Greenhouse Gas Emissions and Fuel Use within the Natural Gas Supply Chain – Sankey Diagram Methodology

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Overview

Substantial quantities of methane (CH_4) and carbon dioxide (CO_2) emissions occur throughout the natural gas infrastructure. In 2012, approximately 155 million metric tons CO_2 equivalent (MMt CO_2e) of CH_4 were emitted as a result of inadvertent leakage and routine venting. In the same year, the natural gas industry emitted a similar amount of CO_2 (approximately 164 MMt CO_2e), primarily from the combustion of natural gas that is used as a fuel for compression and flared gas but also from the removal of non-hydrocarbon gases from raw gas by processing plants. Combined, these "midstream" and "upstream" emissions from natural gas infrastructure accounted for approximately 20% of total 2012 greenhouse gas (GHG) emissions from natural gas systems; the other 80% of GHG emissions from natural gas result from gas combustion by end-use consumers. The Sankey diagrams in this paper examine these emissions in some detail, focusing in particular on the production, processing, transmission and storage, and distribution segments of natural gas infrastructure.

1.0 Introduction and Terminology

Natural gas infrastructure produces, processes, transports, stores, and distributes natural gas. However, not all of the raw natural gas reaches consumers. For example, when raw gas is extracted from geologic reservoirs through production processes, it frequently contains impurities that need to be removed before it is marketable for use as a fuel or feedstock. Furthermore, as natural gas travels through production, processing, transmission, distribution, and compression facilities, small portions are routinely used as fuel, vented, flared, or inadvertently leaked to the atmosphere. This paper describes the analytical and methodological bases for three diagrams of the losses and emissions from these processes, in terms of natural gas volumes and associated GHG emissions.

Common terminology used throughout this paper includes the following:

- **Natural gas system**: Natural gas production, transmission and storage, processing, distribution, and end-use consumption.
- **Natural gas infrastructure**: Natural gas production, transmission and storage, processing, and distribution. This term does not include consumption of natural gas by end-use consumers.
- **Fuel use**: Natural gas's use as a fuel at various points throughout natural gas infrastructure. The primary use is to drive natural gas compression equipment, through combustion in engines or turbines. More than 8% of U.S. natural gas consumption in 2012 was used in gas infrastructure as "lease and plant fuel" and for "pipeline and distribution use."[1]
- **Venting**: The deliberate or routine release of natural gas into the atmosphere. Venting includes blowdowns (e.g., when gas is evacuated from a section of pipeline for the purpose of conducting tests, repairs, or maintenance), emissions from pneumatic devices (which operate natural gas-driven controllers and natural gas-driven pumps, both of which emit natural gas as a function of routine operation), and the emissions of non-hydrocarbon gases (including CO_2), which are removed from the raw natural gas during processing.

- **Flaring**: A method of disposing of natural gas that cannot be economically used on site or transported via pipeline. The gas is burned using flares, usually at production sites or at gas processing plants (EIA, 2015).
- **Fugitive emissions:** Leaked natural gas, which includes losses of natural gas from natural gas infrastructure that occur inadvertently as a result of malfunctioning or aging equipment (e.g., damaged seals or loose fittings).

Three Sankey diagrams[*] are presented below, along with discussion of the data, calculations, and assumptions that were used to develop the diagrams. The diagrams illustrate the scale of emissions from various parts of the natural gas system, with a particular focus on emissions from natural gas infrastructure upstream of end-use consumers. The first diagram (Figure 1) presents this information in terms of volume of natural gas, measured in billion cubic feet (Bcf). The second and third diagrams (Figures 2 and 3) present comparable information in terms of GHG emissions and CO_2e units. For the purposes of this analysis, natural gas infrastructure is broken into four distinct stages/segments upstream of end-use consumers: production, processing, transmission and storage, and distribution.[†] For the purposes of this analysis, production facilities include gathering and boosting equipment that enables the transportation of natural gas from the well pad to processing facilities.[‡] The term "end-use consumers" includes the residential, commercial, industrial, vehicle fuel, and electric power sectors.

1.1 Data Sources and Uncertainty

All of the data used for this analysis are derived from the U.S. Energy Information Administration (EIA) website and the U.S. Environmental Protection Agency's (EPA's) 2014 GHG inventory report. The specific data used for each part of the analysis are discussed in detail below. This analysis includes only data from 2012, which are the most recently available. EPA estimates the 95% confidence interval for their estimate of 2012 CH_4 emissions from the natural gas sector to be 125.2 to 201.1 MMT (equivalent to teragrams [Tg]) CO_2e, which is -19% to +30% of their most probable value of 154.6 MMT CO_2e.[2,§] EIA does not provide uncertainty estimates for their data. Though the data presented here represent the vast majority of GHG emissions from natural gas infrastructure, this analysis does not constitute a life cycle analysis. For example, emissions associated with diesel equipment operating at production sites or electricity generation that powers electric drive natural gas compressors are not accounted for here.

1.2 Natural Gas Composition

Raw natural gas comprises methane and other gases. The composition of raw natural gas varies regionally and is dependent on the source of the gas. Gas composition varies depending on the geology

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[*] Sankey diagrams are a type of flow diagram in which the width of the arrows is proportionate to the size of the represented flow. In this case, the flow quantities represent emissions.

