the Energy to Lead

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An Introduction to Methane and the Center for Methane Research

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Introduction

The Center for Methane Research (CMR) was established to provide a centralized industry-wide technical and policy support resource focused on the presence, measurement and potential impacts of methane in the atmosphere. The strategic approach to achieving this goal includes adopting a "good science / common sense" philosophy that addresses the end-to-end process of natural gas exploration, production, processing, transportation and ultimately end-use. Development of this "wellhead-to-burner tip" industry resource will provide a common platform of technical understanding that can be used in the decision making process in support of balanced policy decisions that impact both the environment, the industry and ultimately the consumer.

The objectives of CMR are:

- To act as a liaison between industry, university and government research organizations, regulators, and other technical and policy advocates to ensure that current start-of-the-art fact based information on methane is developed, accessible, and underpinned by stakeholder collaboration
- To provide transparency and accessibility of the best available technical information and fit-for-purpose communication tools such that the collaborative stakeholder group speaks with a common technical voice where appropriate when addressing questions from the media, policy makers and other interested parties.
- To establish a centralized approach to data collection, analysis and an information repository that includes:
  - Historical studies
  - Policy directives
  - Publicly available research results
  - An inventory and description of privately held research studies
  - An on-going analysis of methane emission trends and atmospheric concentration levels, including specific contributions of natural gas production, processing, transportation and end-use.
- Provide on-going evaluation of information gaps and facilitate development of new research efforts focused on bridging these gaps. Conduct new scientific investigations as appropriate on the role of methane in global warming, with an emphasis on (1) atmospheric methane concentration and chemistry and (2) methane radiative physics, to ensure appropriate values are used for methane's existing atmospheric background concentrations, Global Warming Potential (GWP) and radiative forcing.
- To serve as a repository for information on the potential contribution of methane to global warming with an emphasis on the nexus with natural gas industry segments.

This document is the first step in achieving the abovementioned goals and provides an unbiased first principles approach to understanding the complexity of global methane cycling and the need for the CMR. The ultimate goal of the CMR is to provide a sustainable information and analysis forum addressing the needs of multidisciplinary stakeholders in developing a well-balanced, factual approach to technical conclusions and policy decisions that are in the best interest of both the environment and the public. This introduction is intended to be a dynamic document that will change over time as new important information becomes available. It is, however, not meant to be a completely exhaustive or definitive source for all information on methane. More information on any topic can be requested, at which point a more thorough chapter can be prepared.

Global methane cycle

Methane gas is ubiquitous in the atmosphere resulting in a background atmospheric concentration of approximately 2ppmv. The global background concentration is a mass or pool of methane that has been increasing at varying rates since the industrial revolution resulting from a combination of sinks (removal mechanisms) and sources (both natural and anthropogenic). The dynamic equilibrium of sources, sinks and resulting pools forms a complex global methane cycle. This cycle is impacted by a number of complex variables making predictions of pooling characteristics with a reasonable degree of confidence extremely challenging.

Methane in the environment cycles continuously between reservoirs in/on Earth's crust and the atmospheric reservoir. Figure 1 summarizes and estimates quantities for the movement (fluxes) and reservoirs (stocks) of methane. Quantifying the magnitude of methane cycle fluxes is complex and in many cases uncertain leading to inconsistent conclusions on how to best manage influential variables. The CMR was formed to help address this uncertainty by creating a common technical resource and repository of both historical and state-of-the-art technical information that helps drive technically supported decision making. The CMR will also provide communication tools to help reasonably and rationally describe facts that influence public opinion and policy decisions that impact the natural gas industry.

