Centre for Policy Studies

Pointmaker

THE FACTS ABOUT FUGITIVE METHANE

Elizabeth A. Muller and Richard A. Muller

SUMMARY

- Shale gas production and use is transforming the energy landscape, both increasing the total amount of energy resources available and replacing other fossil fuels (especially coal) for electricity generation. Yet there are still many fears about the increased use of natural gas, and in particular, the use of shale gas. One such fear is over methane leaks, both at the production site and throughout the supply chain.

- This paper tries to take an objective look at the maths around methane leakage. How much leakage would negate the global warming benefits of using natural gas as compared to coal? How concerned should we be about such "fugitive" methane?

- Replacing coal-fired electric power plants with ones using natural gas as a fuel can help reduce global greenhouse emissions. New high efficiency natural gas plants reduce emissions of carbon dioxide by 63% if they replace a typical 33% efficient US, UK, or European coal plant, for the same electric power generated. If they replace future coal plants (which would have higher efficiency themselves) the advantage is still large, with carbon dioxide reductions of about 50%.

- Methane, the main component of natural gas, has a high greenhouse potential, and opponents argue that even if one or two percent of the gas leaks, the advantage of natural gas over coal would be negated.

- This estimate is incorrect; over a 100 year time span, an implausible 12% of the produced natural gas used today would have to leak in order to negate an advantage over coal. The best current estimates for the *average* leakage across the whole supply chain are below 3%; even at 3% leakage natural gas would produce less than half the warming of coal averaged over the 100 years following emission.

- Half this 100 year average comes from the first 10 years; three-quarters from the first 20 years; the warming at 100 years is almost entirely from the (relatively low) CO_2 produced from burned methane, not from the leaked methane itself.

- An additional reason to produce electric power from natural gas is that the *legacy* advantage of natural gas is enormous; after 100 years, only 0.03% of leaked gas remains in the atmosphere, compared to 36% for remnant carbon dioxide.

1. INTRODUCTION

Most of the greenhouse emissions of the future are expected to come from the developing world. That inevitably places severe constraints on the practicality of paths to near-zero emission carbon targets such as solar, wind, and nuclear power, at least in the short to medium term.

The discovery of vast reserves of shale gas around the world offers a potentially beneficial transition approach to less (or zero-) carbon-intensive energy sources. Natural gas, while not zero emission, offers the possibility of reducing greenhouse emissions by factors of two to three, both by replacing older highly-emitting sources, and by substituting for higher emission power plants that would otherwise be built. In the US, the recent reduction of greenhouse emissions has been significantly aided by the replacement of some old inefficient coal facilities by high efficiency natural gas plants.

Although, in principle, natural gas offers a very large greenhouse benefit compared to coal, several objections have been raised. These include the concern that natural gas, even though lower in emissions, is still not a zero-carbon source of energy. Building new plants that emit carbon dioxide, no matter how low the emissions may be, subverts the long-term goal of moving to near zero-carbon options.

Second, since such plants are typically cheaper than near-zero plants, the increased use of natural gas could, it is said, delay the development of zero-carbon alternatives.

A third concern is a belief that fracking, the mining method behind the rise in natural gas production, leads to local problems, including leakage of gas into ground water, 'flaming faucets' as depicted in the movie *Gasland,* and air and water pollution.[1] In most cases, these concerns could be readily controlled through tighter (but reasonable) regulation and fines for polluters. In general, enforcement of industry best practice for all development would be sufficient.

But there is a fourth concern which has not yet been properly addressed: the threat from leaked "fugitive" methane. For there is a concern, held by many thoughtful people and others, that the danger of fugitive methane is a compelling reason to stop all development of shale gas. For example, a simple number published by Alvarez et al.[2] has been widely used by policy makers: they say that for equivalent greenhouse emissions compared to a coal plant, the maximum leakage is 3.2%. They do accept that that value is for immediate effect only, and does not take into account the short lifetime of methane in the atmosphere.

It is on this question that the dangers of shale gas is greatly overestimated. This is the issue addressed in this paper.

2. SOME SIMPLE (BUT INCORRECT) MATHS

The concerns over fugitive methane is based on the following true but easily misinterpreted facts about methane, which makes up 87% to 96% of natural gas.

- Methane, when released to the atmosphere, has Global Warming Potential (GWP) of 86 over a 20 year period. This means that methane is 86 times more potent as a

[1] The authors have examined most of these concerns previously and their findings are discussed in a series of memos available at www.BerkeleyEarth.org/memos, and www.berkeleyearth.org/papers.