[†] This analysis does not include transfers to and from natural gas storage, as net transfers to and from storage are assumed to balance over time.

[‡] This scope is consistent with how emissions are reported by EPA and also how fuel use (i.e., "lease fuel") is reported by the EIA.

[§] As explained below, this assumes a global warming potential of 25 for methane.

of the source rock (regional or play**-specific results are beyond the scope of this study).[3] Table 1 shows nationally averaged natural gas composition, by mass, before and after processing to refine the gas and increase the methane content ("production" and "pipeline quality" natural gas, respectively).

Table 1: Natural gas composition by mass, before and after processing.[4]

Component	Production	Pipeline Quality
CH_4 (Methane)	78.3%	92.8%
NMVOC (Non-Methane Volatile Organic Compounds)	17.8%	5.54%
N_2 (Nitrogen)	1.77%	0.55%
CO_2 (Carbon Dioxide)	1.51%	0.47%
H_2S (Hydrogen Sulfide)	0.5%	0.01%
H_2O (Water)	0.12%	0.01%

2.0 Emissions and Fuel Use throughout Natural Gas Infrastructure, by Volume

This section describes the methodology that was used to calculate the volume of natural gas that is used as fuel, vented, flared, and leaked from each segment of natural gas infrastructure. Figure 1 shows that the volume of natural gas that is emitted or used as fuel by the infrastructure itself is much smaller than the volume that is delivered to consumers. Note that data in the text and figures may not always match exactly, due to rounding.

2.1 Production

2.1.1 Flaring and venting

At the production stage, the volume of natural gas that was flared or vented in 2012 was 212.848 Bcf.[5,††] Flaring and venting take place at multiple stages throughout natural gas infrastructure. However, EIA only reports flared and/or vented gas from the production segment.[‡‡] The volume of natural gas that EIA reports as flared, which is used in this analysis, includes some natural gas that is produced from crude oil wells. The percentage of EIA's natural gas flaring volume attributable to crude oil production varies by year, but could be over 50%, as shown in Appendix 1.

** A "play" is defined as a set of known or postulated oil and or gas accumulations sharing similar geologic, geographic, and temporal properties, such as source rock, migration pathways, timing, trapping mechanism, and hydrocarbon type.

†† The United Nations Global Gas Flaring Reduction program reported 7.1 bcm, or 251 Bcf, of flared gas in the United States in 2011, as estimated from satellite data.

‡‡ EIA reports volumes of "vented and flared" natural gas. However, EPA reports methane emissions associated with vented natural gas separately from CO_2 emissions associated with flared natural gas. Therefore, Figure 1 includes some overlap (i.e., double counting) with respect to the relatively small *volumes* of "flared and vented" emissions (which are from EIA) and the methane emissions (which are converted from EPA data). This is an issue only for volumes of natural gas presented in Figure 1; subsequent figures do not include any double-counted data.

2.1.2 Methane emissions

EPA reports that 1,992 gigagrams (Gg) of methane were emitted from the production segment of natural gas infrastructure in 2012.[6] This mass of methane is converted to a corresponding volume of natural gas as follows. First, mass of methane is converted to mass of natural gas using the methane composition in the "production" column of Table 1:

1,992 Gg methane / 0.783 = 2,544 Gg natural gas

Mass of natural gas is then converted to volume using the conversion factors (see Appendix 2 for development):

2,544 Gg natural gas * 41.239 = 82,148 MMcf natural gas = 82.15 Bcf natural gas

Figure 1. Volumes of natural gas consumption for fuel, emissons, and delivered to consumers, 2012[7,8,§§]