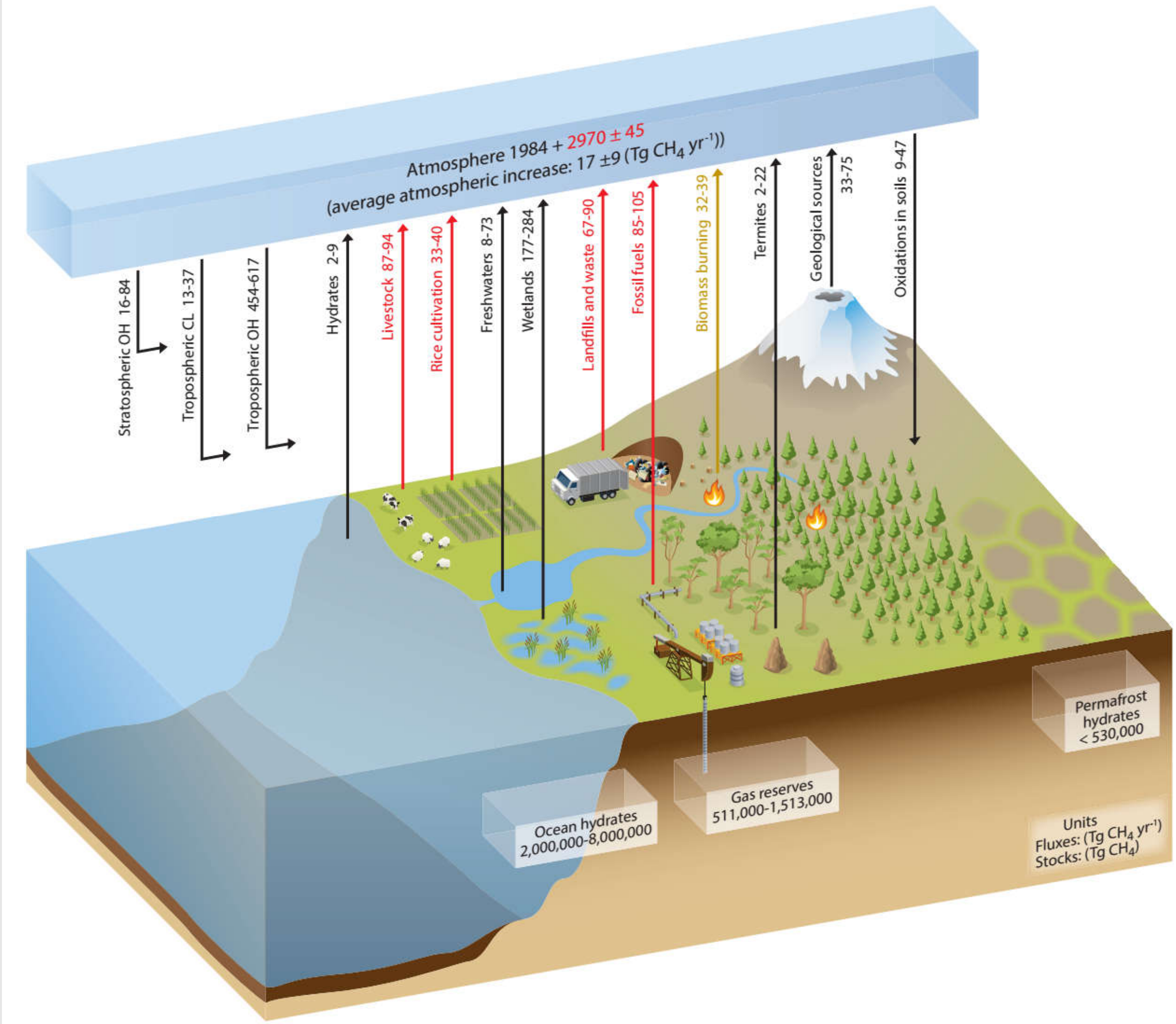

Figure 1. Global Methane Cycle

Global methane cycle schematic from the IPCC 5th Assessment Report (AR5) Working Group I Chapter 6 (Ciais, Sabine et al. 2013).

Methane Reservoirs

Methane reservoirs or pools are areas where methane accumulation has occurred over time. There are two main types of subsurface methane reservoirs – hydrates and gas reserves while the third main reservoir is the atmosphere. The atmospheric reservoir is two orders of magnitude smaller than the subsurface reservoirs which can naturally drive fluxes. Overall movement of methane from the subsurface has the potential to be large and greatly impact the much smaller atmospheric reservoir.

The scientific name for methane hydrates is actually methane clathrate. Clathrate means a lattice or structure that contains molecules, in this case a lattice of water (ice) containing methane. These substances exist below the Arctic permafrost and the ocean floor and are thought to be potentially hundreds of meters thick containing a large reservoir of methane. There is currently much work being done to explore how to develop this potentially important resource.

Methane Emissions

Methane emissions involve the movement from the surface or subsurface of the earth to the atmosphere. These emissions can be either of natural or anthropogenic (caused by human activity) origin within several source categories.

Natural

Wetlands

Wetlands are the single largest source (177 – 284 Tg CH_4 yr^{-1}) of methane to the atmosphere (Reay, Smith et al. 2010, Ciais, Sabine et al. 2013), roughly twice what is emitted from all fossil fuels. Small changes in emissions from this source can have significant implications for methane pooling in the atmosphere. Methane is produced in the waterlogged anaerobic parts of the soil in wetlands by the microbial process of methanogenesis. Methane emissions from wetlands are biologically produced and are therefore heavily influenced by changes in precipitation and temperature that impact the manifestation of microbes producing the methane. Despite the size of this source, there are still large uncertainties associated with quantifying impacts of emissions from wetlands which may be affected by changes in global temperatures. For instance, a recent study showed that increases to methane in the atmosphere that occurred between 2007 and 2014 were the result of increased emissions from tropical wetlands (Nisbet, Dlugokencky et al. 2016) and not fossil fuels.

Geological methane

Methane is constantly released from geologic reservoirs via geothermal and volcanic emissions and in sedimentary seepage (Reay, Smith et al. 2010) which includes onshore mud volcanoes, water seeps (e.g., bubbling springs), dry seeps (e.g., gas venting from outcropping rocks, through the soil horizon or river/lake beds), and sea floor seeps (e.g., cold seeps, mud volcanoes, and pockmarks). Uncertainties surrounding the amount of methane that is released from individual methane sources is actually quite low. However, the global distribution of these features is not entirely known, therefore, adds uncertainty to the estimate. Some upper estimates of this source indicate that emissions can be as high as 75 Tg CH_4 yr^{-1}, comparable to some estimates of fossil fuel emissions (85 – 105 Tg CH_4 yr^{-1}).

Termites

Termites, in some humid tropical areas, can make up a significant amount of the animal biomass (e.g., up to 15% in the central Amazonian rainforest; Fittkau and Klinge, 1973). The shear mass of termites globally coupled with the fact that methanogenic microorganisms inhabit the termite gut (producing methane) make termites a measureable source of methane to the atmosphere annually.

Hydrates

Methane hydrates are typically subject to elevated subsea pressure. When a reduction in pressure occurs, or an increase in temperature occurs, methane can be released from the crystalline structure (i.e., the hydrate is brought to the surface). The methane emission from methane hydrates is thought to be occurring as a response to global temperature rise, however, this emission is highly speculative (i.e., high uncertainty) at this point. The IPCC AR5 report indicates that the current estimate of 2 – 9 Tg CH_4 yr^{-1} for hydrates may change as temperature increases in tundra permafrost, thus releasing methane contained in that reservoir.

Freshwater

Methane is thought to be emitted from freshwaters through several different pathways, including bubble fluxes from sediments, diffusive flux, and plant-mediated transport through certain aquatic plants

(Bastviken, Tranvik et al. 2011). Emission of methane from lakes and rivers, however, is a fairly recent recognized large global source to the atmosphere. For instance the source appears in the IPCC AR5 report (Figure 1) but does not appear in a recent book describing methane emissions to the atmosphere in detail (Reay, Smith et al. 2010). In fact, there is little discussion of the source in the AR5 report except for noting a recent re-evaluation and increasing trend in contributions from this source in the overall global methane budget resulting in an overall larger global methane emission being estimated from bottom-up estimation techniques. This source is highly uncertain with the range of emissions identified by the IPCC AR5 report being 8 to 73 Tg CH_4 yr^{-1} from these sources, but one article cited by to the report actually reports 103 Tg CH_4 yr^{-1} from these sources globally. The inconsistency in reports highlights the uncertainty in these emissions and raises several questions as to why the updated range of estimates was not specifically noted in AR5.

