Gas Lifecycle Methane Emissions, Richards Bay Review

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Synopsis

This report summarizes the latest research on the greenhouse gas emissions of "natural" gas (from here forward, "gas"). It concludes that the climate impacts of gas are greater than those of coal per unit of energy produced when evaluated in a 20-year timeframe, the period most relevant for climate change if humans are to avoid catastrophic run-away warming. The science summarized reveals the following:

- Though gas emits less carbon dioxide at combustion per unit energy than coal, its upstream greenhouse gas (GHG) emissions are more problematic for the climate, as it releases potent methane in leaks and venting throughout its lifecycle.
- Researchers have been able to detect emissions across the lifecycle of gas ever more accurately given new methodologies and technologies (particularly "top-down" measurements using satellite and aerial assessments); these new studies have consistently shown that emissions from gas production are higher than were previously estimated using "bottom-up" facility-based measurements. New research is also revealing higher downstream gas emissions than earlier predicted (i.e., in gas transmission, distribution, and end use).
- The average lifecycle emissions of gas are growing globally because
    - Shale gas is growing as a percentage of all gas, and its production likely emits more methane and other greenhouse gases than conventional gas production; and
    - Liquified Natural Gas (LNG) markets are growing, and turning gas into a liquid for shipping requires large amount of gas to be burned, greatly increasing the gas's GHG emissions.
- While it is unclear where gas will come from to feed the proposed Richards Bay 3000 MW CCPP, the environmental review materials suggest that leading candidates include shale gas from the Karoo, or LNG, potentially from shale reserves in the US or Australia, or closer African countries like Angola, Algeria, or Namibia that are increasingly looking to develop shale gas resources.
- Methane emissions from shale gas are particularly worrisome because
    - Methane (CH_4) is 86 times more potent than carbon dioxide (CO_2) on a 20-year timescale; and
    - Global methane emissions are accelerating, and appear to be rising at the rate that would be predicted to result from the shale gas boom.

The report is comprised of five sections:

I. Gas system emissions research
II. Methane's role in climate change
III. Gas lifecycle stages
IV. Emissions from stages of gas lifecycle
V. Comparison of gas and coal emissions on the climate

1 Gas system emissions research

New research methodologies and technologies have revealed that, contrary to common wisdom of twenty years ago, methane leakage from the gas system negates the climate benefits of gas at its end use over coal or heavy fuel oil.

For about two decades, many world leaders, and even environmental NGOs, assumed that "natural" gas (from here forward, "gas") would be an improvement over coal for the climate because gas produced fewer CO_2 emissions when combusted per unit energy. This enabled leaders to support domestic extraction of gas from shale using a new combination of techniques termed hydraulic fracturing, or "fracking," and the build-out of gas infrastructure to replace coal-fired power plants. Gas was described as a "bridge fuel" that allowed a continued use of fossil fuels for a few decades while phasing out coal and moving towards and eventual fossil-fuel-free future based on only renewable energy.

The new flurry of gas buildouts in the 2000s led independent researchers, particularly in the United States, to begin to examine more closely the climate impacts of gas throughout its lifecycle. It was already well-established that gas differed from coal because coal emissions are primarily comprised of those generated by end-use combustion, while gas, being comprised primarily of methane gas, is prone to leak throughout its lifecycle.[1] The extent of these leaks across the gas system was poorly understood, however, given challenges to measuring them.

Assessments of gas system emissions to date had come from "bottom-up" assessments of average leakage across a relatively small sample of the types of infrastructure used across gas lifecycles. These estimates were based on evaluating individual emission sources on the ground and summing these up to get total emissions. These figures have long been used to estimate national greenhouse gas emissions from the gas sector.

Yet new technologies have been developed over the last decade that allow researchers to assess greenhouse gas emissions from the gas lifecycle from the "top-down." These new technologies, including satellites and aerial measurements, have revealed that bottom-up estimates severely underestimate actual emissions.[2]

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[1] c.f. P. A. Okken, *Methane leakage from natural gas*, 18 ENERGY POLICY 202–204 (1990), https://www.sciencedirect.com/science/article/pii/030142159090147V (last visited Apr 3, 2021).

[2] S. M. Miller et al., *Anthropogenic emissions of methane in the United States*, 110 PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES 20018–20022 (2013), http://www.pnas.org/cgi/doi/10.1073/pnas.1314392110 (last visited Nov 21, 2019); Robert W. Howarth, *A bridge to nowhere: methane emissions and the greenhouse gas footprint of natural gas*, 2 ENERGY SCIENCE & ENGINEERING 47–60 (2014), https://onlinelibrary.wiley.com/doi/abs/10.1002/ese3.35 (last visited Apr 3, 2021); Timothy L. Vaughn et al., *Temporal variability largely explains top-down/bottom-up difference in methane emission estimates from a natural gas production region*, 115 PNAS 11712–11717 (2018), https://www.pnas.org/content/115/46/11712 (last visited Feb 26, 2020); Ramón A. Alvarez et al., *Assessment of methane emissions from the U.S. oil and gas supply chain*, SCIENCE eaar7204 (2018), http://www.sciencemag.org/lookup/doi/10.1126/science.aar7204 (last visited Nov 20, 2019); Xinrong Ren et al., *Methane Emissions from the Marcellus Shale in Southwestern Pennsylvania and Northern West Virginia Based on Airborne Measurements*, 124 JOURNAL OF GEOPHYSICAL RESEARCH: ATMOSPHERES 1862–1878 (2019), https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018JD029690 (last visited Feb 26, 2020).