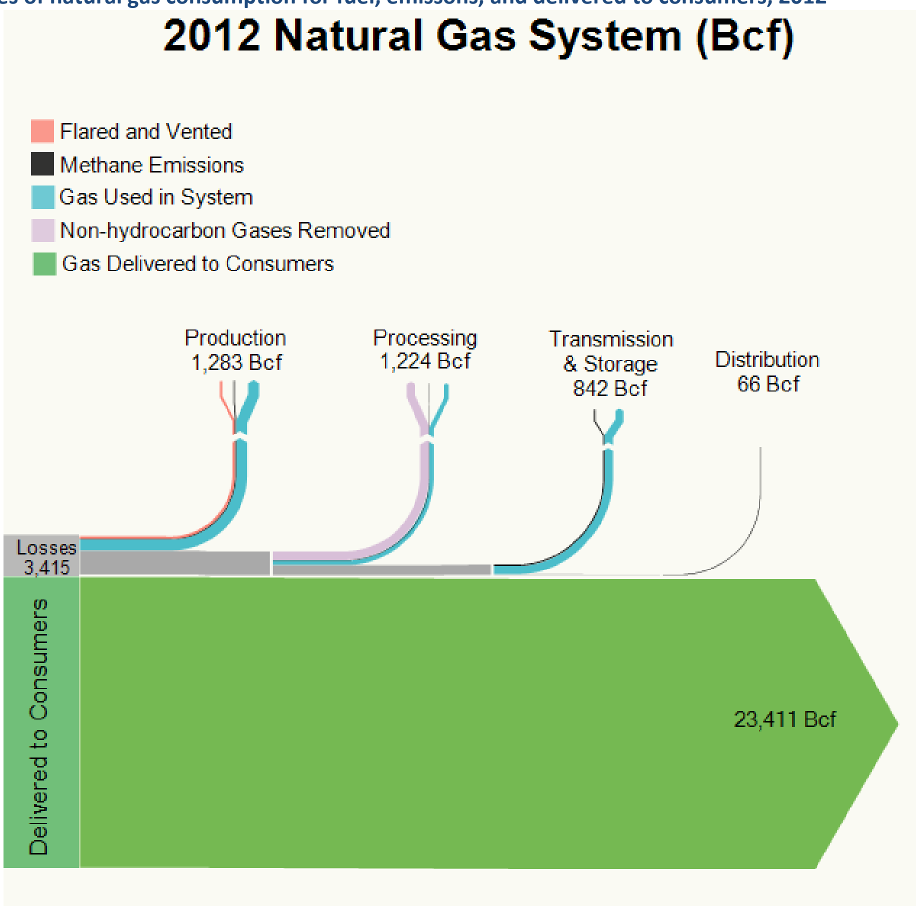

Diagram includes natural gas at varying stages of composition. The hydrocarbon composition of natural gas changes with the removal of non-hydrocarbon gases during the processing stage. This change in composition (and volume) resulting from processing is represented in the diagram with the removal of non-hydrocarbon gases.

[§§] Natural gas used in the production stage (i.e., "lease fuel") includes some activities associated with oil wells. Flaring and venting data also reflect these activities occurring at both oil and natural gas wells. Otherwise, all data in Figure 1 reflect fuel use and emissions that are exclusively associated with the natural gas system. For context, note that EIA estimated that "associated natural gas" production (gas produced along with oil) made up roughly 10% of total U.S. dry gas production in 2012 (according to the 2014 Annual Energy Outlook).

2.1.3 Natural gas fuel use

In addition to consumption by the electric power sector and other end-use consumers, EIA's website reports "Natural Gas Consumption by End Use" for "lease fuel," "plant fuel," and "pipeline and distribution use." EIA defines lease fuel as "natural gas used in well, field, and lease operations, such as gas used in drilling operations, heaters, dehydrators, and field compressors." For the purpose of the following analysis, "lease fuel" is considered to be natural gas combusted within the production stage of natural gas infrastructure. The volume of natural gas that was combusted as lease fuel in 2012 was 987,957 MMcf (987.957 Bcf).[9]

2.2 Processing

2.2.1 Non-hydrocarbon gas removal

The volume of non-hydrocarbon gases (CO_2, helium, hydrogen sulfide, nitrogen, etc.) that were removed during natural gas processing in 2012 was 768.598 Bcf.[10] These non-hydrocarbon gases are part of the raw natural gas that is extracted at wellheads, and they are removed through processing to reduce impurities and to raise the hydrocarbon content of pipeline-quality natural gas. Non-hydrocarbon gases removed during processing are typically vented to the atmosphere, which can include venting of CO_2 (included in red line in Figure 1).

2.2.2 Methane emissions

EPA reports that 892 Gg of methane was emitted by natural gas processing facilities in 2012.[11] This volume of methane was converted to a volume of natural gas using the same conversion process used for fugitive emissions from the production sector (Section 2.1.2), the only difference being the different hydrocarbon composition of processed natural gas. The composition of process-stage natural gas is assumed to be a weighted average of pre-processed (32%) and post-processed (68%) natural gas:[12]

892 Gg methane / (0.783 * 0.32 + 0.928 *0.68) = 961 Gg natural gas

961 Gg natural gas * (41.239 * 0.32 + 49.703 * 0.68) = 47,550 MMcf natural gas = 47.55 Bcf natural gas

2.2.3 Natural gas fuel use for processing

EIA defines "plant fuel" as "natural gas used as fuel in natural gas processing plants." For the purpose of this analysis, "plant fuel" is considered to be the natural gas combusted by processing plants. The volume of natural gas combusted as "plant fuel" in 2012 was 408,316 MMcf (408.316 Bcf).[13]

2.3 Transmission and Storage

2.3.1 Methane emissions

EPA reports that 2,071 Gg of methane was emitted from the transmission and storage stage in 2012.[14] This was converted to a volume of natural gas using the same conversion process used for fugitive emissions from the processing sector (Section 2.2.2):

2,071 Gg methane / 0.928 = 2,231 Gg natural gas

2,231 Gg natural gas * 49.703 = 110,920 MMcf natural gas =110.92 Bcf natural gas

2.3.2 Natural gas fuel use

EIA's natural gas "pipeline and distribution use" is assumed to be the natural gas that is combusted in the transmission and storage segment. The volume of natural gas that was combusted for transmission and distribution in 2012 was 730,790 MMcf (730.79 Bcf).[15]

2.4 Distribution

Distribution systems are located downstream of city gates and distribute pipeline-quality natural gas to residential, commercial, and industrial customers.[***] There is very little natural gas used as fuel by natural gas distribution companies. Though EIA reports "pipeline and distribution use" of natural gas together, for the purposes of this exercise, it is assumed that all of this gas is used as a fuel for transmission and storage (including liquefied natural gas storage) and that none is used for local distribution.