Another more recent interesting finding is the indication that between 3 and 14 Tg CH_4 yr^{-1} originates from specific manmade hydroelectric reservoirs (Deemer, Harrison et al. 2016). Therefore, a large amount of methane is emitted to the atmosphere from an electrical generating sector that was thought to be completely methane emission free and should ultimately viewed as an anthropogenic input to the atmosphere.

Anthropogenic

Biomass burning

Biomass burning is both a natural and anthropogenic source that arises from the incomplete combustion of "a wide range of sources including woodlands, peatlands, savanna and agricultural waste" (Reay, Smith et al. 2010). It is suggested that slash and burn techniques in the tropics far outweigh the naturally occurring burns globally (Reay, Smith et al. 2010).

Rice cultivation

Rice is typically grown in monsoon Asian countries where it is a staple food for as much as 66% of the population. Rice is grown in waterlogged soils, essentially artificial wetlands, that are anoxic and carbon rich, conditions that facilitate methanogenesis and emission of methane (Reay, Smith et al. 2010). Between 1935 and 2005, the area where rice was grown doubled globally making these areas potentially large sources of methane. The source is thought to be 33 – 40 Tg CH_4 yr^{-1}, roughly half of all fossil fuel emissions alone.

Ruminants (livestock)

Cattle, sheep, goats and deer (ruminant animals) emit methane as a by-product of digestion (i.e., feed fermentation). The source, particularly from dairy cows, is large (87 – 94 Tg CH_4 yr^{-1}) roughly equal to all fossil fuel emissions, thus greater then emissions from the natural gas sector alone. Much recent work has been focused on methane emissions from livestock, with California passing a recent law to reduce methane emissions from dairies and livestock by 40 percent from 2013 levels by 2030. To that end, researchers have found that adding seaweed to the feedstock at dairies has the potential to reduced methane emissions by up to 99%.

Manure and wastewater

Manure and wastewater (including human sources) can produce significant amounts of methane via microbial methanogenesis due to prevailing anoxic conditions and presence of substrates (Reay, Smith et al. 2010). These emissions are separate from what is produced directly by ruminant animals. Manure is often stored and treated directly on the farm, but can sometimes be centrally processed, and will produce methane due to anaerobic fermentation as a consequence of enteric bacteria being present in the manure from the animals (Reay, Smith et al. 2010). These processes are attractive to energy developers for bio-gas recovery and treatment resulting in bio-methane, completely compatible with current commercial pipeline supplies and a valuable energy resource.

Anaerobic digestion of combined sewage waste including industrial and domestic wastewater results in another recoverable bio-gas product that otherwise would be released to the environment. Digester gas from sewage treatment facilities can be further processed to meet bio-methane requirements, utilized on-site or potentially injected into the gas distribution pipeline grid. For wastewater and sludge, emissions can come from open sewers, sludge from centralized treatment of wastewaters, anaerobic reactors, septic tanks, and open pits/latrines (Reay, Smith et al. 2010).

Landfills

In the U.S., landfills are the second largest source of methane emissions behind ruminant animals (Reay, Smith et al. 2010). Landfills can contain large amounts carbon rich substrate and have a lack of oxygen, producing the anoxic conditions needed for microbial methanogenesis. The emission of methane from landfills has been known for many years with the capture of methane from landfills being used as a power supply in some areas since 1975. Bio-gas recovery from landfills, like digester gas, is also further processed to meet bio-methane requirements and subsequently injected into pipeline grids. These emissions have also been regulated for some time, with some landfills installing flares to limit the methane emissions.

Fossil Energy

Several fossil energy methane emission sources exist. In addition to natural gas specific emissions discussed below, methane can be released in the extraction of oil, due to natural gas being associated with the oil reserves. Further, significant amounts of methane can be released from coal beds when the coal is mined. These emissions are typically larger for underground mines which account for approximately 90% of U.S. coal sector emissions as carbon content and methane increases with coal seam depth

Methane removal

Methane is removed from the atmosphere by chemical conversion to other substances. These natural processes can be influenced by anthropogenic factors, thus ultimately impacting the residence of methane in the atmosphere.

Atmospheric oxidation

Methane can be destroyed (i.e., converted to other substances such as carbon dioxide and water) in the troposphere (lowest layer of the atmosphere extending from the surface to 8 - 10km and containing 75 to 80% of total mass of the atmosphere) and stratosphere (second layer of the atmosphere above the troposphere extends to about 50 km and containing about 20% of the mass) by hydroxyl (OH) radicals and to a lesser extent chlorine radicals in the marine boundary layer (the lowest layer of the troposphere extending from the surface to a few hundred or a few thousand meters depending on conditions). OH oxidation is the largest sink by far removing 470 to 701 Tg CH_4 yr^{-1} giving methane its low atmospheric lifetime.

Soil oxidation

A much smaller removal process is via soil oxidation which is facilitated by methanotrophic bacteria in soils. The methanotrophs are microorganisms that work in the opposite direction of methanogens, converting methane into carbon and energy. These organisms can exist in both aerobic and anaerobic conditions, therefore can be present in all soils, acting as a removal mechanism.

Natural Gas Industry Methane Emissions

The U.S. EPA collects methane emissions data from companies through the Greenhouse Gas Reporting Program (GHGRP) and the Greenhouse Gas Inventory (GHGI). EPA data indicates that the oil and natural gas production sectors combined are the largest contributors of methane emissions accounting for 72% of overall emissions, with 145 million metric tons of CO_2 equivalent (MMT CO_2e) of a total of 202 MMT CO_2e for the industry in 2015 (Figure 2). Natural gas emissions from production accounted for 107 MMT CO_2e (53%) of the total 145 MMT CO_2e from oil and gas production. This is followed by 34 MMT CO_2e for transmission and storage (17%), 11 MMT CO_2e for gas processing (6%), and lastly 11 MMT CO_2e from gas distribution (5%; USEPA 2017). The relative nature of emission sources from wellhead to burner tip highlights the need for collaboration across the entire natural gas value chain in order to effectively and efficiently reduce emissions.