Emissions measured bottom-up have underestimated leaks in part because these bottom-up methods require permission from gas operators to access sites, likely biasing measurements toward companies and sites with more controlled methane leaks.[3] In addition, the bottom-up estimates do not include all possible individual emission sources within the gas lifecycle. For instance, to date not a single published study using bottom-up approaches to estimate methane emissions from shale gas has included the emissions during the initial well drilling phase, which can be high,[4] and the emissions from venting of tanks storing the wastewater produced in gas extraction. The snapshot bottom-up analyses may miss variation in emissions at different times of the day, such as the regular periods when liquids are unloaded as part of the production of fracked wells.[5] Bottom-up leakage estimates with smaller samples selected by the gas companies are prone to miss large emissions sources known as "super-emitters" that significantly pull up emissions averages.[6]

At the same time, sensor and infra-red camera technologies have also advanced quickly, increasing the ease with which pipeline emissions in downstream segments of the gas lifecycle can be observed and measured. Methane is invisible to the naked eye, but can be easily visualized with these new technologies. New methods for measuring atmospheric methane and parsing its source – whether from agriculture, wetlands, or fossil gas – have also increased scientific understanding of the role of gas in climate change. The results of this research, in combination with findings that climate change is accelerating faster than predicted, has, in contrast to earlier assumptions, shown continued gas expansion globally to be incompatible with a livable climate.

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[3] Robert W Howarth, *Chapter 7: Methane and Climate Change*, *in* ENVIRONMENTAL IMPACTS FROM DEVELOPMENT OF UNCONVENTIONAL OIL AND GAS RESERVES 21 (John F. Stolz, W. Michael Griffin, & Daniel J. Bain eds., 2021).

[4] Dana R. Caulton et al., *Toward a better understanding and quantification of methane emissions from shale gas development*, 111 PNAS 6237–6242 (2014), https://www.pnas.org/content/111/17/6237 (last visited Nov 25, 2019).

[5] Stefan Schwietzke et al., *Improved Mechanistic Understanding of Natural Gas Methane Emissions from Spatially Resolved Aircraft Measurements*, 51 Environ. Sci. Technol. 7286–7294 (2017), https://doi.org/10.1021/acs.est.7b01810 (last visited May 11, 2020).

[6] Adam R. Brandt, Garvin A. Heath & Daniel Cooley, *Methane Leaks from Natural Gas Systems Follow Extreme Distributions*, 50 ENVIRON. SCI. TECHNOL. 12512–12520 (2016), https://doi.org/10.1021/acs.est.6b04303 (last visited Nov 21, 2019); Christian Frankenberg et al., *Airborne methane remote measurements reveal heavy-tail flux distribution in Four Corners region*, 113 PNAS 9734–9739 (2016), https://www.pnas.org/content/113/35/9734 (last visited Nov 21, 2019); Daniel Zavala-Araiza et al., *Toward a Functional Definition of Methane Super-Emitters: Application to Natural Gas Production Sites*, 49 ENVIRON. SCI. TECHNOL. 8167–8174 (2015), https://doi.org/10.1021/acs.est.5b00133 (last visited Nov 21, 2019).

2 Methane's role in climate change

Methane, the principal component in fossil gas, is a particularly potent greenhouse gas and a substantial driver of climate change, and its concentrations in the atmosphere are accelerating.

To explain why gas buildouts are incompatible with a safe climate future, it is important to review scientists' evolving view of the role of methane in climate change. Both methane and carbon dioxide are critical to global warming and climate disruption. These two carbon gases are the two most important for the rate of warming observed over the past few decades, with 25% of all warming observed to date ascribed to methane.[7] For the time both gases are in the atmosphere, methane is 105-times more potent as a greenhouse gas, [8] but methane emissions are considerably less than those for carbon dioxide. It is important to note that methane has a shorter residence time the in atmosphere as well: with a half-life of some 12 years, the influence of a pulse of methane emitted today lasts "only" for some 40 to 50 years into the future. Carbon dioxide emitted today will have an influence that will last for at least several centuries. It is for this reason that all climate scientists argue that we need to immediately and greatly reduce emissions of carbon dioxide. But it is also essential to reduce methane emissions. As shown in Figure 1 (modified from Shindell et al. 2012), we are on a trajectory to warm the Earth by 1.5^{O} C within the next 7 years, given current trajectories.[9] Note that warming since this paper was published in 2012 has risen steadily along the green-line trajectory that reflects no serious reductions in greenhouse gas emissions. The 1.5^{O} C threshold is critical: in Paris in Dec 2015 the nations of the world came together at COP21 to pledge to try to keep the planet well below 2^{O} C of warming, with the clear recognition that 1.5^{O} C of warming will be dangerous. We are already seeing significant damage globally from human-caused climate disruption, and as we reach these thresholds of warming – only 25 years from now to reach 2^{O} C of warming, we may well encounter tipping points in the Earth's climate system leading to runaway global climate disruption for the next thousand years or beyond.[10]

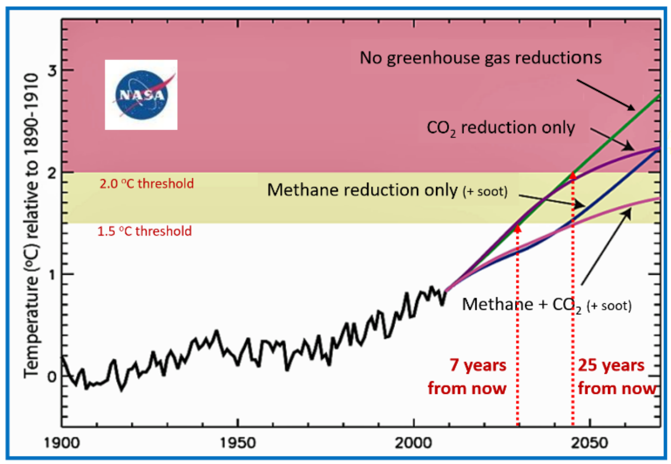

Figure 1. Observed global temperatures through 2009 and projected temperatures thereafter, relative to the 1890-1910 mean. Modified from Shindell et al. 2012

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[7] IPCC, *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (2013).
[8] *Id.*
[9] Drew Shindell et al., *Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security*, 335 SCIENCE 183–189 (2012), https://science.sciencemag.org/content/335/6065/183 (last visited Apr 3, 2021).
[10] IPCC, *supra* note 7; IPCC, *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of*

The Shindell et al. 2012 study concluded that reducing methane emissions was one of the most immediate ways to slow the rate of global warming.[11] As indicated in Figure 1, had we begun to reduce methane emissions (and emissions of black carbon, or soot) as of 2011, we would already be on a better trajectory of a slower rate of global warming. To only reduce emissions of carbon dioxide without reducing methane emissions is far less effective, essentially contributing nothing over the short term; global warming only starts to slow after 30 or more years of reduced carbon dioxide emissions. Increasingly, scientists are calling for a reduction of methane emissions in the face of a possible imminent threat of runaway climate disruption.[12]