[2] R. Alvarez et al., "Greater focus needed on methane leakage from natural gas infrastructure", *Proc. National Acad. Sci.* vol 109, 6435-6440, (2012) www.pnas.org/cgi/doi/10.1073/pnas.1202407109.

greenhouse gas than CO_2, pound for pound, averaged over the 20 years following the emission.

- Methane leakage has been observed to range from 6.2% to 11.7% based on measurements taken of the air above some drilling areas.[3]

The combination of these facts sounds devastating. Here is the way the (incorrect) logic follows: Because of methane's high GWP of 86, one might estimate that even 1% leakage, added to the CO_2 from burning the gas that didn't leak, would negate all advantage over coal.[4] A 2% leakage would be twice as bad as coal.[5] Since leakage occurs not only during drilling and production, but also during distribution and use, it may prove impossible to reduce average leakage below 1%. If the leakage averaged 10%, the warming would be nearly nine times worse than if coal were used.[6] And such leakage has been reported for at least one site.

Based on such simple (but wrong) estimations, the case against natural gas appears to be overwhelming. Together with worries over local water pollution, this has been the inspiration for a strong movement to ban fracking.

As there are even larger reserves of shale gas in China, and if new technology enables them to exploit these, there is therefore a concern that natural gas leakage will completely overwhelm the benefits of developing shale gas.

But the maths described above is incorrect, and as a result the conclusions are incorrect. The bulleted items below are based on well-known numbers, given in the IPCC and other accepted reports. They give the key facts that were ignored in this simple but mistaken calculation.

- **When comparing coal to methane for equal *electric power*, the 20-year global warming potential of methane compared to carbon dioxide is 11, not 86**. The GWP of 86 assumes equal *weights* of methane and CO_2. But: (a) methane is lighter than CO_2, molecule per molecule, by a factor[7] of 0.36; (b) coal produces only 0.60 of the heat, molecule per molecule (since it contains less hydrogen);[8] and (c) for equal heat, coal produces only 0.61 as much electric power.[9] Combine

[3] Karion, A., et al. (2013), Methane emissions estimate from airborne measurements over a western United States natural gas field, Geophys. Res. Lett., 40, 4393–4397, doi:10.1002/grl.50811.

[4] The following is not meant to be an example of a calculation found in the peer-reviewed literature; rather it is the sort of calculation done informally by knowledgeable people (including one Nobel Laureate) who were concerned and not being careful. For 1% leakage, the effect of fugitive methane is assumed to be 86 x 0.01 = 0.86 compared to coal. Add in 0.31 from carbon dioxide released through burning, and you get 0.86+0.31 = 1.17 times worse than coal. We will show that this commonly-made calculation is incorrect.

[5] 86 x 0.02 = 1.72 from methane leakage. Add in 0.31 from carbon dioxide released through burning, and you get 1.72+0.31=2.03, meaning that leaked methane would be 2.03 times worse than carbon dioxide. We will show that this commonly made calculation is incorrect.

[6] 86 x 0.1 = 8.60 from methane leakage. Add in 0.28 from carbon dioxide released through burning of the remaining methane, and you get 8.60+0.28=8.88, meaning that leaked methane would be 8.88 times worse than carbon dioxide. We will show that this is a commonly made but incorrect calculation.

[7] The molecular weight of CH_4 is 16, and of CO_2 is 44. The ratio 18/44 = 0.36.

[8] Counting by molecules is required since one molecule of leaked methane replaces one molecule of produced CO_2. Coal results in 92 grams CO_2 per MJ heat, while gas results in 55 grams CO_2 per MJ; see Hayhoe, H. Kheshgi, A. Jain, D. Wuebbles, Climate Change vol 54, 107-139 (2002); DOI 10.1023/A:1015737505552.

[9] We assume 54% efficiency for new natural gas plants, and 33% for the coal plants they are replacing. Newer

these, and the GWP of methane, for equal power, is reduced from 86 to 11. When considering substituting a methane plant for an equal power coal plant, 11 is the appropriate GWP, not 86. This is not in dispute among scientists. In the following calculations, however, we will use the traditional value of 86 and keep track of the weight and efficiency factors to keep our maths transparent.

