. Therefore, as biomass burning decreased, the carbon-13 content of atmospheric methane would be expected to decrease, a decrease earlier attributed to an increase in emissions that were depleted in carbon-13. When models are corrected for this change, Worden et al. (2017) concluded that the largest increase in emission sources since 2007 was from fossil fuels, not biogenic sources.

I took the analysis one step further, noting that the methane from shale gas may have slightly less carbon-13 than does methane from conventional natural gas. This is due to fractionation as some methane is oxidized over geological time scales during migration from shale formations to conventional gas reservoirs. Fractionation is the tendency for the oxidation reaction to slightly favor the lighter carbon-12 isotope, so that the methane that migrates ends up having a slightly higher proportion of the heavier carbon-13 isotope. Correcting for this difference in the carbon-13 content of methane, I estimated that methane from shale gas contributed at least one-third of the total increase in global methane emissions since 2007, with total emissions from the oil and gas industry (including shale) contributing approximately two-thirds of the total global increase in methane fluxes. This corresponds to emission rates of 2.8% to 3.5% of production for conventional natural gas, and 3.5% to 4.1% of production for shale gas (Howarth 2019). There is much uncertainty in these estimates, but they are broadly consistent with the upstream emissions volume-weighted mean of 2.6% (Table 6.2) plus estimates for downstream emissions of 0.8% or more discussed above. If anything, it would appear that my estimate based on global changes in the carbon-13 of methane over time underestimated total emissions from shale gas, but not greatly so.

My interpretation has been questioned by Milkov et al. (2020) who relied on a published data base to conclude that there is no difference in the carbon-13 composition of methane from shale gas compared to conventional natural gas. However, the “shale gas” referred to in this data set includes data on methane that has migrated from shale formations to conventional reservoirs over geological time. As noted above, the older geological literature refers to this as shale gas, but it is not the gas that is released from shale by high-volume hydraulic fracturing with slickwater. This migrated gas would be called conventional gas in terms of production statistics, and would be expected to be enriched in carbon-13 compared to actual produced shale gas. When I wrote the Howarth (2019) paper, I was well aware of the data set that Milkov et al. (2019) used and found it to be an unreliable source of information on the carbon-13 of the shale gas that has actually been produced (see my published response to a reviewer, part of the interactive public review process for *Biogeosciences*, available at <https://bg.copernicus.org/preprints/bg-2019-131/bg-2019-131-AC3-print.pdf>). I would note further that the Milkov et al. (2020) approach leads to an estimate of methane

emission from shale gas that is very much lower than any of the estimates presented in Table 6.1. These independent data simply do not support the analysis or conclusions of Milkov et al. (2020).

The use of carbon-13 and other isotopes as tracers of methane in the atmosphere and groundwater is discussed in more detail in another chapter in this book (Townsend-Small, in press).

6.7 What methane emission estimate should policy makers use?

In January of 2020, legislation took effect in New York State that outlines a new approach for evaluating greenhouse gas emissions. Under the new rules, New York is to account for all methane emissions associated with the use of natural gas and other fuels in the state, including those emissions that occur outside of the state’s boundaries. Previously, New York, in common with all other states and most nations, only included methane emissions that occurred within its state boundaries in its greenhouse gas inventory. New York chose this new methodology, using a consumer-based approach to indicate the entire greenhouse gas consequences of different fuels, to better allow comparisons of different energy choices. The new law also requires the state to estimate methane emissions based on the best, peer-reviewed science in the literature, and not rely on the inventory estimates of the US Environmental Protection Agency.

In Howarth (2020), I give guidance on how the state of New York might implement this, suggesting that total methane emissions for natural gas be calculated as 3.6% of the consumption of gas within the state. Note that 3.6% of consumption is equivalent to 3.2% of natural gas production; consumption is less than production both because some of the produced gas is emitted to the atmosphere before it reaches consumers and because the gas industry uses some of the produced gas to power their operations, including the compressors that move gas through high-pressure pipelines. My suggested factor for total emissions associated with natural gas (primarily shale gas) is at the low end of what I estimated from the global carbon-13 data or compared to volume-weighted upstream methane emission rate reported in Table 6.2. I chose to be deliberately conservative in the interests of helping to promote a consensus value for the state to use. I based my recommendation on the Alvarez et al. (2018) synthesis, using their average bottom-up estimates for upstream emissions, increasing this by 11% to better reflect the top-down estimates with which they compare their values, and using the downstream emission estimate from Plant et al. (2019). Note that in concluding that top-down estimates were 11% greater than their bottom-up estimates, Alvarez et al. (2018) did not include several of the higher top-down estimates shown in Table 6.1, including the estimates by Peischl et al. (2013), Caulton et al. (2014), Schneising et al. (2014), Zhang et al. (2020) and Schneising et al. (2020) – five out of the 12 papers in Table 6.1.