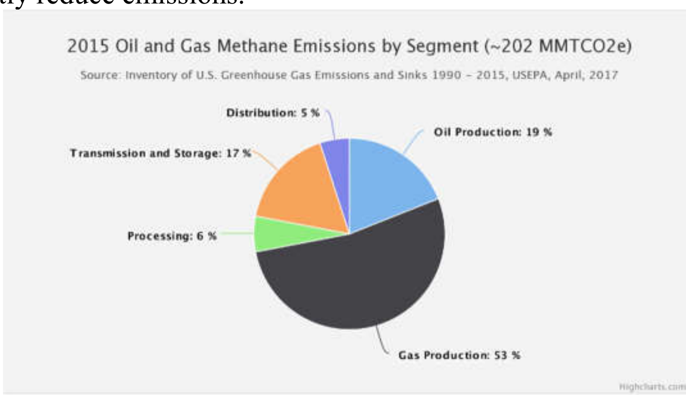

Figure 2. Methane emissions by Oil and Gas Segment

Source: https://www.epa.gov/natural-gas-star-program/overview-oil-and-natural-gas-industry#sources

Production

Emissions from the gas production industry segment are greater than all natural gas sectors in the U.S. Emissions from gas recovery processes including venting of pneumatic controllers and gathering and boosting stations account for 67% of emissions from this sector (Figure 3). In particular, pneumatic controllers use gas pressure to perform some mechanical operation, usually the opening or closing of a valve. Each time the controller operates gas/methane is released to the atmosphere. Gathering and boosting stations consist of several large compressors to enable injection of production gas into gathering and transmission pipelines. Although more modern, state-of-the-art compressor stations have significantly reduced emissions, historically compressor station operations have been known as elevated emitters due to the mechanical nature of operation and venting of various components to ensure safe operations.

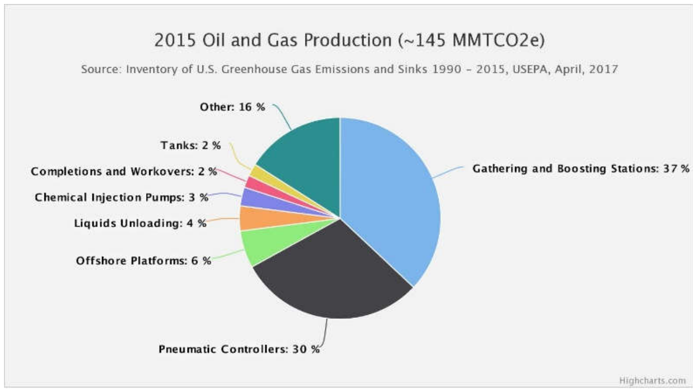

Figure 3. Methane emissions from Oil and Gas Production

Source: https://www.epa.gov/natural-gas-star-program/overview-oil-and-natural-gas-industry#sources

Processing

The largest source of methane emissions from gas processing is gas engines accounting for 52% of emissions from this sector (Figure 4). This is a significant change from the report issued in 2016 where compressor operations made up the majority of emissions. Reciprocating compressors or piston compressors use a piston to compress a gas and with each operation of the piston small amounts of methane can seep past seals (especially as they age) and vent to the atmosphere for safety purposes. Centrifugal compressors are designed to emit less gas as they use a wet seal system involving an oil that limits by-pass of gas through the sealing surface. However, potential emission sources remain as gas is dissolved in the oil and once the oil returns to a central crankcase it is released through a safety breather/vent system. New research must have informed this change.

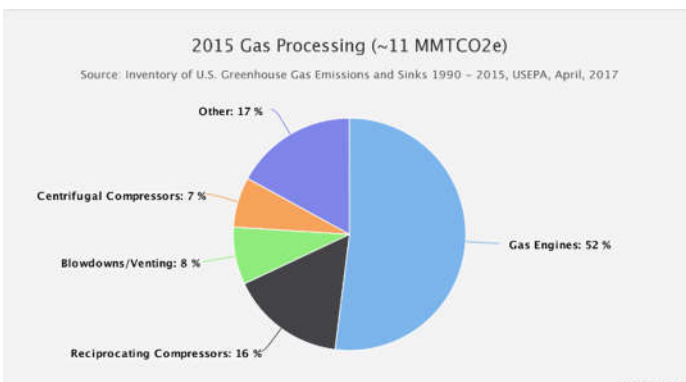

Figure 4. Methane Emissions from Gas Processing

Source: https://www.epa.gov/natural-gas-star-program/overview-oil-and-natural-gas-industry#sources

Transmission and Storage

The largest emissions from the transmission and storage sector remains compressors accounting for 43% of emissions (Figure 5). The next highest categories are station fugitives (unintended releases) and station venting account for 20% of emissions. Station fugitive emissions are a combination of unintended consequences of routine operations from both transmission and storage compressor stations (USEPA 2016).

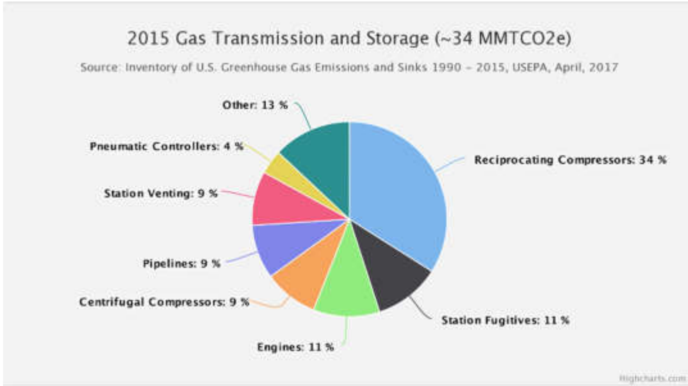

Figure 5. Methane Emissions from Gas Transmission and Storage

Source: https://www.epa.gov/natural-gas-star-program/overview-oil-and-natural-gas-industry#sources

Distribution

The largest known sources of emissions in the distribution sector are referred to as "mishaps" and are a consequence of third party damage from excavation operators to distribution facilities and outdoor residential pressure regulator and meters (Figure 6). Mishaps are currently estimated by multiplying total distribution main and estimated service mileage reported by the Pipeline and Hazardous Materials Safety Administration (PHMSA) by a per mile emission factor (USEPA 2016). The residential estimate is based on multiplying the total number of reported residential meters by a per meter emission factor (USEPA 2016).