The global warming potential of methane is defined as the radiative forcing of methane compared to carbon dioxide for a specified time period into the future for a one-time pulsed release of both gases.[13] Roughly speaking, how does methane contribute to warming compared to carbon dioxide? The time frame is critical, since as noted above methane is a far more powerful greenhouse gas but it also has a far shorter lifetime in the atmosphere. Since the Kyoto Protocol was ratified in 1997, almost all greenhouse gas inventories globally have used a global warming potential for the 100-year time period, presumably based on recommendations from the IPCC. However, this greatly understates the role of methane in global warming over shorter time periods, and nor does it accurately reflect the intent of the IPCC. In 2013, the IPCC AR5 synthesis report stated: "The GWP has become the default metric for transferring emissions of different gases to a common scale; often called 'CO2 equivalent emissions' (e.g., Shine, 2009). It has usually been integrated over 20, 100 or 500 years consistent with Houghton et al. (1990). Note, however that Houghton et al. presented these time horizons as 'candidates for discussion [that] should not be considered as having any special significance'. The GWP for a time horizon of 100 years was later adopted as a metric to implement the multi-gas approach embedded in the United Nations Framework Convention on Climate Change (UNFCCC) and made operational in the 1997 Kyoto Protocol. The choice of time horizon has a strong effect on the GWP values — and thus also on the calculated contributions of CO2 equivalent emissions by component, sector or nation. There is no scientific argument for selecting 100 years compared with other choices (Fuglestvedt et al., 2003; Shine, 2009)."[14] The bottom line is that the past time choice was arbitrary, and many scientists now call for

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strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (2018).

[11] Shindell et al., *supra* note 9.

[12] Robert W. Howarth, Renee Santoro & Anthony Ingraffea, *Methane and the greenhouse-gas footprint of natural gas from shale formations: A letter*, 106 CLIMATIC CHANGE 679–690 (2011), http://link.springer.com/10.1007/s10584-011-0061-5 (last visited Nov 25, 2019); Shindell et al., *supra* note 9; William J. Collins et al., *Increased importance of methane reduction for a 1.5 degree target*, 13 ENVIRON. RES. LETT. 054003 (2018), https://doi.org/10.1088%2F1748-9326%2Faab89c (last visited Nov 25, 2019).

[13] IPCC, *supra* note 7.

[14] *Id.* Citing Keith P. Shine, *The global warming potential—the need for an interdisciplinary retrial: An editorial comment*, 96 Climatic Change 467–472 (2009), http://link.springer.com/10.1007/s10584-009-9647-6; J. T. Houghton, G. J. Jenkins & J. J. Ephraums, *Climate change* (1990), https://www.osti.gov/etdeweb/biblio/6041139; and Jan S. Fuglestvedt et al., *Metrics of Climate Change: Assessing Radiative Forcing and Emission Indices*, 58 Climatic Change 267–331 (2003), https://doi.org/10.1023/A:1023905326842 (last visited Apr 3, 2021).

using a shorter time period such as 20 years.[15] The State of New York declared by law in the 2019 Climate Leadership and Community Protection Act that the 20-year time period be used.[16]

Unfortunately, society has not reduced emissions of either carbon dioxide or methane. Methane emissions have continued to rise, and the very latest data on the global levels of methane in the atmosphere are highly disturbing. Figure 2, released by the US National Oceanographic & Atmospheric Administration in March 2021 shows not only the increase in methane in the atmosphere since 2005, but a recent acceleration. Methane levels in 2020 are higher than at any other time in human history.

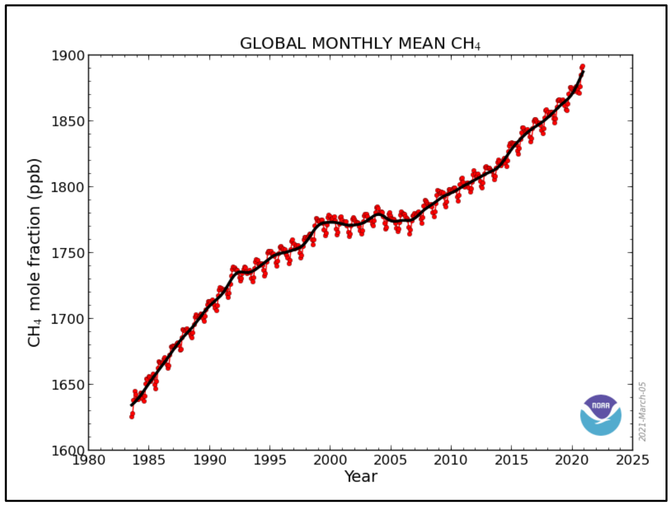

Figure 2. Mean monthly methane concentrations, 1983-2020

How do current emissions of carbon dioxide and methane compare in terms of global warming? In 2015 emissions of carbon dioxide from burning fossil fuels and producing cement were 36 billion metric tons. Emissions of methane from all human-influenced sources were approximately 0.38 billion metric tons (updated from Begon et al. 2014).[17] At the time of emission, methane is 105-times more potent as a greenhouse gas, and for an integrated 20-year period following a pulsed emission of the two gases, methane is 86-times more powerful.[18] Therefore, the methane emissions are equivalent to 39 billion metric tons of carbon dioxide emissions at first emission and to 32 billion metric tons of carbon dioxide for the average 20-year period after emission. The bottom line: over the next 20 years, methane emissions from all sources globally are contributing as much to global warming as are the total emissions of carbon dioxide globally.[19] These next 20 years are a critical time, given the very high risk of global runaway warming and climatic disruption.