- **Legacy warming from fugitive methane is minuscule compared to that of carbon dioxide**. The 20-year average typically used in the comparisons doesn't show the enormous subsequent reductions from atmospheric methane destruction. Nor does the 100-year average, since most of that average effect comes from the first few decades. Only 0.03% of fugitive methane released today will still be in the atmosphere 100 years from now. In contrast, 36% of the carbon dioxide will linger. The difference in atmospheric lifetime completely overwhelms the higher greenhouse effect of methane, making carbon dioxide, not fugitive methane, the long-term threat. The commonly-used limit of 3.2% leakage totally ignores this legacy effect.

- **Average leakage today is far below dangerous levels**. Although *up to* 10% leakage has been reported, the best estimates for the *average* leakage today, including by the EPA, are *under* 3%. Yet even with 3% leakage, natural gas would cause less than half the warming of coal (assuming same electric energy produced, 100 year average). In some extensive regions (the Marcellus in Pennsylvania) recent measurement in the air above the sites indicate leakage has been kept below 0.41%.[10] The bulk of the leakage comes from a small number of "super emitters". The cost to reduce the emissions from these super emitter sites can be recovered by the added value of the gas. This is a case where the environmental motive and the profit motive are aligned, and there is economic incentive to reduce leakage from identified super emitters.

Ignoring the leakage, when used for electricity generation the benefits of natural gas over coal are huge; new plants replacing the average US coal plants produce only 37% the carbon dioxide. That means switching electric power production to natural gas could extend the time available to develop zero-carbon solutions significantly. In fact, some people oppose natural gas specifically for this reason, because it reduces the urgency to develop carbon-free alternatives. Z. Hausfather has analysed this in some detail and at different leakage rates, and shown that even if such alternatives are delayed by natural gas use, the benefits in slowing greenhouse warming are substantial.[11]

These facts are not controversial. Nevertheless, they surprise many people because they conflict with what they have read or heard in media summaries. In order to reconcile these facts with those that are typically discussed by those opposed to natural gas, we'll go into more detail.

power plants can have higher efficiency; the highest in the world may be the Avedøre Power Station in Denmark; it achieves 49% efficiency.

10 Quantifying atmospheric methane emissions from the Haynesville, Fayetteville, and northeastern Marcellus shale gas production regions, J. Peischl, T. B. Ryerson, K. C. Aikin, J. A. de Gouw, J. B. Gilman, J. S. Holloway, B. M. Lerner, R. Nadkarni, J. A. Neuman, J. B. Nowak, M. Trainer, C. Warneke and D. D. Parrish, JGR Atmospheres, DOI: 10.1002/2014JD022697.

11 Z. Hausfather, *Climate Impacts of Coal and Natural Gas*, Berkeley Earth memo available at http://static.berkeleyearth.org/pdf/climate-impacts-of-coal-and-natural-gas.pdf.

3. GREENHOUSE POTENCY OF METHANE COMPARED TO CARBON DIOXIDE

The global warming potential, GWP, of methane is defined as the greenhouse effect that a kilogram of methane will have when released to the atmosphere in a single pulse, compared to the effect from the release of a kilogram of carbon dioxide. The IPCC gives the GWP of methane as 86, averaged over the first 20 years after release, and as 34, averaged over the first century. Note that these GWPs are *averages*. In fact, most of the 100-year GWP comes from the 30 years, before the methane leaves the atmosphere.

There has been quite a bit of discussion over which is the most useful timeframe for comparison. Those who worry that we could reach a tipping point in the next 20 years prefer to use the 20-year horizon. Those who worry about long-term warming, and point out that previously anticipated tipping points never materialized, may prefer the 100-year horizon. Rather than get into this discussion, we provide numbers for all of the commonly used time horizons (see Table 1 below).

The standard GWP refers to equal weights of methane and carbon dioxide. But for the same electrical energy, natural gas plants produce less CO_2 than do coal plants, so a better comparison would be for the same electric energy output. Much less methane (by weight) is used to get the same output as from coal.[12] For the same heat energy produced, burning natural gas produces only 60% the carbon dioxide as burning coal. In addition, as we said earlier, heat from natural gas is more efficiently used at turning heat into electricity. The average US, UK, or European coal plant produces electricity with 33% efficiency. Modern combined-cycle natural gas plants have 54% efficiency.[13] That high efficiency comes from burning the natural gas directly in a turbine, and then making use of the "waste heat" to run a second steam turbine; the two-stage system is called a combined cycle gas plant. The higher efficiency reduces the relative carbon dioxide produced even further, from 60% (above) to 37% of the emissions of the coal plant that is being replaced. Put another way, the emissions from a coal plant are 2.7 times greater than those from a natural gas plant that produces equal electric power. We call 2.7 the "advantage factor" of natural gas. Calculations of GWP by both weight and energy output are provided in Table 1.