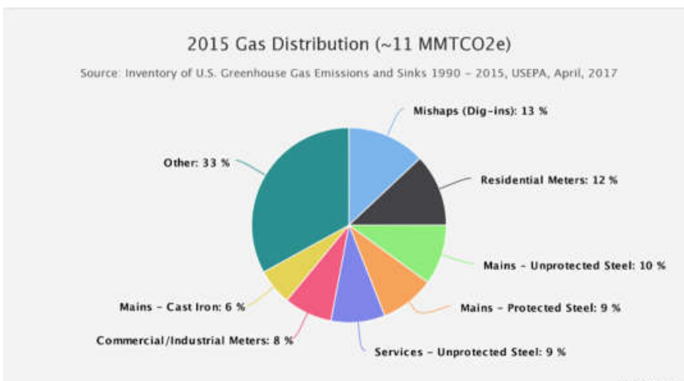

Figure 6. Methane Emissions from Gas Distribution

Source: https://www.epa.gov/natural-gas-star-program/overview-oil-and-natural-gas-industry#sources

Utilization

Individual sources of methane emissions are not high enough to be currently tracked by EPA. However, a number of sources arise, from incomplete combustion or releases by components beyond the meter. For instance, for natural gas vehicles there are several components at compressed natural gas stations, where customers fill up that have the potential for intermittent release of gas as a consequence of routine operations. These can include compressors, valves (either engineered releases or failures), and fittings (either within the station or at the filling attachment to the vehicle).

Methane emissions from residential, commercial and industrial facilities is captured in the distribution sector by the number of meters each company has on record. The use of natural gas for electric power generation is not explicitly captured as a separate category in the US EPA Greenhouse Gas Inventory but in part gets factored in as an industrial facility. However, emissions from any components beyond the meter are not captured.

Methane Studies

A recent "study of studies" conducted by ICF for the Natural Gas Council, released in April 2016 (ICF 2016), summarized 75 methane emission studies conducted over the last 20 years that are directly related to the natural gas industry. However, the study does not summarize historically important papers that have indirect impacts on the industry such as papers that influence the global warming potential (discussed below) that is used by the Intergovernmental Panel on Climate Change (IPCC). For instance, a study published in December 2016 has indicated that radiative forcing of methane should actually be 25% higher on the 20 year timeframe and 14% higher on the 100 year timeframe (Etminan, Myhre et al. 2016). Studies like these can ultimately influence what is reported in the period IPCC reports and slowly influence governmental policy and regulations, such as the California's recent passing of Senate Bill 32 and Assembly Bill 197 forcing reductions of greenhouse gas emissions to be below 1990 levels by 2020.
A number of other studies are underway or have been recently published focused on understanding methane emissions from the natural gas industry and their impacts on the global methane cycle. Due to the dynamic nature of these new studies, a commissioned review of methane emissions studies, such as the ICF/NGC study, although quite thorough, only reflects the knowledge at the time it was written. The knowledge is not carried forward in a sustainable "knowledge base" as new studies are funded and results come available. For instance, since April 2016 when the ICF/NGC report was made public, several new studies with important findings that impact the industry have been published. These include three studies published in high ranking scientific journals in April, September and October 2016 that show recent increases of global atmospheric methane concentrations are not being caused by fossil fuels (Nisbet, Dlugokencky et al. 2016, Schaefer, Fletcher et al. 2016, Schwietzke, Sherwood et al. 2016). One other study that indicates the importance of quantifying and fixing methane leaks from abandoned wells (Kang, Christian et al. 2016) was published in November 2016. Another study published in October 2016 focused on the importance of "fat-tailed" or "super-emitters" (a few very large leaks) in driving overall methane emissions (Brandt, Heath et al. 2016).

In addition to these newly published studies, there are several other studies currently underway that may have implications for the industry. GTI and the CMR are actively involved in several of these studies. They include studies funded by the US Department of Energy (DOE) to investigate methane emissions from industrial meters, new vs. older plastic pipe, and plastic-lined steel and cast iron pipe and by the California Energy Commission to study methane emissions from natural gas electric generating units and compressed natural gas vehicle fueling stations.

The large number of studies along with the breadth of findings pertaining to methane cycling and emissions that may impact the industry are primary reasons the CMR exists. Continued focus and development of additional technical information and resulting conclusions requires on-going collaborative monitoring and sustainable information management to ensure transparency of policy influencing communications. .

Methane and Climate Change

Methane emissions in general are considered by some to be the low hanging fruit for mitigation of climate change. Of all known atmospheric anthropogenic methane sources, many groups tend to view the oil and natural gas industry as the lowest hanging fruit primarily due to overall visibility of the industry itself. They view the industry as having a wherewithal and potential financial motivation to efficiently contain the product that they sell. One of the issues that has hindered the complete embracing of natural gas as a viable source of energy moving forward by all constituents has to do with the releases of methane from the entire natural gas value chain or "life-cycle." Although the burning of natural gas produces half the carbon emission of coal for the same energy output, since natural gas is in gaseous form there is more opportunity for it to escape to the atmosphere before it can be burned by the end-user. This presents a two-fold problem. One, the gas that escapes is lost by the industry and cannot ultimately be sold to the end-user. Two, the gas that escapes is largely methane which has a larger potential to warm the atmosphere than CO_2 alone.

Methane emissions has become an important global environmental issue and is often referred to as the most important greenhouse gas aside from carbon dioxide. The subject of climate change and in particular the contribution of methane and the natural gas industry has recently come to the forefront of the discussion. Several certainties exist when it comes to climate change:

1) The climate is changing (that is actually natural).
2) Carbon concentrations (including carbon dioxide and methane) are increasing in the atmosphere.
3) Humans have contributed to the issue by increasing the input of carbon and greenhouse gases to the atmosphere.