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[15] Howarth, *supra* note 2; Ilissa B. Ocko et al., *Unmask temporal trade-offs in climate policy debates*, 356 Science 492–493 (2017), https://science.sciencemag.org/content/356/6337/492 (last visited Apr 3, 2021); Lukas P. Fesenfeld, Tobias S. Schmidt & Alexander Schrode, *Climate policy for short- and long-lived pollutants*, 8 Nature Climate Change 933–936 (2018), http://www.nature.com/articles/s41558-018-0328-1 (last visited Apr 3, 2021).
[16] Robert W. Howarth, *Methane emissions from fossil fuels: exploring recent changes in greenhouse-gas reporting requirements for the State of New York*, 17 Journal of Integrative Environmental Sciences 69–81 (2020), https://www.tandfonline.com/doi/full/10.1080/1943815X.2020.1789666 (last visited Apr 3, 2021).
[17] Michael Begon, Robert W. Howarth & Colin R. Townsend, Essentials of Ecology, 4th Edition (4th edition ed. 2014).
[18] IPCC, *supra* note 7.
[19] Howarth, *supra* note 3; Howarth, R.W. 2021. “Blue hydrogen” and carbon capture and storage,” briefing to US Congress, March 19, 2021.

3 Gas lifecycle stages

The full lifecycle of gas includes production, processing, transportation, and end use, and there are several forms that each of these stages might take depending on the source of the gas, the location of end use, and the end use purpose.

The gas lifecycle is comprised of various segments, from production, through to processing. Figure 3 provides an overview of these stages, and the descriptions of each stage below refer to the numbers in this figure.

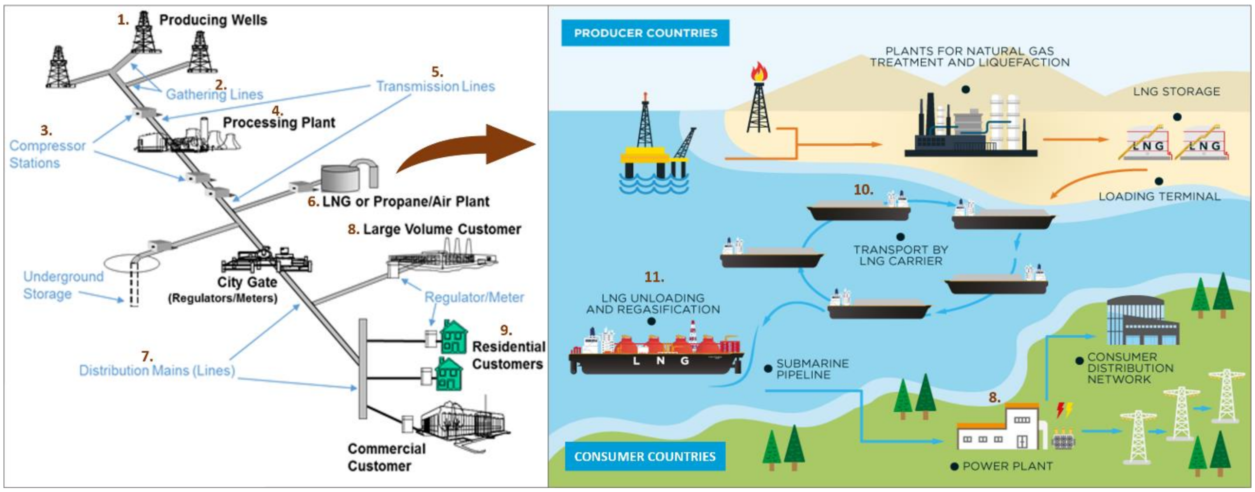

Figure 3. Gas lifecycle stages. Images adapted from American Gas Association (left) and OLT Offshore Italy (right)

3.1 Production

Methane gas may be produced (1) from several different geologic formations, with extraction techniques varying accordingly (see Figure 4).

Conventional gas refers to gas trapped in conventional reservoirs either with ("associated") or without ("nonassociated") oil. This gas has typically migrated over time from shale source rock to pockets of air created in more permeable geologic formations.

Shale gas is methane trapped in sedimentary rock formations and is considered one form of "unconventional" gas. There was virtually no commercial development of shale gas until early in the 21st Century when industry began to use two new processes to release this methane: high-precision directional drilling and high-volume hydraulic fracturing ("fracking"). Shale gas production has grown rapidly over the past 15 years, and between 2005 and 2015 two-thirds of the increase in all-natural gas production globally was from shale gas.[20]

[20] Robert W. Howarth, *Ideas and perspectives: is shale gas a major driver of recent increase in global atmospheric methane?*, 16 BIOGEOSCIENCES 3033–3046 (2019), https://www.biogeosciences.net/16/3033/2019/bg-16-3033-2019.html (last visited Jan 22, 2020).

Other forms of "*unconventional*" gas resources include coalbed methane (also known as coal seam gas), which is gas collocated with coal deposits, and "tight gas," which is gas trapped in sandstone or limestone formations. Gas can also be synthesized from coal in a process known as "coal gasification."

Coal bed methane is typically the shallowest reservoir of gas, followed by conventional deposits, while the sedimentary formations that are fracked for shale gas are often several kilometers or more below the surface.

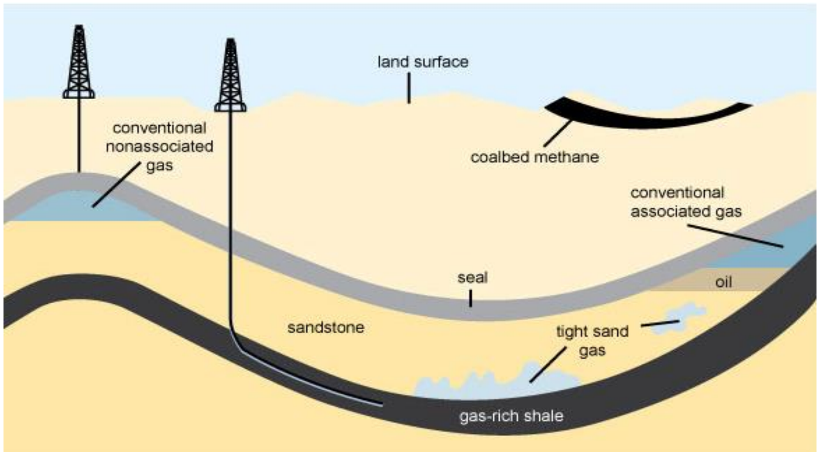

Figure 4. Gas resource schematic. Source: U.S. Energy Information Administration (EIA), Where our natural gas comes from*, U.S. ENERGY INFORMATION ADMINISTRATION (EIA) (2020), https://www.eia.gov/energyexplained/natural-gas/where-our-natural-gas-comes-from.php.*

The steps involved in the gas production process vary based upon the kind of resource being extracted, and the emissions from these varied production steps will be detailed in Section 3.