6.8 Greenhouse gas footprint of gas compared to coal and petroleum

Figure 1 compares the greenhouse gas footprint of natural gas, coal, and petroleum products, including both the direct emissions of carbon dioxide from the burning of the fuels and the full lifecycle emissions of unburned methane associated with developing and using the fuels. Methane emissions in this figure are based on the emission factors presented in Howarth (2020), where I give guidance to New York for greenhouse gas accounting. To obtain the same amount of heat energy, the carbon dioxide emissions from natural gas are smaller than those from coal and petroleum, and this is the foundation of the natural gas as a bridge-fuel concept. However, when methane emissions are included (as carbon dioxide equivalents), the greenhouse-gas footprint of natural gas is substantially larger than that even of coal. And as stressed above, methane emissions may well be greater than the values used in this figure, 3.6% of consumption for the natural gas estimate.

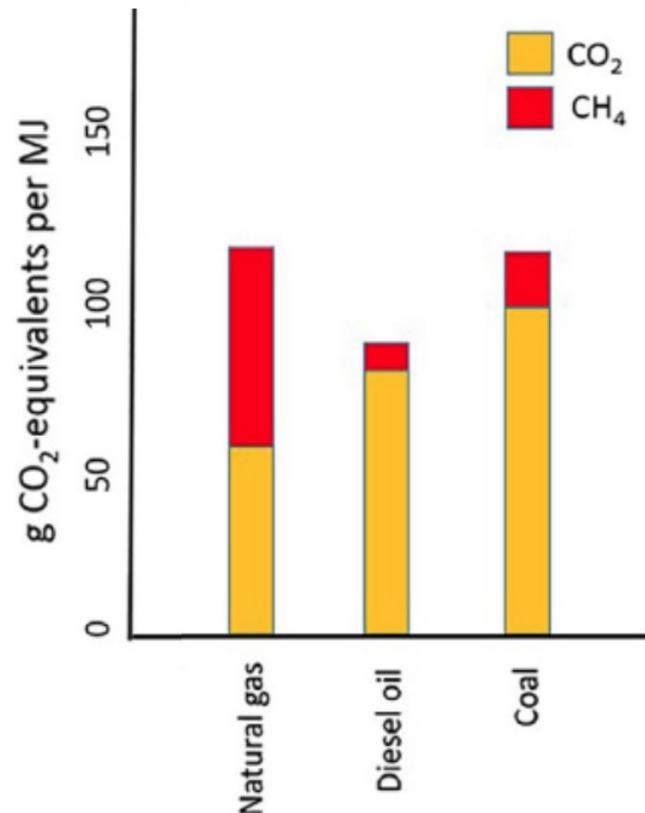


Figure 1. Greenhouse gas footprint of natural gas (including shale gas), diesel oil, and coal per unit of heat energy released as the fuels are burned. Direct emissions of carbon dioxide are shown in yellow. Methane emissions expressed as carbon dioxide equivalents are shown in red. As discussed in the text, the methane emission rate used here for natural gas, 3.6% of consumption is conservative. Emission estimates are from Howarth (2020).

Methane emissions are converted to carbon-dioxide equivalents in Figure 1, allowing a direct comparison with carbon dioxide emissions. Methane is a far more potent greenhouse gas, and here the methane emissions are multiplied by a factor that reflects this greater warming potential, putting both the methane and carbon dioxide emissions into the same units. This factor, called the global warming potential, compares the warming of methane relative to carbon dioxide on average for a defined period of time after a pulse emission of both gases to the air. In Figure 1, I use a 20-year time period for this global warming potential. This is consistent with the new climate legislation in New York state but differs from the approach used in almost all greenhouse gas inventories in other states and nations, which use a 100-year time frame based on a recommendation from the Kyoto Protocol of 1997. The 100-year time frame severely understates the role of methane in global warming since most of the influence of methane on the climate occurs in the first 30 years after emission, as seen in Figure 2 (IPCC 2013; Howarth 2020).

The original choice of 100 years by the Kyoto Protocol was arbitrary (IPCC 2013), and as we have learned more about the role of methane in global warming in the years since 1997, a growing number of researchers have called for using a 20-year time frame, either instead of (Howarth 2014, 2020) or in addition to the 100-year approach (Ocko et al. 2017; Fesenfeld et al. 2018). Note that both carbon dioxide and methane are critical drivers of global warming, and both the shorter time frame and longer time frame are important to consider, as discussed briefly earlier in this paper. However, combining methane emissions and carbon dioxide emissions into a common metric is a poor approach to communicate information on these emissions, particularly when using the 100-year global warming potential. A better approach is to separately provide information on methane and carbon dioxide, in equivalent units of carbon-dioxide equivalents, using the 20-year or other shorter time frame for methane (Howarth 2014, 2020). The long-term perspective is best characterized simply from the data on carbon dioxide emissions.

