Methane Emissions from Natural Gas Systems

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The past few years have seen major changes both in our understanding of the importance of methane as a driver of global climate change and in the importance of natural gas systems as a source of atmospheric methane. Here, we summarize the current state of knowledge, relying on peer-reviewed literature.

Methane is the second largest contributor to human-caused global warming after carbon dioxide. Hansen and Sato (2004) and Hansen et al. (2007) suggested that a warming of the Earth to 1.8° C above the 1890-1910 baseline may trigger a large and rapid increase in the release of methane from the arctic due to melting of permafrost. While there is a wide range in both the magnitude and timing of projected carbon release from thawing permafrost in the literature (e.g. Schaefer et al., 2011), warming consistently leads to greater release. This release will therefore in turn cause a positive feedback of accelerated global warming (Zimov et al. 2006).

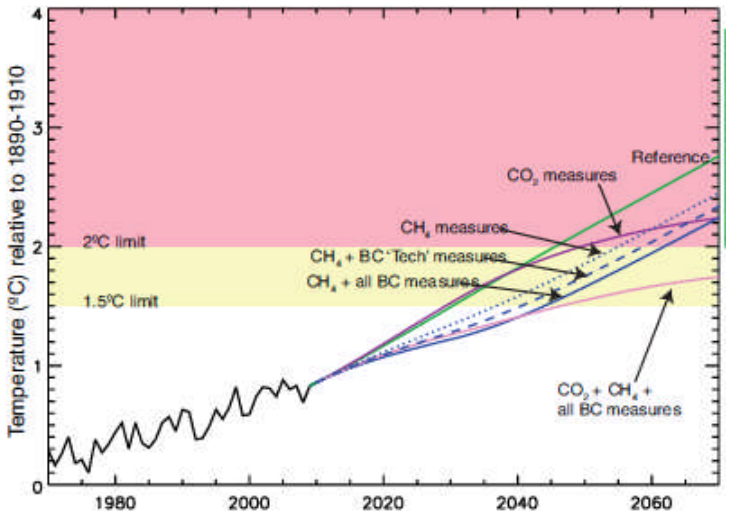

Fig. 1. Observed global mean temperature from 1900 to 2009 and projected future temperature under various scenarios of controlling methane + black carbon (BC) and carbon dioxide, alone and in combination. An increase to 1.5° to 2.0 ° C above the 1890-1910 baseline (illustrated by the yellow bar) poses high risk of passing a tipping point and moving the Earth into an alternate state for the climate system. Reprinted from Shindell et al. (2012).

Shindell et al. (2012) noted that the climate system is more immediately responsive to changes in methane (and black carbon) emissions than carbon dioxide emissions (Fig. 1). They predicted that unless emissions of methane and black carbon are reduced immediately, the Earth will warm to 1.5° C by 2030 and to 2.0° C by 2045 to 2050 whether or not carbon

dioxide emissions are reduced. Reducing methane and black carbon emissions, even if carbon dioxide is not controlled, would significantly slow the rate of global warming and postpone reaching the 1.5° C and 2.0° C marks by 12 to 15 years. Controlling carbon dioxide as well as methane and black carbon emissions further slows the rate of global warming after 2045, through at least 2070.

Natural gas systems are the single largest source of anthropogenic methane emissions in the United States (Fig. 2), representing almost 40% of the total flux according to the most recent estimates from the U.S. Environmental Protection Agency (EPA) as compiled by Howarth et al. (2012). Note that through the summer of 2010, the EPA used emission factors from a 1996 study to estimate the contribution of natural gas systems to the U.S. greenhouse gas (GHG) inventory. Increasing evidence over the past 16 years has indicated these emission factors were probably too low, and in November 2010 EPA began to release updated factors. The estimates for natural gas systems in Fig. 2 are based on these updated emission factors and information released through 2011 in two additional EPA reports, as presented in Howarth et al. (2012). Note that the use of these new methane emission factors resulted in a doubling in the estimate of methane emissions from the natural gas industry. Note also that, to date, EPA has only increased emission factors for "upstream" and "midstream" portions of the natural gas industry (leaks and emissions at the well site and in processing gas). Factors for "downstream" emissions (storage systems and transmission and distribution pipelines) are still from the 1996 report, although EPA is considering also modifying these (Howarth et al. 2012).