3.2 Gathering, Processing

Gas is then collected from the various well pads on which it is being produced in a central location, via gathering lines (2). The gas is then piped to a processing plant (4) where it is cleaned of impurities and prepared for being sent through transmission pipelines.

3.3 Transportation

There are several ways of transporting gas from its production site to its end use, and pipelines (5, 7) and LNG (6) are the primary means by which gas is transported today.

3.3.1 Pipelines

Gas needs to be compressed to be sent through pipelines, and compressor stations (3) play this role along gathering lines, transmission lines, and distribution lines. These compressor stations, located at 64 to 160 km intervals on transmission pipelines, typically run on the gas passing through them. However, some compressor stations, like those moving gas directly from the wellhead, also run on diesel.

3.3.1.1 Transmission pipelines

Transmission pipelines carry gas from producing regions to major consumers, either entire cities of commercial, industrial, and residential use, or directly to major power plants or industrial users located outside of a city. They may also carry gas directly ports for processing into LNG for export. These pipelines, buried underground, are typically between 76 and 91 cm in diameter, but can be as big as 122 cm for particularly important gas corridors.[21]

3.3.1.2 Distribution pipelines

Distribution pipelines (7) take gas from the transmission lines into the city to consumers. They are smaller in diameter and run under city streets. The larger distribution pipelines are known as "mains."

3.3.2 Liquified Natural Gas (LNG)

Liquified Natural Gas (LNG) is gas that is liquified near a port area in a producer country (6), loaded onto LNG carrier ships to be transported to another country (10), and then re-gasified in the importer/consumer country for local use (11). The liquefaction process cools the gas to -164°C, and the methane must remain at -164°C throughout the journey so that the methane, much more compact as a liquid, is contained.

3.4 End use

After its transportation journey, gas is employed in a range of end uses, including industrial processes (8), combined cycle or open cycle power plants, and residential uses or commercial uses (9), such as space and water heating and cooking.

4 Emissions from stages of gas lifecycle

Each of these stages of the gas lifecycle releases methane, carbon dioxide, and other greenhouse gases, most of which were not accounted for in the consideration of the climate impacts of the Richards Bay 3000 MW Combined Cycle Gas to Power Plant.

4.1 Production

Methane is emitted to the atmosphere whenever natural gas is extracted, including from conventional and unconventional resources.[22] My work suggests that on average around 2.8-3.5% of conventional gas taken from the ground leaks into the atmosphere in the production stage.[23] There are indications that these emissions may be greater from shale gas, which is becoming an ever-larger share of global gas production and LNG,[24] than from conventional natural gas. For instance, in the days to weeks following high-volume hydraulic fracturing, a large portion of the injected fluids return to the surface ("flowback water") carrying large volumes of methane with them.[25] Although this methane gas can in theory be captured from the liquids, this is expensive and slows down the time necessary to bring wells to production. In the United States, the EPA has regulated these emissions since 2015, requiring that the methane from this flowback period be flared (burned) rather than released to the atmosphere as

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[21] S.M. Folga, *Natural Gas Pipeline Technology Overview* 3 (2007), https://corridoreis.anl.gov/documents/docs/technical/APT_61034_EVS_TM_08_5.pdf (last visited Jul 19, 2020).
[22] Howarth, Santoro, and Ingraffea, *supra* note 12; Howarth, *supra* note 2; Alvarez et al. *supra* note 1.
[23] Howarth, *supra* note 20.
[24] US EIA, *Shale gas production drives world natural gas production growth*, US Environmental Information Agency Department of Energy, (2016), https://www.eia.gov/todayinenergy/detail.php?id=27512).
[25] Howarth, Santoro, and Ingraffea, *supra* note 12; Howarth, *supra* note 2; Howarth, *supra* note 3.

unburned methane, if the gas is not captured and if it is technically possible to flare the gas.[26] However, there are many loopholes in the rules; reporting is also voluntary, and enforcement of the regulation is largely lacking. In practice, venting of unburned methane due to unlit flares seems common.[27]

Another difference in emissions from shale gas compared to conventional natural gas relates to the depth of the shale gas formation and the history of earlier fossil-fuel development in many shale gas areas. Caulton et al. 2014 observed methane emissions during well drilling in the Marcellus shale region in southwestern Pennsylvania, even before the drillers reached the shale.[28] As I explain in my latest work on methane, "This area has a long history of fossil-fuel exploitation, with development of oil, conventional gas, and coal dating back to the 1800s. The emissions during shale-gas well drilling may be the result of hitting pockets of trapped methane from these earlier fossil-fuel operations, which must be drilled through to reach the shale, which is much deeper underground. In such an environment, the gas industry sometimes employs 'underbalanced' or negative-pressure drilling to reduce the chance of blowouts, and this could increase the emission of methane from any pockets that are encountered while drilling (Caulton et al. 2014)."[29] The negative-pressure drilling means that the drillers are pulling a vacuum on their rig rather than drilling under high, positive pressure. While this does reduce the chance of blowouts, it increases the sucking out of methane from underground gas pockets.

While it is presently unclear where the gas feedstock for the Richards Bay power plant would be produced and what techniques would be needed to capture it, there are indications that it could come from either shale gas fracked in South or Southern Africa, or from shale gas-heavy LNG imported from lead LNG exporters like Australia or the United States.[30]

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[26] Environmental Protection Agency, *Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources* (2016), https://www.govinfo.gov/content/pkg/FR-2016-06-03/pdf/2016-11971.pdf.

[27] Hiroko Tabuchi & Jonah M. Kessel, *It's a vast, invisible climate menace. We made it visible*, The New York Times, December 12, 2019, https://www.nytimes.com/interactive/2019/12/12/climate/texas-methane-super-emitters.html (last visited Feb 9, 2020); Howarth, *supra* note 3.

[28] Caulton et al., *supra* note 4.