It is critically important to reduce methane emissions in a shorter time frame in order to reduce the risk of moving past tipping points in the climate system, reduce damage to society and natural ecosystems from global warming over the coming decades, and provide the best chance of meeting the COP21 climate goals (Shindell et al. 2012; Collins et al. 2018). From this viewpoint, natural gas is far worse than coal. It is also important to note that the global warming potential approach compares the warming influence of methane to carbon dioxide based on single pulsed releases of both gases. As long as one continues to use natural gas, the global warming consequences remain worse than for coal or oil, and for at least two-to-three decades after natural gas is no longer used as a fuel. Given the state of increasing climate disruption in 2020, the continued use of natural gas would be a bridge to disaster.

The comparison of footprints presented in Figure 1 is based

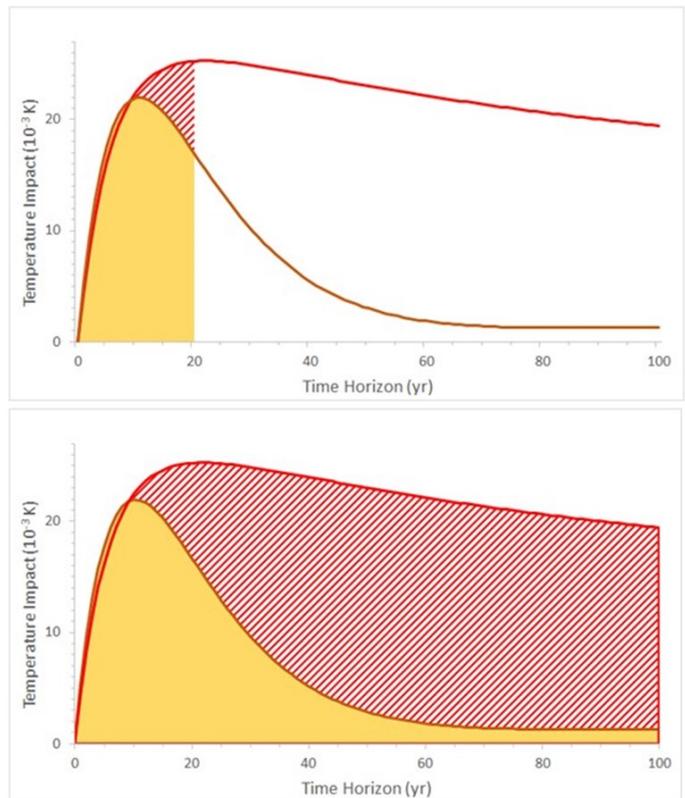


Figure 2. Stylized comparison of the global temperature response over time from carbon dioxide and methane emitted for a 1-year pulse of each gas at time zero. Top shows area under curve integrated for the time zero to year 20 time period, with methane shown as solid yellow and carbon dioxide as striped red. Bottom panel is the same except through the 100 year time period. Note that the integrated area for carbon dioxide in both panels also underlies the area for methane, except for the extreme left-handed side of the curves. Adapted from IPCC (2013), and is based on the absolute global temperature change potential. Reprinted from Howarth (2020).

on the generation of heat. How this heat energy is used matters in the comparison of fuels. For instance, electric power plants powered by natural gas are often (but not always) more efficient than those powered by coal, which tend to be older. On the other hand, internal combustion engines in cars and trucks have a lower efficiency when powered by natural gas than when powered by petroleum products (Alvarez et al. 2012).

Including efficiency concerns, methane emissions from natural gas must be less than 3.2% of consumption in order for natural gas to have a lower greenhouse-gas impact than coal for generating electricity, and methane emissions from natural gas must be less than 1% of consumption in order for natural gas to be preferred over diesel fuel for use in long-distance, heavy trucks (Alvarez et al. 2012). In Hong and Howarth (2016), we demonstrated that greenhouse gas emissions from using natural gas water heaters in homes are greater than from using high efficiency heat pumps, with the electricity to power the heat pumps coming from either natural gas or coal, if methane emissions from natural gas are

greater than 0.8% of consumption. It makes no sense to use natural gas as a transportation fuel, and the use of natural gas for heating—which is the largest use of gas globally and in the United States—should be phased out as quickly as possible. Even with an increase in electricity production needed for heat pumps, and even if this electricity were to come from fossil fuels (until electricity generation becomes 100% renewable), greenhouse gas emissions are reduced by switching away from natural gas as the energy source for heating buildings and hot water (Hong and Howarth 2016).

6.9 Conclusions

A large and growing body of evidence indicates that methane emissions from the development and use of shale gas are substantial, probably in the range of 3.4% of production based on the most recent top-down estimates for upstream and downstream emissions, such as shown in Table 6.1. Such emissions give shale gas a large greenhouse-gas footprint, greater than that of coal or other fossil fuels when emissions are considered on a 20-year time frame after an emission. Atmospheric methane has been rising rapidly over the past decade, after having been stable to the first decade of the 21st Century. Given a full lifecycle emission rate of 3.4% of production, shale gas is responsible for 40% of the total global increase in atmospheric methane from all sources since 2005. This increase makes it far more difficult to meet the COP21 target of keeping the Earth well below 2°C from the pre-industrial baseline.

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