2.4.1 Methane emissions

The EPA reports that 1,231 Gg of fugitive methane was emitted from distribution systems in 2012.[16] This was converted to a volume of natural gas using the same conversion process used for fugitive emissions from the processing sector (Section 2.2.2):

1,231 Gg methane / 0.928 = 1,338 Gg natural gas

1,338 Gg natural gas * 49.703 = 65,930 MMcf natural gas =65.93 Bcf natural gas

2.5 Consumer End Use

End-use combustion is the largest component of natural gas consumption in the natural gas system. The amount of natural gas consumed by end users in 2012 was 23,411,423 MMcf (23,411 Bcf).[17]

3.0 Greenhouse Gas Emissions from the Natural Gas System, by Mass

Each type of natural gas fuel use, leakage, and venting from the natural gas system has associated greenhouse gas (GHG) emissions, either from fugitive emissions and venting, release of naturally occurring CO_2 from raw natural gas, or CO_2 created by combusting natural gas. The Sankey diagram in Figure 2 shows the magnitudes of the GHG emissions associated with each stage and the sources of emissions, presented in terms of CO_2 equivalents. The Sankey diagram in Figure 3 shows the same GHG emissions shown in Figure 2, in addition to GHG emissions associated with end uses of natural gas by consumers. Note that data in the text and figures may not always match exactly, due to rounding.

Methane is a potent greenhouse gas; it is more than 25 times more potent a GHG than CO_2[18] on a 100-year basis. Global-warming potential (GWP) is commonly used to quantify the globally averaged relative

[***] Natural gas used by electric generation units and other large industrial facilities is generally delivered directly from the transmission network (as opposed to being purchased from local distribution companies), and this gas does not pass through city gates.

radiative forcing of GHGs relative to CO_2[†††] (i.e., CO_2 equivalent).[19] The CO_2 equivalent of methane leakage is equal to the quantity (in grams, or other unit of mass) of methane leaked multiplied by a factor representing the GWP of methane. In this analysis, a GWP of 25[‡‡‡] for methane was used to be consistent with EPA.

3.1 Production

3.1.1 Flaring and venting of "non-combustion CO_2"

The EPA inventory reports "non-combustion" CO_2, which, at the production site, is primarily the result of flaring. The resulting GHG emissions from flaring are 13,662.6 Gg of CO_2 (13.66 MMT CO_2).[20] EPA also reports 930.6 Gg of CO_2 (0.93 MMT CO_2)[21] from other non-combustion sources.

3.1.2 Methane emissions

EPA reports that 1,992 Gg of methane were emitted from natural gas production facilities in 2012.[22] This mass of methane is converted to an equivalent mass of CO_2 emissions using the GWP of methane:

1,992 Gg methane * 25 = 49,800 Gg CO_2e = 49.8 MMT CO_2e

3.1.3 Natural gas fuel use

As in the analysis for Figure 1, EIA's "lease fuel" is considered to be the natural gas combusted by production facilities. The volume of natural gas that was combusted as "lease fuel" in 2012 was 987,957 MMcf (987.957 Bcf).[23] This was converted to a mass of natural gas using the conversion factor developed in Appendix 2:

987,957 MMcf of natural gas / 41.239 = 23,956.9 Gg natural gas

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[†††] GWP is a general concept that can be applied to any greenhouse gas. The Intergovernmental Panel on Climate Change (Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Chapter 8: Anthropogenic and Natural Radiative Forcing) describes GWP as "the time-integrated radiative forcing due to a pulse emission of a given component, relative to a pulse emission of an equal mass of CO_2."

[‡‡‡] Calculating the GWP of a GHG depends on many factors, including the length of time over which the GWP is evaluated and whether additional climate feedback mechanisms are included. The Intergovernmental Panel on Climate Change's Fifth Assessment Report (AR5) uses a GWP of 84 methane evaluated over a 20-year time horizon (86 with additional climate feedbacks), and 28 when evaluated over a 100-year time horizon (34 with additional climate feedbacks) (Intergovernmental Panel on Climate Change, Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, page 714, Table 8.7). Including the climate impacts of oxidation of methane from fossil sources increases the GWP of methane by 1 on a 20-year time horizon (to 87) and 2 on a 100-year time horizon (to 36). The uncertainty in these GWP values is estimated to be ±30% and ±40% for 20- and 100-year time horizon, respectively (for 90% uncertainty range), resulting primarily from uncertainties in the long-term climate impact of CO_2 and the indirect climate feedbacks associated with methane. The GWP value of 25 used in this analysis is from the 2007 version of the IPCC report (AR4). Climate-carbon feedback effects were not used in calculating GPWs for GHGs other than CO_2 in the 2007 IPCC report (including the GWP for methane used in this report), but climate-carbon feedback effects are included in calculating the GWP of all GHGs in the more recent IPCC report (AR5). As noted in IPCC's documentation for AR5, the inclusion of climate-carbon feedbacks introduces additional uncertainty of +/- 20% to the GWP factors. So, while the inclusion of climate-carbon feedbacks in the more recent IPCC GWPs does more consistently account for broader impacts from GHG emissions, it introduces further uncertainty. The 100-year GWP of 25 is used by the EPA in its GHG inventory.