[29] Howarth, *supra* note 3.

[30] The project's Climate Change Impact Assessment (CCIA) asserts that, "The proposed CCPP plant will be fueled with piped natural gas or liquefied natural gas (LNG). It intends to take advantage of the large natural gas discoveries in the Rovuma Basin in Mozambique. This reserve presents a reasonably priced regional gas resource that could be transported to the Richards Bay area via pipeline or ship as LNG**."[30]** The Environmental Impact Assessment Report also notes: "The Gas Utilization Master Plan (GUMP) identifies that there are potential gas reserves in the Karoo basin, deep offshore, and at the Ibhubesi basin."[30] Currently Mozambique is not exporting LNG, construction has not begun on the pipeline described in the CCIA, and the towns and LNG infrastructure under development in the Rovuma Basin region referenced in the CCIA are under the control of an armed group known as Al-Shabab.[30] The EIA reference to the GUMP suggests that any domestic gas used in the CCPP would likely come from shale gas in the Karoo basin or offshore oil and gas production. With shale gas exploration underway in Namibia, Algeria, and Angola, it seems plausible that the gas might also come from those more local shale reserves in the future. Given the current state of gas and LNG development in all of these possible source countries, it seems likely that for the foreseeable future the gas would be sourced as LNG from Qatar, Australia, the United States, or several other leading and distant global LNG producers. Australia and United States LNG includes significant shale gas in their LNG mixtures.

I have recently reviewed all of the peer-reviewed literature on top-down estimates for methane emissions from shale gas.[31] These studies are synthesized in Table 1 and include 12 studies based on aircraft data published in 9 different papers and 3 studies based on satellite data published in 2 different papers. The estimates are for emissions that occur at the gas well sites and in the nearby area, including processing plants and some storage facilities, but generally do not include emissions from high-pressure gas transport pipelines or lower-pressure gas distribution pipelines. The studies synthesized in Table 1 show that between 0.2% and 17% of the natural gas production is emitted to the atmosphere as unburned methane, again not including the "downstream" emissions associated with transport and distribution of gas. All of the studies presented in Table 1 appear to be well conducted. The variation in emission rates probably reflects real variation in both time and space: for instance, emissions may be higher during times of greater drilling and fracking activity compared to times of low fracking. Further, some companies may follow better procedures and take greater care to reduce emissions.

Table 1. Top-down estimates for upstream emissions of methane from natural gas systems, including studies based on aircraft flyovers and satellite remote-sensing data. Studies are listed chronologically. Estimates are the percentage of the methane in natural gas that is produced*.

Aircraft data		
Peischl et al (2013)	Los Angeles Basin, CA	17%
Karion et al. (2013)	Uintah shale, UT	9.0%
Caulton et al. (2014)	Marcellus shale, PA	10%
Karion et al. (2015)	Barnett shale, TX	1.6%
Peischl et al. (2015)	Marcellus shale, PA	0.2%
Peischl et al. (2016)	Bakken shale, ND	6.3%
Barkley et al. (2017)	Marcellus shale, PA	0.4%
Peischl et al. (2018)	Bakken shale, ND	5.4%
	Eagle Ford shale, TX	3.2%
	Barnett shale, TX	1.5%
	Haynesville shale, LA	1.0%
Ren et al. (2019)	Marcellus shale, PA & WV	1.1%
Satellite data		
Schneising et al. (2014)	Eagle Ford shale, TX	9.1%*
	Bakken shale, ND	10.1%*
Zhang et al. (2020)	Permian Basin shale, NM	3.7%

*Schneising et al. (2014) estimated the percentage of methane emitted relative to the combined production of natural gas and oil; these estimates are therefore minimal estimates for the percentage of methane in natural gas that is produced.

Table 2, also from Howarth 2021, presents a detailed exploration of methane emissions and shale gas production for six shale gas fields.[32] The emission data are from Table 1, while production data are from EIA.[33] Quality data for both emissions and production in 2015 exist for only these six shale-gas fields, but these represent a total production of 325 billion cubic meters per year, or three-quarters of the total global production of shale gas that year.[34] Comparing the total mass of methane emitted (7.2 Tg per year) with the production for these six fields (325 billion cubic meters per year), the volume-weighted average rate of upstream emissions is 3.3% (Table 2). Applied to the global increase in shale gas production over the period 2005-2015, this 3.3% upstream emission rate leads to an estimated increase

[31] Howarth, *supra* note 3.
[32] *Id.*
[33] EIA, *Natural Gas: Dry Shale Gas Production Estimates by Play*, Energy Information Agency, U.S. Department of Energy (2020), https://www.eia.gov/naturalgas/data.php.
[34] Howarth, *supra* note 20.

Table 2. Shale gas production and upstream methane emissions from various major shale-gas producing fields in 2015.

	Production (billion m^3/yr)	% emitted upstream (with 90% CL)	Mass emitted upstream (Tg/yr)*
Marcellus	155	2.93 % (+/- 3.4 %)	3.0
Eagle Ford	50	6.65 % (+/- 3.9 %)	2.2
Barnett	38	1.55 % (+/- 0.06 %)	0.39
Haynesville	36	1.0%	0.24
Permian	36	3.7 %	0.88
Bakken	10	7.37% (+/- 1.9 %)	0.49
Total for above fields	325		7.2
Volume-weighted average		3.3 %**	
Global total	435		9.5***

*Assumes 93% of produced gas is methane (Schneising et al. 2014).