Some companies have embraced the potential for climate change taking a proactive stance. For instance, ExxonMobil has recently stated that "the risk of climate change is clear and the risk warrants action. Increasing carbon emissions in the atmosphere are having a warming effect. There is a broad scientific and policy consensus that action must be taken to further quantify and assess the risks" (ExxonMobil 2016).

The issues of climate change that are known present several questions – can humans do anything to reverse or slow the effects of climate change? If not, should we then just use the energy sources we have until something naturally forces us to find an alternative? What is the greater societal cost – completely eliminating use of fossil fuels in the near term or engineering/combating the future effects of climate change such as sea level rise, fires, droughts, severe storms, etc.?

The future climate and weather is incredibly uncertain, therein lies the controversial part of the climate debate. What will the consequences be? Should the industry do everything within reason that is economically feasible to reduce air pollution and potential impacts to climate? Yes, to retain the social license to operate.

Natural gas combustion is more efficient and cleaner than coal, with fewer impurities. The overall net impact to air quality of switching to natural gas is a positive. The emphasis should therefore be on quantifying the local economic/human health benefits of using natural gas as an energy source compared to the overall economic/human health impact of climate change.

Climate Metrics

Transparency around the development, use and understanding of climate metrics is critical to our discussion of the role that the natural gas industry plays in influencing overall methane concentrations and the climate. These metrics are used to put the presence of greenhouse gases (gases that absorb energy in the form of the sun's radiation) such as methane in the atmosphere into perspective with another greenhouse gas such as carbon dioxide. The calculation of these metrics is incredibly complex and they often get cited as justification for more regulations/legislation by governments. For instance, the US EPA uses global warming potentials (GWPs) when comparing technologies and making recommendations, such as the benefit or harm of using natural gas vehicles over diesel vehicles (less benefit with higher GWP for methane). The EPA provides a discussion on global warming potentials at https://www.epa.gov/ghgemissions/understanding-global-warming-potentials.

Climate metrics are used as a tool that attempts to put impacts on climate into perspective. The purpose of the metrics is to simplify how climate change is influenced by different types of emissions. However, metric calculations are incredibly complicated and involve several complex modeled parameters and assumptions with inherent uncertainty associated with each parameter. The important thing to note is that metrics such as global warming potential were initially developed to simplify communication of a complex problem and illustrate how difficult that problem truly was (Shine 2009, Ciais, Sabine et al. 2013). They were not intended to be used to set policy limits and impart governing regulations. However, once published they unexpectedly (to scientists) made their way into the Kyoto Protocol and they have been a part of policy ever since (Shine 2009). Due to the importance of these metrics it is imperative to understand their technical basis and where they come from, their advantages and disadvantages. What follows is a discussion of the basics behind the individual metrics.

Radiative Forcing

Radiative forcing (RF) is an incredibly complex parameter that is the source of much of the uncertainty in climate models. Further the calculated radiative forcing is used in the calculation of other parameters such as the global warming potential (GWP) and the global temperature potential (GTP). The simplest definition of RF, also called climate forcing or stratospherically adjusted RF, the change in energy in the atmosphere due to emissions of a particularly greenhouse gas. More specifically, RF of a gas is the difference between incoming solar radiation and outgoing infrared radiation caused by the increased concentration of that gas. Radiative forcing is expressed in watts per square meter ($W\ m^{-2}$) or the rate of energy change per unit area of the globe as measured at the top of the atmosphere (Myhre, Shindell et al. 2013).

Unfortunately, that is where the simple explanation ends, as even the definition of what the "top of the atmosphere" means is difficult due to the highly dynamic nature of the atmosphere and fluctuations in the heights of different atmospheric layers. Complex radiative transfer models are used to determine RF for each gas, and due to changes in atmospheric conditions and concentrations RF also changes over time.

Global Warming Potential (GWP)

Global Warming Potential (GWP) was originally developed partially to put climate change mitigation into perspective with CO_2 (the most important greenhouse gas). It is defined "as the time-integrated RF due to a pulse emission of a given component relative to a pulse emission of an equal mass of CO_2." Since the calculation is time integrated, short-lived atmospheric species such as methane will decrease as the time horizon increases from 20 to 100 years. Since GWP is calculated from RF, the complexities and uncertainties are then passed on to this number.

From a climate mitigation perspective, many groups focus on GWP. For instance a GWP of 28 for methane, regardless of time frame (20 or 100 year), means that every 1 kilogram or pound or ton (the unit of measure does not matter) of the methane prevented from being emitted to the atmosphere is equivalent to preventing 28 kilograms or pounds or tons of CO_2 from being emitted to the atmosphere. There is no accounting for the economics of the removal. Therefore, if a technology or regulation can prevent 29 kilograms or pounds or tons of CO_2 from being emitted to the atmosphere for a similar net cost of mitigating one kilogram or pound or ton of the other chemical then those methods should also be explored. The interpretation of GWP in this manner has therefore placed blinders on some, focusing solely on the stoppage of one kilogram or pound or ton of a chemical such as methane being emitted to the atmosphere.

Global Temperature (Change) Potential (GTP)

Global temperature potential (GTP) is the change in global mean surface temperature at a particular point in time in response to an emission pulse relative to that of CO_2 (Myhre, Shindell et al. 2013). Unlike GWP, GTP is not integrated over time, therefore since methane is a short-lived atmospheric species, GTP for methane increases each year for the first 12 years (the atmospheric lifetime of methane) then decreases each year after that. The GTP at 20 years (GTP20) is therefore the exact potential for a temperature

change driven by a ton of methane that was emitted 20 years ago, compared to a ton of CO_2 that was emitted 20 years ago.
Some believe that GTP more accurately represents the impact of short-lived species on climate time scales (usually 100+ years) since the impact is greater for shorter time frames and lesser for longer time frames, since the calculation is not integrated over longer time frames (or horizons) such as GWP.

Methane Health Effects

Aside from flammability and explosive hazards, "methane in its gas form is an asphyxiant, which in high concentrations may displace the oxygen supply you need for breathing, especially in confined spaces. Decreased oxygen can cause suffocation and loss of consciousness. It can also cause headache, dizziness, weakness, nausea, vomiting, and loss of coordination" from the National Institutes of Health (NIH) Hazardous Substance Data Bank (https://toxnet.nlm.nih.gov/newtoxnet/hsdb.htm).