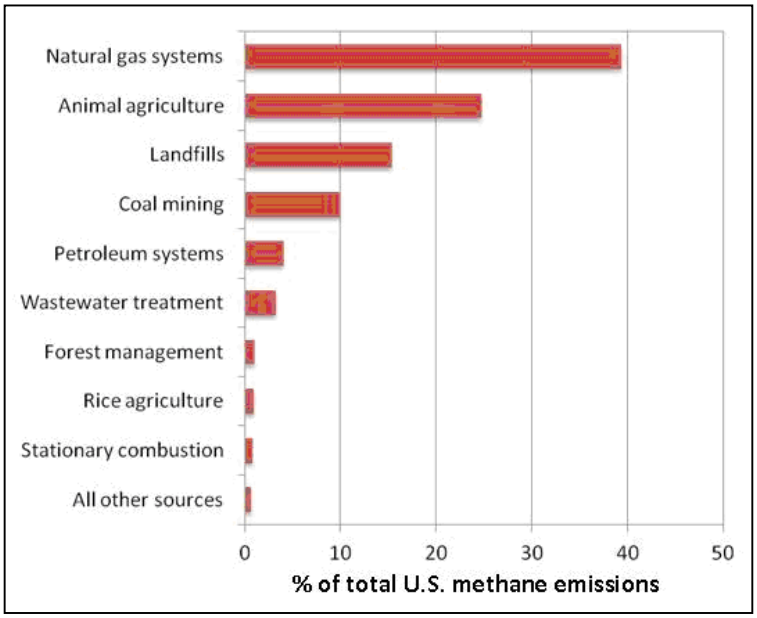

Fig. 2. Human-controlled sources of atmospheric methane from the United States for 2009, based on emission estimates from the U.S. Environmental Protection Agency in 2011. Reprinted from Howarth et al. (2012).

The natural-gas-system emissions in Fig. 2 are based on an average emission of 2.6% of the methane produced from natural gas wells over their production lifetime, with 1.7% from upstream and midstream emissions (for the national mix of conventional and unconventional gas in 2009) and 0.9% from downstream emissions (Howarth et al. 2012). As discussed below, these methane emission estimates from natural gas systems are based on limited data and remain uncertain.

Recent estimates in the peer-reviewed literature for downstream emissions of methane from natural gas systems range from 0.07% to 10% of the methane produced over the lifetime of a well (Table 1). It is important to note that only Lelieveld et al. (2005) presented actual data on emissions, in their case leakage from high-pressure transmission pipelines. Other estimates are based on emission factors from the 1996 EPA study, on emission factors from a more recent report from the American Petroleum Institute, or on reports of "lost and unaccounted for gas" to governmental agencies, leading to high uncertainty. Lelieveld et al. reported a leakage rate from high-pressure transmission pipelines of 0.4% to 1.6%, with a "best estimate" of 0.7%; they used the 1996 EPA emission factors to estimate emissions from storage and distribution systems, yielding an estimate for total downstream emissions of 1.4% (or twice their measured value for just transmission). Howarth et al. (2011) took the "best estimate" of 1.4% from Lelieveld et al. (2005) as their low-end estimate, arguing that the 1996 EPA emission factors were probably low. For their high-end estimate, Howarth et al. (2011) used data on "missing and unaccounted for gas" from Texas. Their mean estimate of 2.5% is identical to the "best estimate" from Hayhoe et al.

Table 1. Estimates of methane emission from downstream emissions (transmission pipelines and storage and distribution systems) expressed as the percentage of methane produced over the lifecycle of a well. Studies are listed chronologically by date of publication. Modified from Howarth et al. (2012).

Hayhoe et al. (2002)	2.5 %	("best estimate;" range = 0.2% – 10%)
Lelieveld et al. (2005)	1.4 %	("best estimate;" range = 1.0% – 2.5%)
Howarth et al. (2011)	2.5 %	(mean; range = 1.4% – 3.6%)
EPA (2011)*	0.9 %	
Jiang et al. (2011)	0.4 %	
Hultman et al. (2011)	0.9 %	
Ventakesh et al. (2011)	0.4 %	
Burnham et al. (2011)	0.6 %	
Stephenson et al. (2011)	0.07 %	
Cathles et al. (2012)	0.7 %	

* The EPA (2011) estimate is as calculated in Howarth et al. (2012), using national emissions from EPA reports and national gas production data from US Department of Energy reports.