The mass of CO_2 resulting from natural gas combustion is calculated in Appendix 3:

23,956.9 Gg natural gas combusted *2.70 = 64,683 Gg CO_2e = 64.68 MMT CO_2e

3.2 Processing

3.2.1 Non-hydrocarbon gas removal

EPA reports 21,403.6 Gg of CO_2 is released during the processing stage.[24] Venting from non-hydrocarbon gas removal[§§§] accounts for 99.7% of these process-related (i.e. non-combustion) CO_2 emissions.

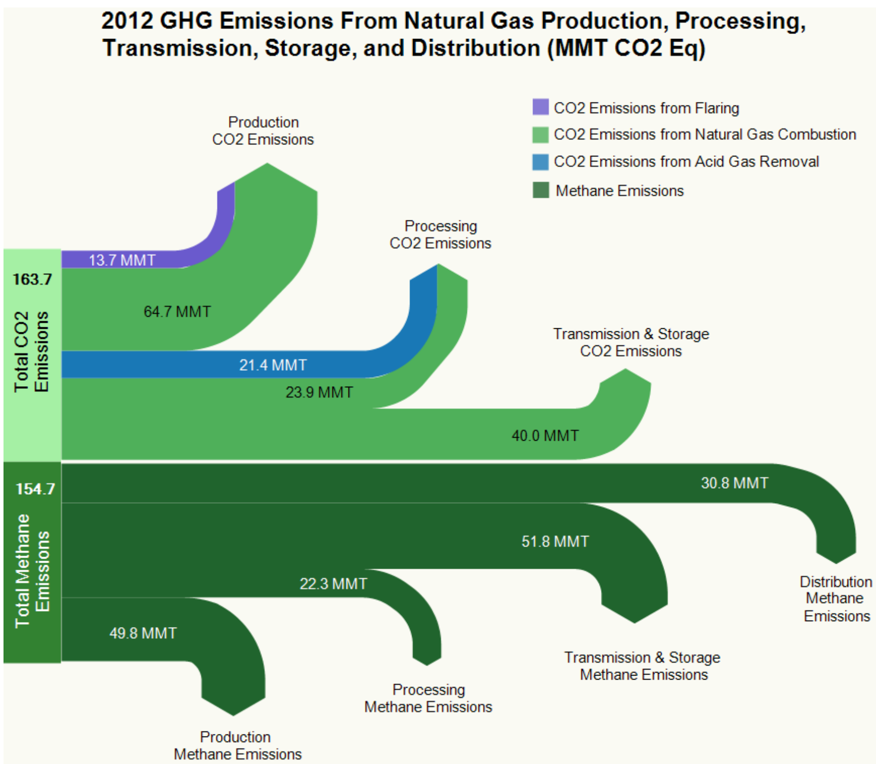
21,403.6 Gg of CO_2 = 21.4 MMT CO_2e

3.2.2 Methane emissions

EPA reports that 892 Gg of methane were emitted from the processing stage in 2012.[25] This mass of methane is converted to an equivalent mass of CO_2 emissions using the GWP of methane:

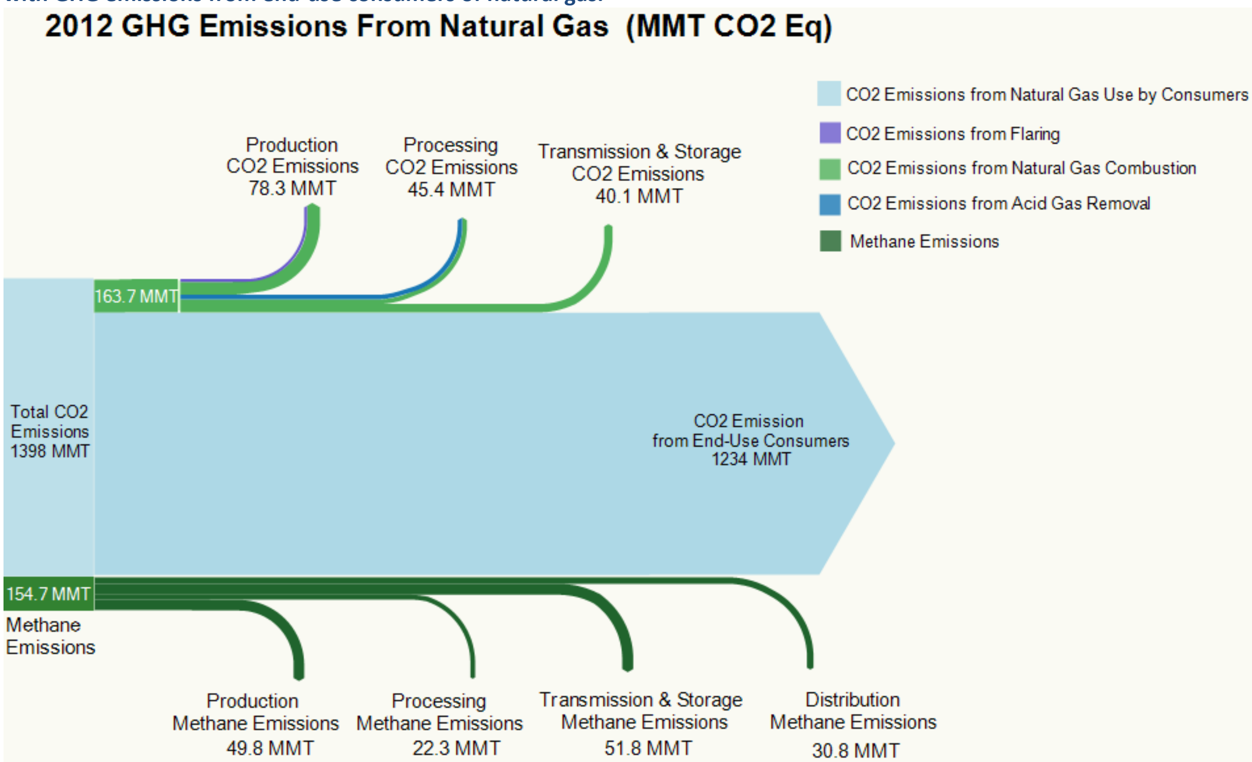
892 Gg methane * 25 = 22,300 Gg CO_2e = 22.3 MMT CO_2e

Figure 2. 2012 GHG emissions from natural gas production, processing, transmission, storage, and distribution. Note that this figure does not show GHG emissions from end-use consumers (see Figure 3 for image of all GHGs from natural gas systems).[26,27,28]



[§§§] EPA reports "non-combustion CO_2 emissions" but specifies that 99.7% of these emissions are due to "acid gas removal." EPA uses the phrase "acid gas removal" to denote the process called "non-hydrocarbon gas removal" in this analysis.

Figure 3: 2012 GHG emissions from natural gas production, processing, transmission, storage, and distribution compared with GHG emissions from end-use consumers of natural gas.[29,30]



3.2.3 Natural gas fuel use

As in the previous section, EIA's "plant fuel" is considered to be the volume of natural gas combusted by processing plants. The volume of natural gas that was combusted as "plant fuel" in 2012 was 408,316 MMcf (408.316 Bcf).[31] This was converted to a mass of natural gas using the conversion factor developed in Appendix 2, taking into account the change in composition that occurs when gas is processed:

408,316 MMcf of natural gas * (2.70 / 41.239 * 0.36 + 2.72 / 49.703 * 0.64) = 23.92 MMT CO_2e

3.3 Transmission and Storage

3.3.1 Methane emissions

EPA reports that 2,071 Gg of methane were emitted from the transmission and storage stage in 2012.[32,****] This mass of methane is converted to an equivalent mass of CO_2 emissions using the GWP of methane:

2,071 Gg methane * 25 = 51,775 Gg CO_2e = 51.78 MMT CO_2e

3.3.2 Natural gas fuel use

EIA's natural gas "pipeline and distribution use" is assumed to be the volume of natural gas that is combusted in the transmission and storage segment. The volume of natural gas that was combusted for

**** EPA also reports 63 Gg of non-combustion CO_2 emissions from the transmission and storage sector. These emissions are very small relative to those shown in Figures 2 and 3 and were omitted for legibility.

transmission and distribution in 2012 was 730.79 Bcf.[33] This was converted to a mass of natural gas using the same conversion used for natural gas fuel use in the processing segment:

730,790 MMcf of natural gas / 49.703 = 14,703.1 Gg natural gas

The mass of CO_2 resulting from natural gas combustion is calculated in Appendix 3:

15,736.7 Gg natural gas combusted *2.72 = 39,992 Gg CO_2e = 39.99 MMT CO_2e

3.4 Distribution

3.4.1 Methane emissions

EPA reports that 1,231 Gg of methane were emitted from distribution systems in 2012.[34,††††] This mass of methane is converted to an equivalent mass of CO_2 emissions using the GWP of methane:

1,231 Gg methane * 25 = 30,775 Gg CO_2e = 30.78 MMT CO_2e

3.5 Consumer End Use Combustion

End-use combustion is the largest source of CO_2 emissions associated with the natural gas life cycle, as shown in Figure 3. Specifically, EIA reports 1,362.49 MMT CO_2 emissions associated with natural gas combustion.[35] Total CO_2e emissions from consumer end-use combustion were estimated as the difference between total natural gas combustion CO_2 emissions and CO_2 emissions from natural gas combustion within the natural gas supply chain:

1,362.49 Gg CO_2 – 64.68 Gg CO_2 – 23.92 Gg CO_2 – 39.99 Gg CO_2 = 1,233.9 Gg CO_2

Note, total CO_2 emissions from natural gas broadly is the combination of emissions from combustion (1,362.49 MMT CO_2), plus emissions from non-hydrocarbon gas removal (21.4 MMT CO_2) and from flaring (13.66 MMT CO_2), resulting in the following: 1397.6 MMT CO_2.