[12] For methane, the greater energy per molecule comes from the fact that methane contains more hydrogen than coal. The water vapour produced when hydrogen burns quickly condenses and does not contribute to warming.

[13] The efficiency is sometimes stated as 60%, but that is calculated using the lower heating value. For a fair comparison, we use the higher heating value consistently for both coal and natural gas, and that reduces the efficiency from 60% to 54%.

Table 1. GWP of Methane by Weight and by Energy Output

(referenced to GWP = 1 for carbon dioxide)

	0 yr	0 to 20 yr average	20 yr	0 to 100 yr average	100 yr*
GWP of methane per weight	120	86	34	34	1.5
GWP of methane per energy output	15	11	4.3	4.3	0.5

* After 100 years, the methane from a pulse injection is virtually gone from the atmosphere; the GWP is dominated by the CO_2 produced *in the atmosphere* originating from the chemical reactions that destroyed CH_4. A reasonable estimate for that is 1.5 kg of CO_2 produced for every kg of CH_4 leaked to the atmosphere.[i] Table 1 includes the CO_2 produced in the atmosphere in all timeframes, though it is significant only in the 100-year timeframe.

[i] N P Myhrvold and K Caldeira, Greenhouse gases, climate change and the transition from coal to low-carbon electricity, (2012). Environ. Res. Lett. 7 014019 doi:10.1088/1748-9326/7/1/014019.

Of course, one can still use the IPCC values per unit weight, but they need to be used with care, compensating for different weights required. For longer durations, the potency of fugitive methane is reduced enormously because of its short atmospheric lifetime. This will be discussed next.

4. LEGACY WARMING FROM FUGITIVE METHANE

Carbon dioxide has a long legacy, and persists in the atmosphere far into the future. After 100 years, 36% of emitted carbon dioxide is still in the air. Methane, the dominant greenhouse component of natural gas, is strikingly different. Methane reacts with hydroxide radicals in the atmosphere, and is removed with a half-life of 8.6 years.[14]

After 100 years only 0.03% of methane remains in the atmosphere. This means that if we were to implement zero carbon solutions on a global scale in the future, in order to bring global temperatures back down, it is better to have emitted more methane, and less carbon dioxide.[15]

So from a legacy perspective, carbon dioxide is much worse than methane. Figure 1 shows the persistence of methane and carbon dioxide in the atmosphere.[16]

14 The IPCC gives the "lifetime" as 12.4 years; however, that is not the half-life but the mean life, the time it takes the gas to reduce to 36.8% of its initial value. The half-life is the time that it takes for the gas to reduce to half of its initial value. Mathematically, half-life = ln(2) x mean-life = 0.693 x mean-life.

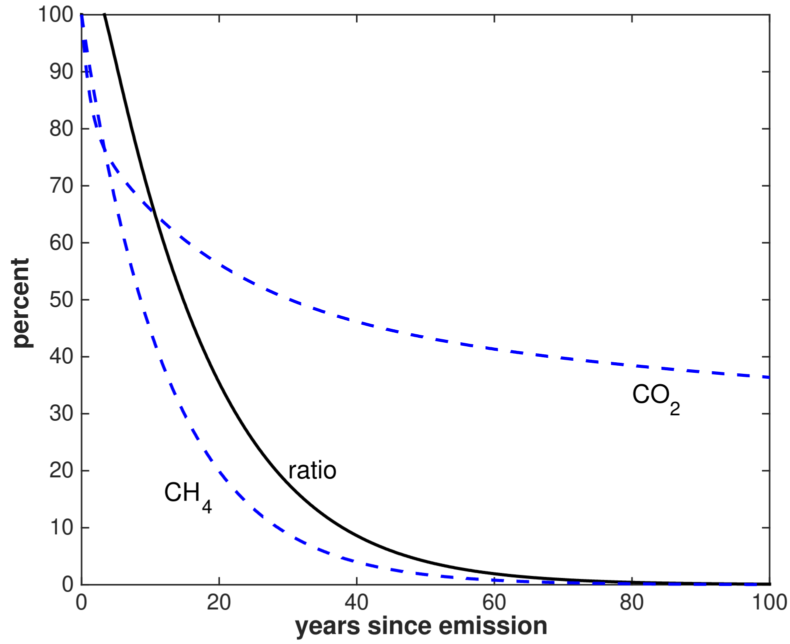
15 This is discussed in detail in Z. Hausfather, *Climate Impacts of Coal and Natural Gas*, Berkeley Earth memo available at: http://static.berkeleyearth.org/pdf/climate-impacts-of-coal-and-natural-gas.pdf.