(2002). The estimates of Jiang et al. (2011), Hultman et al. (2011), Ventakesh et al. (2011), Burnham et al. (2011), and Cathles et al. (2012) are all based on various permutations of the 1996 EPA emission factors, factors that were developed before the measurements of Lelieveld et al. (2005). The "best estimate" of measured emissions from transmission pipelines of 0.7% by Lelieveld et al. (2005) is similar to or greater than the estimates for all downstream emissions (including storage and distribution) from these studies that used the 1996 EPA emission factors. The estimate of Stephenson et al. (2011) includes only transmission pipelines, is based on emission factors reported by the American Petroleum Institute in 2009 (which in turn are derived from the EPA 1996 emission factors), and is far lower than any other estimate. Comparisons of predicted and observed methane concentrations in Los Angeles have indicated that emissions factors for leakage from natural gas systems may be underestimated (Wunch et al. 2009; Hsu et al. 2010). A new study using stable isotopic and radiocarbon signatures of methane confirms that emission from natural gas systems is likely the dominant source of methane in Los Angeles (Townsend-Small et al. 2012).

Most recent estimates for upstream emissions (those that occur during well completion and production at the well site) and midstream emissions (those that occur during gas processing) for conventional natural

Table 2. Conventional natural gas, estimates of methane emissions from upstream (at the well site) plus midstream (at gas processing plants), expressed as the percentage of methane produced over the lifecycle of a well. Studies are listed chronologically by date of publication. Modified from Howarth et al. (2012).

Hayhoe et al. (2002)	1.2 %	("best estimate")
Howarth et al. (2011)	1.4 %	(mean; range = 0.2% to 2.4%)
EPA (2011)*	1.6 %	
Hultman et al. (2011)	1.3 %	
Venkatesh et al. (2011)	1.8 %	
Burnham et al. (2011)	2.0 %	
Stephenson et al. (2011)	0.4 %	
Cathles et al. (2012)	0.9 %	

* The EPA (2011) estimate is as calculated in Howarth et al. (2012), using national emissions from EPA reports and national gas production data from US Department of Energy reports.

gas cluster fairly closely to the new EPA estimate of 1.6% (Table 2). The mean estimate from Howarth et al. (2011) is 1.4%; the Howarth et al. (2011) low-end value of 0.2% is an estimate of what is possible using best technologies, while 2.4% reflects emissions using poor technologies. Other estimates range from 0.4% to 2.0% (Table 2). As for the downstream emissions, the lowest number (0.4%) comes from Stephenson et al. (2011).

Table 3. Unconventional gas (shale gas and gas from tight sands), estimates of methane emissions from upstream (at the well site) plus midstream (at gas processing plants), expressed as the percentage of methane produced over the lifecycle of a well. Studies are listed chronologically by date of publication. Modified from Howarth et al. (2012).

Howarth et al. (2011)	3.3 %	(mean; range = 2.2% to 4.3%)
EPA (2011)*	3.0 %	
Jiang et al. (2011)	2.0 %	
Hultman et al. (2011)	2.8 %	
Burnham et al. (2011)	1.3 %	
Stephenson et al. (2011)	0.6 %	
Cathles et al. (2012)	0.9 %	
Petron et al. (2012)	4.0 %	("best estimate;" range = 2.3 to 7.7%)

* The EPA (2011) estimate is as calculated in Howarth et al. (2012), using national emissions from EPA reports and national gas production data from US Department of Energy reports.

Estimates for upstream plus midstream methane emissions from unconventional gas (obtained from shales and tight-sands) vary from 0.6% to 4.0% for mean or "best" estimates (Table 3). The US EPA 2011 data indicate an estimated loss of 3.0% for upstream plus midstream emissions from unconventional gas (Howarth et al. 2012).