[††††] EPA also reports 37 Gg of non-combustion CO_2 emissions from the distribution sector. Similar to the transmission and distribution sector, these emissions were omitted from Figures 2 and 3 for legibility.

Appendix 1: Natural gas flaring associated with crude oil production

Natural gas that is co-produced with crude oil and natural gas liquids can be flared intentionally near production sites. This can occur as a result of infrastructure constraints that limit the ability of producers to transport natural gas to market at profitable rates. The Bakken shale in North Dakota and the Eagle Ford shale in Texas are two areas with high rates of natural gas flaring, which, for the purpose of this analysis, is assumed to be associated with oil production.

As shown in Table 2, flaring in North Dakota and the Eagle Ford shale are estimated to account for more than half of natural gas flaring in the United States in 2012. The state-wide flaring numbers for North Dakota are assumed to be wholly associated with oil production in the Bakken shale, as the Bakken is the dominant shale play in North Dakota. Flaring numbers in the Eagle Ford shale are assumed to be wholly associated with oil production in that basin. These data form the basis for the estimate of the national percentage of flaring associated with oil production shown in the last row. This estimate likely includes some flaring associated with natural gas production in North Dakota and excludes oil-associated flaring in other states and other parts of Texas. Additional analysis beyond the scope of this study would be needed to more precisely attribute national totals of natural gas flaring to oil, natural gas liquids, or natural gas production wells.

Table 2: Flaring (in Bcf), for North Dakota and the Eagle Ford shale in particular, compared to flaring for the entire U.S. natural gas system.

	2011	2012	2013
US total (EIA)[36]	209[37,‡‡‡‡]	213	260
North Dakota total[38]	57	90	115
Texas total[39]	35	48	77
Eagle Ford total[40]	14	21	
Estimated oil associated flaring (ND + Eagle Ford, bcf)	71	111	
Estimated oil associated flaring (% of US total flaring)	**34%**	**52%**	

‡‡‡‡ For comparison, the World Bank estimates that 251 Bcf of natural gas was flared in the U.S., in 2011 (data for years after 2011 are not yet available).

Appendix 2: Natural gas mass and volume conversions

This appendix develops factors for converting natural gas volumes to mass, accounting for average compositions and densities of natural gas components.

The density of natural gas was calculated based on the gas composition shown in Tables 1 and 3. These compositions were weighted by the densities of individual compounds in Table 1.

Table 3. Densities of natural gas components.[41]

Component	Density (kg/m^3)
Methane	0.656
Ethane	1.356
Propane	2.010
iso-Butane	2.510
n-Butane	2.480
N_2	1.251
CO_2	1.977
H_2S	1.360
H_2O	0.804

For example:
Pipeline quality density = (methane density x 92.8%) + (ethane density x 3.7%) + (propane density x 0.9%) etc.

The resulting density conversions are 41.239 MMcf per Gg of natural gas before processing and 49.703 MMcf per Gg after processing.

Appendix 3: CO_2 emissions from natural gas combustion

The following subsections explain the methodologies used to determine the amount of CO_2 emissions resulting from a given quantity of natural gas as a fuel source in the natural gas supply chain. EIA provides natural gas fuel use in terms of volumes of natural gas. The following three appendices describe, in three steps, the conversion factors that were used to convert from a volume of natural gas combustion to resulting CO_2 emissions.

A3.1 CO_2 emissions from combustion of methane in natural gas

The CO_2 emissions from methane used for combustion in the natural gas supply chain were calculated using the following reaction:

$CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$ implies that 16 Gg methane + 64 Gg oxygen → 44 Gg carbon dioxide + 36 Gg water = 2.75 Gg of CO_2 are produced for every Gg of methane that is combusted

A3.2 CO_2 emissions from combustion of non-methane hydrocarbons in natural gas

The CO_2 emissions from combustion of non-methane hydrocarbons in natural gas were calculated assuming the following higher-chain hydrocarbon composition of natural gas:

Table 4. Non-methane hydrocarbon composition of natural gas, by mass.[42]

Component	Production	Pipeline quality
Ethane	12.0 %	3.7 %
Propane	3.0 %	0.9 %
Butane	1.7 %	0.5 %
Pentane	0.7 %	0.2 %
Hexane	0.4 %	0.1 %
Total non-methane	17.8 %	5.5 %

Chemical equations were developed for each of the five non-methane components listed in Table 4. For example, considering ethane:

$2C_2H_6 + 7O_2 \rightarrow 4CO_2 + 6H_20$ so 60.1 Gg ethane combusted produces 176.0 Gg CO_2, or 2.93 Gg of CO_2 per Gg of ethane combusted

This process was repeated for all five hydrocarbons, and the results were weighted according to the pipeline quantities in Table 4. The resulting weighted average is 2.96 Gg CO_2 generated per Gg of non-methane hydrocarbons combusted, which is slightly higher than the 2.93 Gg of CO_2 per Gg of ethane combusted due to the small contributions of propane and other non-methane hydrocarbons. The result of 2.96 Gg CO_2 per Gg of non-methane hydrocarbons is the same using both the production and pipeline quality gas composition weighting.