Other than at high concentrations, such as mentioned in the NIH Data Bank, there is little information on the impacts of lower concentrations of methane. The lack of reliable information leaves this topic completely open for interpretation and misrepresentation. For instance, one study recently (Fleischman, McCabe et al. 2016) indicated that methane emissions contribute directly to the local formation of tropospheric (layer of the atmosphere closest to the ground) ozone, which in has a number of known important detrimental health effects, such as increased risk of asthma. News outlets quickly sensationalized the report linking the natural gas industry directly to asthma in children. They play on the fact that methane technically is an ozone precursor like NOx and higher molecular weight volatile organic compounds (specifically called non-methane hydrocarbons) which lead directly to the local chemical formation of ozone in the atmosphere. Although methane is an ozone precursor, methane emissions do not lead to the direct and immediate formation of local ozone. The statements of the study were over-interpreted for the purpose of creating publicity around the topic.

The importance of having an information center like the CMR becomes clear for issues such as the release of the Fleischman et al., 2016 study. Because the story was sensationalized, however, does not mean that there was not also important information that can be gained by digging into the topic of ozone formation from methane. The study took the fact that methane reacts with the atmospheric hydroxyl radical, which as an atmospheric "cleaner" and stretched it to scare people. This reaction occurs more slowly than other reactions with the hydroxyl radical, therefore does not directly impact local air quality. There is an effect, however, on slower global scale, as methane concentrations build and the global background methane concentrations ozone concentrations can slowly increase over time. The effect on ozone concentrations over time is an important topic that may need further study in the future.

A Look Toward the Future

The fundamental societal issues surrounding methane emissions and resulting potential impacts on the environment will drive scientific and policy interest for many years to come. The broad implications of methane emissions to the overall climate change equation is driving the industry, policy makers and regulators to view business differently and influence decision making processes in day to day operations. For instance, NGOs may feel it is more important than ever to become involved in issues such as rate cases or any area where they can make stances on methane emissions. Also, states such as California that have instituted aggressive regulations on methane emissions may feel the need to be even more aggressive.

Extensive research is currently underway, particularly looking at quantification and reduction of methane emissions from the production sector through the Department of Energy's ARPA-E MONITOR program. Other segments of the natural gas value chain are also in need of much investment to understand how emissions can be reduced. For instance, in the end-use segment, enhanced emission determinations from natural gas vehicles and fueling stations is needed, as current models such as the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, a widely used model for the transportation sector may not accurately reflect current technology and operations, leading to significant uncertainties and limitations associated with adopting natural gas vehicles. Also, large uncertainties remain surrounding quantification of methane emissions from underground storage facilities in the transmission and storage segments. There are many such gaps in our knowledge all across the value chain particularly with how to quantify "fat-tailed" emissions mentioned in the "Methane Studies" section.

In summary, a tremendous accumulation of knowledge has occurred in proportion to the need to address policy decisions around global climate change; but more needs to be done. Rather than having policy and science collide in our pursuit of finding the absolute solution to the methane challenge, the CMR promotes a fact driven information sharing environment where good science combined and in balance with a common sense approach to applying the science drives the greatest degree of overall societal impact. The CMR is a sustainable vehicle to engaging stakeholders in developing practical solutions, building on a centralized warehouse of information. In addition, the CMR provides a "toolbox" of factual public awareness communications that industry segments can use and share to help promote the good science/common sense approach to addressing one of the most significant challenges to face the industry in decades.

Citations

Bastviken, D., et al. (2011). "Freshwater Methane Emissions Offset the Continental Carbon Sink." Science **331**(6013): 50-50.

Inland waters (lakes, reservoirs, streams, and rivers) are often substantial methane (CH4) sources in the terrestrial landscape. They are, however, not yet well integrated in global greenhouse gas (GHG) budgets. Data from 474 freshwater ecosystems and the most recent global water area estimates indicate that freshwaters emit at least 103 teragrams of CH4 year−1, corresponding to 0.65 petagrams of C as carbon dioxide (CO2) equivalents year−1, offsetting 25% of the estimated land carbon sink. Thus, the continental GHG sink may be considerably overestimated, and freshwaters need to be recognized as important in the global carbon cycle.

Brandt, A. R., et al. (2016). "Methane Leaks from Natural Gas Systems Follow Extreme Distributions." Environmental Science & Technology **50**(22): 12512-12520.

Future energy systems may rely on natural gas as a low-cost fuel to support variable renewable power. However, leaking natural gas causes climate damage because methane (CH4) has a high global warming potential. In this study, we use extreme-value theory to explore the distribution of natural gas leak sizes. By analyzing ∼15 000 measurements from 18 prior studies, we show that all available natural gas leakage data sets are statistically heavy-tailed, and that gas leaks are more extremely distributed than other natural and social phenomena. A unifying result is that the largest 5% of leaks typically contribute over 50% of the total leakage volume. While prior studies used log-normal model distributions, we show that log-normal functions poorly represent tail behavior. Our results suggest that published uncertainty ranges of CH4 emissions are too narrow, and that larger sample sizes are required in future studies to achieve targeted confidence intervals. Additionally, we find that cross-study aggregation of data sets to increase sample size is not recommended due to apparent deviation between sampled populations. Understanding the nature of leak distributions can improve emission estimates, better illustrate their uncertainty, allow prioritization of source categories, and improve sampling design. Also, these data can be used for more effective design of leak detection technologies.

Ciais, P., et al. (2013). Carbon and Other Biogeochemical Cycles. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panal on Climate Change. T. F. Stocker, D. Qin, G.-K. Plattner et al. Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

Deemer, B. R., et al. (2016). "Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis." BioScience **66**(11): 949-964.