16 The data is based on the memo of Z. Hausfather, Climate Impacts of Coal and Natural Gas, Berkeley Earth memo available at:

http://static.berkeleyearth.org/pdf/climate-impacts-of-coal-and-natural-gas.pdf.

The fraction of initial CO_2 left in the atmosphere as a function of time was calculated using $CO_2(t)$ = 0.217 +

Figure 1. The persistence of carbon dioxide and methane in the atmosphere, as a function of time.* The legacy effect of methane (CH_4) is miniscule compared to that of carbon dioxide (CO_2).



The virtual total disappearance of methane surprises some people, since the IPCC value for the 100-year global warming potential still has the relatively high value of 34. But that number refers to the *average* potential during the first 100 years after the emission. Half of that "100-year average" comes from the first decade, and three-quarters comes from the first two decades. At 20 years, 80% of the methane is already gone; (converted to carbon dioxide); at 100 years, 99.97% is gone. Of course, if the power plant continues to operate, there will be new methane added from any ongoing leaks.

Over longer time frames, the lower warming legacy of methane becomes even more remarkable. If we dump a million tons of carbon dioxide into the atmosphere today, then even after one thousand years, 22% would still be in the air. On the other hand, if we dump a million tons of methane into the atmosphere, then after one thousand years it will be totally gone. By that we mean that less than one atom of those million tons is expected to still be in the atmosphere. If the harm to future generations is the salient issue, then it is critical to note that methane goes away rapidly while large amounts of carbon dioxide persist. The difference is dramatic.

Some argue that it is wrong to use longer time horizons when comparing the long-term impacts of greenhouse gas emissions because there could be tipping points or other factors that would dramatically change our underlying assumptions about global warming. While previously predicted tipping points have not materialised, the next one possibly could. This is true, and possible future tipping points should be considered when thinking about longer time horizons. However, even after a tipping point, methane will still have a dramatically shorter legacy than carbon dioxide, and the materialization of future tipping points are a possibility, not a certainty.

5. NATURAL GAS ADVANTAGE

What percent natural gas leakage would completely negate its benefit compared to coal? Because of the lifetime difference in the atmosphere, the answer depends on time scale of interest. Table 2 gives the results over several time frames.

The calculations include the carbon dioxide from the methane that burns in addition to the methane leaked directly into the atmosphere. We assume that the natural gas is pure methane (of all the constituents, only methane has a high global warming potential, if it is less than 100% methane the global warming advantage of natural gas over coal increases). The detailed calculations for Table 2 are provided in this footnote.[17]

$0.259\, e^{-t/172.9} + 0.338\, e^{-t/18.51}$ + 0.186 e-t/1.186. The equation was based on the work of N. Myhrvold and K. Caldeira, Envir. Res. Lett. 7 (2012), doi: 10.1088/1748-9327/7/1/014019.

17 The equation for the leakage f_e for equivalence to coal, is $f_e = 4.6/(GWP + 4.6)$. This is derived as follows. Let f be the fraction of methane that leaks. We use the global warming potential *GWP* per unit weight. For simplicity, we send 1 kg of natural gas (taken in the worst case to be pure methane) into the power plant. Then f kg will leak, and $(1\text{-}f)$ kg will burn. Each atom that burns combines with oxygen to make CO_2. Because the molecular weight of CO_2 is 44, and that of methane is 16, the burning produces $(44/16)(1\text{-}f) = 2.75\ (1\text{-}f)$ kg of CO_2. In addition to this, the *leaked* methane will have a CO_2 equivalent

Table 2. Methane Leakage to Lose Global Warming Advantage vs Coal

	0 yr	0 to 20 yr average	20 yr	0 to 100 yr average	100 yr*
% leakage for coal equivalence	3.8%	5.3%	12%	12%	65%

* At 100 yr, the warming contribution is dominated by the atmospheric methane that has reacted in the atmosphere to create CO2.[13]

The calculation for methane leakage at the rate of 5.3% shows that at this leakage rate, the effect of fugitive methane, when added to the carbon dioxide warming effect of the 94.7% of gas that is burned, just matches the greenhouse emissions of coal. It does not exceed it, as one may wrongly deduce from the simple statement that "methane is 86 times more potent than carbon dioxide".