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

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

in global methane emissions of 9.5 Tg per year (Table 2), or 40% of the entire global increase in methane over that time period.[35]

One can also estimate the global emissions of methane from shale gas through observing changes in the stable isotopic composition of methane in the atmosphere. Most methane is composed of the C^{12} stable isotope, but some methane is composed on the C^{13} isotope instead. For the first many years of the 21st Century, the methane concentration in the atmosphere remained steady and the C^{13} content of that methane did not change, however, starting at the time of the shale gas revolution in 2005 or so, the concentration of methane in the atmosphere started to rise rapidly, and the C^{13} content of that methane began to fall. Some scientists concluded from this evidence that the increase in methane was due to biological sources such as animal agriculture. These scientists had assumed that the C^{13} content of methane from shale gas is identical to that of methane from conventional natural gas. However, this is not true, in fact the shale-gas methane has somewhat less C^{13}. Using this information, I reanalyzed global methane trends and demonstrated that emissions from shale gas were responsible for at least 33% of total increases in global methane emissions since 2005.[36] This indicates an emission rate of methane from shale gas of 3.5% to 4.1% of the rate of shale gas production. This is for the full lifecycle, including methane emissions at the well site as well as from transport and distribution of gas, although it may not include some of the emissions during well drilling (such as those reported by Caulton et al. 2014[37]): the methane released during drilling, although caused by the drilling, may not have originated from the shale formation and may in fact reflect methane from conventional gas sources or coal operations trapped in underground, abandoned mines and wells. This global ^{13}C approach for estimating shale-gas methane emissions is completely independent of any of the information presented in Table 1 from top-down studies. Yet the magnitude of 3.5% to 4.1% is remarkably close to the sum of 4.1% emission calculated by adding the 3.3% volume-weighted emission

[35] *Id.*
[36] *Id.*
[37] Caulton et al., *supra* note 4.

rate from Table 2 with an 0.8% emission from downstream transmission and distribution pipelines. This greatly increases the confidence in both the top-down and global C^{13} approaches.

Finally, it must be noted that methane emissions at all oil and gas well-heads can continue long after a well has stopped producing oil and gas for market, as even wells that are supposedly properly plugged can leak methane into the atmosphere for decades. In a study of just one state in the United States, for example, researchers found that these plugged and unplugged abandoned wells emitted between 5 and 8% of the state's total annual methane emissions.[38]

4.2 Gathering and Processing

In addition to well pad gas losses, the gathering and processing of all forms of gas before it is sent over transmission pipelines also emits significant quantities of methane. In the bottom-up measurements of Alvarez et al. 2018, for example, researchers found that around 3.32 million tons of methane were emitted from oil and gas gathering and processing alone in the US in 2015, or between a quarter and a half of the total methane emitted by cattle emissions annually across the US in that same year.[39]

4.3 Transportation

The estimate of 3.3% of shale gas production lost in methane emissions explained above also does not include the downstream emissions associated with transporting and distributing the gas through pipelines, or as LNG.

4.3.1 Pipelines

The best available data from top-down studies on downstream emissions suggest at least an additional 0.8% emission rate from the pipeline systems.[40] There has been less study of these downstream transportation and distribution emissions from pipelines than for the emissions at the gas well sites, and so this 0.8% or greater emission should be treated as uncertain. Our knowledge of these pipeline

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[38] Mary Kang et al., *Identification and characterization of high methane-emitting abandoned oil and gas wells*, 113 PNAS 13636–13641 (2016), https://www.pnas.org/content/113/48/13636 (last visited Apr 5, 2021).

[39] Alvarez et al., *supra* note 1; Scot M. Miller et al., *Anthropogenic emissions of methane in the United States*, PNAS (2013), https://www.pnas.org/content/early/2013/11/20/1314392110; US EPA, *Chapter 5: Agriculture - Greenhouse Gas Inventory* (2017), https://www.epa.gov/sites/production/files/2017-02/documents/2017_chapter_5_agriculture.pdf.

[40] Kathryn McKain et al., *Methane emissions from natural gas infrastructure and use in the urban region of Boston, Massachusetts*, 112 PNAS 1941–1946 (2015), https://www.pnas.org/content/112/7/1941 (last visited Apr 3, 2021); Brian K. Lamb et al., *Direct and Indirect Measurements and Modeling of Methane Emissions in Indianapolis, Indiana*, 50 ENVIRON. SCI. TECHNOL. 8910–8917 (2016), https://pubs.acs.org/doi/10.1021/acs.est.6b01198 (last visited Nov 26, 2019); Debra Wunch et al., *Quantifying the loss of processed natural gas within California's South Coast Air Basin using long-term measurements of ethane and methane*, 16 ATMOSPHERIC CHEMISTRY AND PHYSICS 14091–14105 (2016), https://acp.copernicus.org/articles/16/14091/2016/ (last visited Apr 3, 2021); Genevieve Plant et al., *Large Fugitive Methane Emissions From Urban Centers Along the U.S. East Coast*, 46 GEOPHYSICAL RESEARCH LETTERS 8500–8507 (2019), https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019GL082635 (last visited Nov 21, 2019); Howarth, *supra* note 16; Howarth, *supra* note 3.

emissions should improve rapidly in the coming few years due to many more studies using satellite data.[41]

4.3.2 Liquified Natural Gas (LNG)

LNG, as mentioned above, is a likely source of gas identified in the EIA and CCIA for the Richards Bay CCPP. It takes substantial energy to cool methane to the point where it becomes a liquid (-164°C). Usually, additional natural gas is burned to provide this energy, meaning that the use of LNG has additional emissions of carbon dioxide from the burning of this natural gas as well as of methane associated with the natural gas that is burned. A recent study of LNG lifecycle emissions analysis found that emissions from liquefaction, tanker transport, and regasification range from about 8% to 21% of total lifecycle emissions for the LNG, depending on how large production emissions were calculated to be and how far the LNG carriers traveled, with most calculations in the upper end of this range.[42]

In addition, LNG methane is kept in liquefied form while it is transported and stored by allowing some of the methane to evaporate. As with sweat evaporating from one's skin on a hot day, the evaporation of methane cools the LNG to keep it in liquid form. The oil and gas industry calls this "boil off." Ideally, the evaporated methane is burned and used for energy on board tanker ships during transit and at LNG storage terminals, and the studies referenced assume this outcome. However, I am aware of no peer-reviewed objective scientific measurements regarding how much methane may be emitted to the atmosphere from boil off.

If we optimistically assume that the LNG industry does a perfect job in capturing and using methane from boil off, LNG still has the 20% penalty in greenhouse gas emissions compared to regular shale gas, due to the use of gas at the liquefaction step. This means that rather than emissions of 15 g C of carbon dioxide per MJ for shale gas or conventional natural gas,[43] LNG emissions are 18 g C of carbon dioxide per MJ. And if we accept that emissions of unburned methane from using shale gas are 3.5% of production (a low, conservative estimate as I present above), this increases to at least 4.2% for LNG. It is highly probably that some of the evaporated methane from boil off reaches the atmosphere, increasing this estimate further.