A3.3 Total CO_2 emissions from natural gas combustion

The total CO_2 emissions from natural gas comprise the sum of emissions from the combustion of the methane and non-methane components, plus the release of non-combustion CO_2 contained in the natural gas. These sources of GHG emissions were weighted based on the natural gas composition in Table 1. For pre-processed natural gas:

$$2.75 \text{ Gg } CO_2/\text{Gg } CH_4 \times 78.3\% + 2.96 \text{ Gg } CO_2/\text{Gg HC} \times 17.8\% + 1 \text{ Gg } CO_2/\text{Gg } CO_2 \times 1.51\%$$
$$= 2.70 \text{ Gg } CO_2/\text{Gg NG}$$

For pipeline quality natural gas:

$$2.75 \text{ Gg } CO_2/\text{Gg } CH_4 \times 92.8\% + 2.96 \text{ Gg } CO_2/\text{Gg HC} \times 5.54\% + 1 \text{ Gg } CO_2/\text{Gg } CO_2 \times 0.47\%$$
$$= 2.72 \text{ Gg } CO_2/\text{Gg NG}$$

Appendix 4: Data from figures

Table 5. Summary of data and methodology for Figure 1.[§§§§]

Stage	Given	Units	Conversions	NG (Bcf)
Production				**1,282.95**
flaring and venting[43]	212,848	MMcf of NG	MMcf NG -> Bcf NG	212.85
fuel use[44]	987,957	MMcf of NG	MMcf NG -> Bcf NG	987.96
fugitive emissions[45]	1,992	Gg of CH_4	Gg CH_4 -> Gg NG -> MMcf NG -> Bcf NG	82.15
Processing				**1,224.46**
gas removal[46]	768,598	MMcf of gases removed	MMcf gases removed -> Bcf gases removed	768.60
fuel use[47]	408,316	MMcf of NG	MMcf NG -> Bcf NG	408.32
fugitive emissions[48]	892	Gg of CH_4	Gg CH_4 -> Gg NG -> MMcf NG -> Bcf NG	47.55
Transmission and storage				**841.71**
fuel use[49]	730,790	MMcf of NG	MMcf NG -> Bcf NG	730.79
fugitive emissions[50]	2071	Gg of CH_4	Gg CH_4 -> Gg NG -> MMcf NG -> Bcf NG	110.92
Distribution				**65.93**
fugitive emissions[51]	1,231	Gg of CH_4	Gg CH4 -> Gg NG -> MMcf NG -> Bcf NG	65.93
Consumer end use[52]	23,411,423	MMcf of NG	MMcf NG -> Bcf NG	**23,411.42**

[§§§§] Note that data in this table may not always match exactly with data in the figures, due to rounding.

Table 6: Summary of data and methodology for Figures 2 and 3.*****

Stage	Given	Units	Conversions	CO_2e (Tg)
Production				**128.15**
flaring and venting[53]	13,662.6	Gg of CO_2 eq	Gg CO_2 eq -> Tg CO_2 eq	13.66
fuel use[54]	987,957	MMcf of NG	MMcf NG -> Gg NG -> Gg CO_2 eq -> Tg CO^2 eq	64.68
fugitive emissions[55]	1992	Gg of CH_4	Gg CH_4 -> Gg CO_2 eq -> Tg CO_2 eq	49.80
Processing				**67.68**
gas removal[56]	21,403.6	Gg of CO_2 eq	Gg CO_2 eq -> Tg CO_2 eq	21.40
other non-combustion[57]	65.2	Gg of CO_2 eq	Gg CO_2 eq -> Tg CO_2 eq	0.07
fuel use[58]	408,316	MMcf of NG	MMcf NG -> Gg NG -> Gg CO_2 eq -> Tg CO_2 eq	23.92
fugitive emissions[59]	892	Gg of CH_4	Gg CH_4 -> Gg CO_2 eq -> Tg CO_2 eq	22.30
Transmission and storage				**91.77**
non-combustion[60]	63.4	Gg of CO_2 eq	Gg CO_2 eq -> Tg CO_2 eq	0.06
fuel use[61]	730,790	MMcf of NG	MMcf NG -> Gg NG -> Gg CO_2 eq -> Tg CO_2 eq	39.99
fugitive emissions[62]	2071	Gg of CH_4	Gg CH_4 -> Gg CO_2 eq -> Tg CO_2 eq	51.78
Distribution				**30.82**
non-combustion[63]	36.8	Gg of CO_2 eq	Gg CO_2 eq -> Tg CO_2 eq	0.04
fugitive emissions[64]	1,231	Gg of CH_4	Gg CH_4 -> Gg CO_2 eq -> Tg CO_2 eq	30.78
Consumer end-use[65]		Tg CO_2 from combustion	Tg CO_2 combustion - Tg CO_2 process emissions	**1,233.91**

***** Note that data in this table may not always match exactly with data in the figures, due to rounding.

Endnotes

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