Another way of saying this is that if you want to build a natural gas plant instead of a coal plant (and are considering the timeframe of 20 years), 5.3% methane leakage over the entire lifecycle of natural gas would put you at greenhouse emissions equivalency with coal. As shown, a similar calculation for a 100-year period (average GWP of 34) indicates that the methane leakage would have to be 12% to match the warming effect of the replaced coal plant. If we were concerned about the legacy at 100 years (not at the average from now until then), then absurd amounts of methane would have to leak, 65%, to have the greenhouse effect of a coal plant. When worrying about impacts on future generations, natural gas use today is far superior to coal.

Another way of thinking about the same issue is to ask how much better is natural gas than coal at certain leakage rates, and over certain timeframes. We call this advantage factor *A*, and an equation for it is derived in footnote 17. With no leakage, natural gas is 3.2 times better than coal. For 3% leakage, the 100-year-average advantage drops to 2.3. The natural gas advantage for various leakages and time periods is shown in the Table 3. This shows that even if you are most concerned with the near-future, natural gas is dramatically better than coal.

6. AVERAGE LEAKAGE TODAY IS FAR BELOW DANGEROUS LEVELS

How much natural gas is actually leaking? In 2011, concern over the potential threat of fugitive methane was ignited by an article by Robert Howarth and collaborators.[18] They estimated that leakage from new hydraulically fractured natural gas wells and supply chain could be as high as 7.9%. They obtained this number by taking their highest value for leakage from a conventional gas well, 6%, and adding on an additional leakage of 1.9% that could occur during the flowback operation (done for shale gas wells but not for conventional natural gas operations).

effect of (*GWP*)(*f*), making a total CO_2 equivalent global warming effect equal to the sum: 2.75 (1-*f*) + (*GWP*)(*f*). A coal plant, for the same electric power generated produces 2.68 times as much CO_2 as does the methane plant, equal to (2.68)(2.75)(1-*f*) kg of CO_2. The "methane advantage" factor *A* is the ratio of this to that from the methane plant:

$$A = \frac{7.37\,(1-f)}{2.75\,(1-f) + GWP\,f}$$

For coal/methane equivalence value *fe*, we take *A* = 1 and solve for *f* yields *fe* = 4.6/(*GWP* + 4.6).

18 Howarth, R.W., Santoro, R., Ingraffea, A., 2011. Methane and the greenhouse-gas footprint of natural gas from shale formations. Climatic Change 106, 679–690.

Table 3. Global warming advantage of natural gas vs. coal electrical plants at different leakage rates and over different time horizons

	0 yr	0 to 20 yr average	20 yr	0 to 100 yr average	100 yr
At 3% leakage	1.4	1.6	2.3	2.3	3.2
At 2% leakage	1.7	1.9	2.6	2.5	3.2
At 1% leakage	2.2	2.4	2.8	2.8	3.2
At 0% leakage	3.2	3.2	3.2	3.2	3.2

Such leakage happens if the flowback methane is vented to the atmosphere rather than flared. They were being cautionary; in their data from 5 wells, only one had substantial (1.3%) methane emission during flowback.

A more reasonable reading of Howarth would not include the very high potential emissions from transport, storage and distribution, which added 3.6% to the upper range. That leaves the total at 4.3%, more consistent with other estimates.

Howarth's higher 7.9% figure triggered great concern, particularly from readers who did not realize that this was an extreme and unlikely limit.

With a 100-year GWP of 34, many thought (incorrectly) that a 3% leak would negate all advantage over coal. However even the 7.9% leakage number is not disastrous when we take into account the efficiency of natural gas generators. For a 20-year average, 7.9% leakage leads to a natural gas advantage of 0.78, that is, coal is better by a 22%. That's not good, but it is not catastrophic. For the 100-year average at 7.9% leakage, natural gas is still 40% better than coal. And at the 100-year point, the leakage is virtually irrelevant – natural gas is advantageous even if over half leaks.