4.4 End use

Methane leakage at the end use occurs from a variety of sources, including pipelines entering the facility or within the facility, and even at the point of release of the methane. Faulty compressor stations at gas power plants can lead to tons of methane emissions going unchecked, as in the case of a massive leak at

[41] See, for instance European Space Agency, *Monitoring methane emissions from gas pipelines*, EUROPEAN SPACE AGENCY (2021), https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-5P/Monitoring_methane_emissions_from_gas_pipelines (last visited Apr 3, 2021).
[42] CHRISTINA SWANSON ET AL., *Liquefied natural gas is not an effective climate strategy* 30 (2021).
[43] Howarth, Santoro, and Ingraffea, *supra* note 12.

a 690 MW gas power plant in Los Angeles California caught in 2020.[44] Researchers have also detected significant quantities of methane being emitted from gas powerplant stacks, uncombusted.[45]

5 Comparison of gas and coal emissions on the climate

Taken in sum, the latest science on gas suggests that the greenhouse gas footprint of gas is worse than that of either coal or oil, particularly when considered in the 20-year timescale most relevant to our climate future.

In the past, conventional natural gas and shale gas were promoted as bridge fuels to an eventual fossil-free future. The argument was that for the same amount of energy produced, carbon dioxide emissions were less for gas than for oil or coal. This is certainly true.[46] However, the best available evidence shows that methane emissions are greater for shale gas and conventional natural gas than for oil products or coal, per unit of energy produced. This should not be surprising since shale gas and conventional natural gas are composed almost entirely of methane, while methane is a contaminant and small component of either coal or oil. When the methane emissions from shale gas are considered, the greenhouse gas footprint is far worse than that of either coal or oil, particularly when considered over the 20-year time period, as shown in Figure 5.[47] Here, methane emissions are compared to carbon dioxide emissions using the 20-year global warming potential from the IPCC 2013 and assuming a methane emission rate of only 3.2% of natural gas production, an extremely conservative value, as described above. If LNG transportation were included

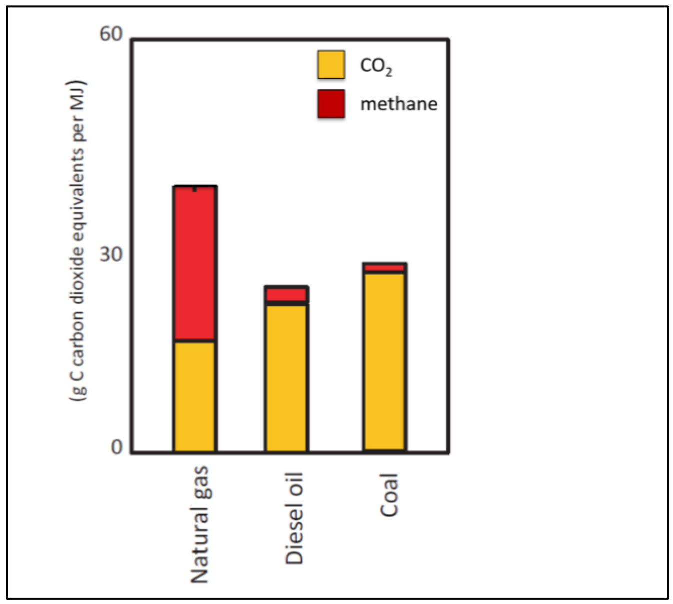

Figure 5. Greenhouse gas footprint of natural gas (including shale gas), diesel oil, and coal per unit of heat energy released as the fuels are burned. Direct emissions of carbon dioxide are shown in yellow. Methane emissions expressed as carbon dioxide equivalents are shown in red. As discussed in the text, the methane emission estimate for natural gas is very conservative and could be up to 2-times greater. Emission estimates are from Howarth 2020.

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[44] Nichola Groom, *Los Angeles natural gas plant has been leaking methane for years*, REUTERS, August 26, 2020, https://www.reuters.com/article/usa-methane-california-idUKL1N2FS29W (last visited Apr 3, 2021).
[45] Tegan N. Lavoie et al., *Assessing the Methane Emissions from Natural Gas-Fired Power Plants and Oil Refineries*, 51 ENVIRON. SCI. TECHNOL. 3373–3381 (2017), https://doi.org/10.1021/acs.est.6b05531 (last visited Apr 23, 2020); Kristian D. Hajny et al., *Observations of Methane Emissions from Natural Gas-Fired Power Plants*, 53 ENVIRON. SCI. TECHNOL. 8976–8984 (2019), https://pubs.acs.org/doi/10.1021/acs.est.9b01875 (last visited Feb 25, 2020).
[46] Katharine Hayhoe et al., *Substitution of natural gas for coal: climatic effects of utility sector emissions*, 54 CLIMATIC CHANGE 107–139 (2002); Robert W. Howarth, Renee Santoro & Anthony Ingraffea, *Venting and leaking of methane from shale gas development: response to Cathles et al.*, 113 CLIMATIC CHANGE 537–549 (2012), https://doi.org/10.1007/s10584-012-0401-0 (last visited Apr 3, 2021); Howarth, *supra* note 16.
[47] Howarth, *supra* note 3; With emissions estimates from Howarth, *supra* note 16.

in this comparison, the results would be even less favorable for natural gas.

One can also view the comparison of natural gas with other fuels in the context of the technology warming potential, which specifies a level of methane emissions from the use of natural gas at which this fuel would not be desirable from a climate perspective. The original presentation of this approach by Alvarez et al. 2012 became somewhat dated quickly when the IPCC 2013 update our understanding of exactly how powerful methane is as a greenhouse gas. Updating the Alvarez et al. 2012 approach with this new information, using natural gas to generate electricity has a climate benefit relative to coal only if methane emissions from natural gas are less than 2.8% or production.[48] Shale gas is likely worse than conventional natural gas, because of increased methane emissions. And LNG is a further negative aggravation that increases emissions of both carbon dioxide and methane.

[48] Howarth, *supra* note 2.