With the exception of the estimate by Petron et al. (2012), all of these upstream emissions for unconventional gas are based on sparse and poorly documented data (Howarth et al. 2011, 2012). The study by Petron et al. (2012) measured fluxes from an unconventional gas field – at the landscape scale – over the course of a year, and is a robust estimate. Although it represents only one field (the Piceance tight-sands basin in Colorado), emissions during the flowback period following hydraulic fracturing for unconventional gas are similar in this basin to other unconventional gas basins for which data are available (Howarth et al. 2011).

The Petron et al. (2012) study should be repeated in other unconventional gas fields, but it nonetheless suggests that most of the estimates in Table 3 are likely to be too low.

The methane emissions during flowback of fracking fluids, which occur during a 1-2 week period following hydraulic fracturing, are the major difference in emissions between unconventional and conventional gas. Flowback emissions are estimated as 1.9% of the lifetime production of an unconventional gas well according to Howarth et al. (2011), although the data of Petron et al. (2012) suggest the flux may in fact be greater. Flowback does not occur when a conventional gas well is completed, and the methane emissions at the time of well completion are far less (Howarth et al. 2011, 2012). Howarth et al. (2012), which was published before the Petron et al. (2012) study was released, concluded that shale gas emissions are 40% to 60% greater than emissions from conventional natural gas, when both upstream and downstream emissions are considered.

The US Department of Energy predicts that the major use of shale gas over the next 23 years will be to replace conventional reserves of natural gas as these become depleted. To the extent that methane emissions associated with shale gas and other unconventional gas are greater than for conventional gas, this will increase the methane emissions from the US from the natural gas industry beyond those indicated in Fig. 2. An increase of 40% to 60% in methane emissions is likely, based on the majority of studies summarized in Howarth et al. (2012), possibly more in light of the new field-based measurements by Petron et al. (2012). Note further that to the extent the US EPA is underestimating emissions from downstream sources (storage, transmission, and distribution), methane emissions from natural gas systems may already be substantially greater than shown in Fig. 2.

Global warming potentials provide a relatively simple approach for comparing the influence of methane and carbon dioxide on climate change. In the national GHG inventory, the US EPA uses a global warming potential of 21 over an integrated 100-year time frame, based on the 1995 report from the Intergovernmental Panel on Climate Change (IPCC) and the Kyoto protocol. However, the latest IPCC Assessment from 2007 used a value of 25, while more recent research that better accounts for the interaction of methane with other radiatively active materials in the atmosphere suggests a mean value for the global warming potential of 33 for the 100-year integrated time frame (Shindell et al. 2009). Using this value and the methane emission estimates based on EPA data shown in Fig. 2, Howarth et al. (2012) calculated that methane contributes 19% of the entire GHG inventory of the U.S., including carbon dioxide and all other gases from all human activities. The methane from natural gas systems alone contributes over 7% of the entire GHG inventory of the U.S. Note that the variation in the global warming potential estimates between 21 and 33 is substantially less than the variation among the methane emission estimates.

The global warming potentials of 21, 25 and 33 are all for an integrated 100-year time frame following emission of methane to the atmosphere. The choice of 100 years is arbitrary, and one can also consider the global warming potentials at

longer or shorter time scales. To date, estimates have typically been provided at time scales of 20 years and 500 years, in addition to the 100-year time frame. An emphasis on the 20-year time frame in addition to the widely-used 100-year timeframe is important, given the urgency of reducing methane emissions and the evidence that if measures are not taken to rapidly reduce the rate of warming, the Earth will continue to warm so quickly that risk of dangerous consequences will grow markedly. We may reach critical tipping points in the climate system, on the time scale of 18 to 38 years (Figure 1).

For the 20-year time frame, Shindell et al. (2009) provide a mean estimate of 105 for the global warming potential. Using this value, Howarth et al. (2012) calculated that methane contributes 44% of the entire GHG inventory of the U.S., including carbon dioxide and all other gases from all human activities. Hence while methane is only causing about 1/5 of the century-scale warming due to US emissions, it is responsible for nearly half the warming impact of current US emissions over the next 20 years. At this time scale, the methane emissions from natural gas systems contribute 17% of the entire GHG inventory of the U.S., for all gases from all sources. We repeat that these estimates may be low, and that the gradual replacement of conventional natural gas by shale gas is predicted to increase these methane fluxes by 40% to 60% or more (Howarth et al. 2012).

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