Collectively, reservoirs created by dams are thought to be an important source of greenhouse gases (GHGs) to the atmosphere. So far, efforts to quantify, model, and manage these emissions have been limited by data availability and inconsistencies in methodological approach. Here, we synthesize reservoir CH4, CO2, and N2O emission data with three main objectives: (1) to generate a global estimate of GHG emissions from reservoirs, (2) to identify the best predictors of these emissions, and (3) to consider the effect of methodology on emission estimates. We estimate that GHG emissions from reservoir water surfaces account for 0.8 (0.5–1.2) Pg CO2 equivalents per year, with the majority of this forcing due to CH4. We then discuss the potential for several alternative pathways such as dam degassing and downstream emissions to contribute significantly to overall emissions. Although prior studies have linked reservoir GHG emissions to reservoir age and latitude, we find that factors related to reservoir productivity are better predictors of emission.

Etminan, M., et al. (2016). "Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing." Geophysical Research Letters: n/a-n/a.

New calculations of the radiative forcing (RF) are presented for the three main well-mixed greenhouse gases, methane, nitrous oxide, and carbon dioxide. Methane's RF is particularly impacted because of the inclusion of the shortwave forcing; the 1750–2011 RF is about 25% higher (increasing from 0.48 W m−2 to 0.61 W m−2) compared to the value in the Intergovernmental Panel on Climate Change (IPCC) 2013 assessment; the 100 year global warming potential is 14% higher than the IPCC value. We present new simplified expressions to calculate RF. Unlike previous expressions used by IPCC, the new ones include the overlap between CO2 and N2O; for N2O forcing, the CO2 overlap can be as important as the CH4 overlap. The 1750–2011 CO2 RF is within 1% of IPCC's value but is about 10% higher when CO2 amounts reach 2000 ppm, a value projected to be possible under the extended RCP8.5 scenario.

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Recent measurements of methane emissions from abandoned oil/gas wells show that these wells can be a substantial source of methane to the atmosphere, particularly from a small proportion of high-emitting wells. However, identifying high emitters remains a challenge. We couple 163 well measurements of methane flow rates; ethane, propane, and n-butane concentrations; isotopes of methane; and noble gas concentrations from 88 wells in Pennsylvania with synthesized data from historical documents, field investigations, and state databases. Using our databases, we (i) improve estimates of the number of abandoned wells in Pennsylvania; (ii) characterize key attributes that accompany high emitters, including depth, type, plugging status, and coal area designation; and (iii) estimate attribute-specific and overall methane emissions from abandoned wells. High emitters are best predicted as unplugged gas wells and plugged/vented gas wells in coal areas and appear to be unrelated to the presence of underground natural gas storage areas or unconventional oil/gas production. Repeat measurements over 2 years show that flow rates of high emitters are sustained through time. Our attribute-based methane emission data and our comprehensive estimate of 470,000-750,000 abandoned wells in Pennsylvania result in estimated state-wide emissions of 0.04-0.07 Mt (1012 g) CH4 per year. This estimate represents 5-8% of annual anthropogenic methane emissions in Pennsylvania. Our methodology combining new field measurements with data mining of previously unavailable well attributes and numbers of wells can be used to improve methane emission estimates and prioritize cost-effective mitigation strategies for Pennsylvania and beyond.

Myhre, G., et al. (2013). Anthropogenic and Natural Radiative Forcing. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. T. F. Stocker, D. Qin, G.-K. Plattner et al. Cambridge, United Kingdom and New York, NY, USA.

Nisbet, E. G., et al. (2016). "Rising atmospheric methane: 2007–2014 growth and isotopic shift." Global Biogeochemical Cycles **30**(9): 1356-1370.

From 2007 to 2013, the globally averaged mole fraction of methane in the atmosphere increased by 5.7 ± 1.2 ppb yr−1. Simultaneously, δ13CCH4 (a measure of the 13C/12C isotope ratio in methane) has shifted to significantly more negative values since 2007. Growth was extreme in 2014, at 12.5 ± 0.4 ppb, with a further shift to more negative values being observed at most latitudes. The isotopic evidence presented here suggests that the methane rise was dominated by significant increases in biogenic methane emissions, particularly in the tropics, for example, from expansion of tropical wetlands in years with strongly positive rainfall anomalies or emissions from increased agricultural sources such as ruminants and rice paddies. Changes in the removal rate of methane by the OH radical have not been seen in other tracers of atmospheric chemistry and do not appear to explain short-term variations in methane. Fossil fuel emissions may also have grown, but the sustained shift to more 13C-depleted values and its significant interannual variability, and the tropical and Southern Hemisphere loci of post-2007 growth, both indicate that fossil fuel emissions have not been the dominant factor driving the increase. A major cause of increased tropical wetland and tropical agricultural methane emissions, the likely major contributors to growth, may be their responses to meteorological change.

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Schaefer, H., et al. (2016). "A 21st-century shift from fossil-fuel to biogenic methane emissions indicated by $^{13}CH_4$." Science **352**(6281): 80-84.

Methane, a powerful and important greenhouse gas, has been accumulating nearly uninterruptedly in the atmosphere for the past 200 years, with the exception of a mysterious plateau between 1999 and 2006. Schaefer et al. measured methane's carbon isotopic composition in samples collected over the past 35 years in order to constrain the cause of the pause. Lower thermogenic emissions or variations in the hydroxyldriven methane sink caused the plateau. Thermogenic emissions didn't resume to cause the subsequent rise. Instead, the ongoing rise is most likely due to biogenic sources, most notably agriculture.Science, this issue p. 80Between 1999 and 2006, a plateau interrupted the otherwise continuous increase of atmospheric methane concentration [CH4] since preindustrial times. Causes could be sink variability or a temporary reduction in industrial or climate-sensitive sources. We reconstructed the global history of [CH4] and its stable carbon isotopes from ice cores, archived air, and a global network of monitoring stations. A box-model analysis suggests that diminishing thermogenic emissions, probably from the fossil-fuel industry, and/or variations in the hydroxyl CH4 sink caused the [CH4] plateau. Thermogenic emissions did not resume to cause the renewed [CH4] rise after 2006, which contradicts emission inventories. Post-2006 source increases are predominantly biogenic, outside the Arctic, and arguably more consistent with agriculture than wetlands. If so, mitigating CH4 emissions must be balanced with the need for food production.%U http://science.sciencemag.org/content/sci/352/6281/80.full.pdf

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END OF REPORT