We now know that Howarth's leakage value of 7.9% was high; a better estimate is 1.9% to 2.6%. A detailed review of leakage studies was published in 2014 by Brandt et al.[19] and further analysed and summarised by Hausfather.[20] The official leakage rates from well inventories report leakages averaging 1.5%; other studies show higher levels of 2% to 4%, including some "super emitters" that leak 6% to 10%. Brandt concludes that the average emissions were probably between 1.9% and 2.6%.[21] A recent report of the Environmental Defense Fund done by the Rhodium Group [22] estimates the world-wide leakage to be about 3%. The effects of leakages are easily read off Table 3; the advantage remains strong for natural gas.

A similar conclusion was reached in a recent paper by J. Peischi et al.[23] They determined from airplane measurements that for the predominant shale gas sites in the US, the fugitive methane leakage varies from a low of 0.18% to a high of 2.8%. The low levels that can be achieved by following industry best practice are illustrated by their measured leakage above the Marcellus: from a low of 0.18 to a high of only 0.41% for that vast and highly fracked region (although this low number may have been achieved in part by other effects, such as fewer liquid unloadings in the dry gas found in this formation). This number

19 Brandt, A.R., Heath, G.A., Kort, E.A., O'Sullivan, F., Pétron, G., Jordaan, S.M., Tans, P., Wilcox, J., Gopstein, A.M., Arent, D., Wofsy, S., Brown, N.J., Bradley, R., Stucky, G.D., Eardley, D., Harriss, R., 2014. Methane Leaks from North American Natural Gas Systems. Science 343, 733-735.

20 Z. Hausfather, Natural Gas Leakage in Brandt et al., Berkeley Earth memo, available at www.BerkeleyEarth.org/memos.

21 Brandt concludes that overall US CH_4 inventories from all sources are underestimated by 1.25x to 1.75x. The implied leakage rates depend on where the excess methane is coming from. You get 1.9% to 2.6% if you assume that the excess methane is distributed proportionately across known sources. There is evidence mentioned by Brandt that other sources (e.g. lifestock) are also significantly underestimated. For details see Brandt and Hausfather.

22 K. Larsen, M. Delgado, P. Marsters, *Untapped Potential, Reducing Global Methane Emissions from Oil and Natural Gas Systems.* Available at:

www.edf.org/sites/default/files/content/rhg_untappedpotential_april2015.pdf

23 Quantifying atmospheric methane emissions from the Haynesville, Fayetteville, and northeastern Marcellus shale gas production regions, J. Peischl, T. B. Ryerson, K. C. Aikin, J. A. de Gouw, J. B. Gilman, J. S. Holloway, B. M. Lerner, R. Nadkarni, J. A. Neuman, J. B. Nowak, M. Trainer, C. Warneke and D. D. Parrish, JGR Atmospheres, DOI: 10.1002/2014JD022697.

does not include leakage from distribution and combustion, but it does illustrate that leakage at the wells can be kept very low.

In terms of true legacy at 100 years (rather than average over the next 100 years), fugitive methane is incapable of offering any threat whatsoever, because of its short 8.6 year half-life in the atmosphere. Even with high leakage, natural gas can be 3 times better than coal after 100 years. If we were to compare future natural gas generators with high efficiency coal, this advantage drops to 2.

Hausfather has analysed a more complex situation, one in which the use of natural gas delays the advent of carbon-free power generation. If this happens, the 100-year benefit of natural gas is reduced, but in most cases there is still a benefit.[24]

7. COMPARISON WITH PRIOR RESULT OF ALVAREZ ET AL.

The most widely quoted number for the acceptable limit for natural gas is that found in the publication by R. Alvarez et al. of 3.2%. This is the number that has been used by policy makers to determine acceptable leakage. It compares to the value of 3.8% in our Table 2, for zero year lag. Our number is slightly higher than that of Alvarez et al. for several reasons. They assumed coal efficiency at 39% (vs. our 33%). That difference is attributable to different goals; they wanted to compare to future coal plants, and we were comparing to the ones that natural gas would replace. They assumed 50% efficiency for natural gas, and we took a higher level of 54%, to see what is the best we could achieve if the global warming considerations were taken to be important for the design. They also used a more detailed model of coal, including methane leakage from its mining and other factors. Our goal was not to try to keep the model simple in order to maximise transparency and ease of use. Taking account of our different goal, we find no conflict of our results with those of Alvarez et al.

Note that the 3.2% limit for acceptable leakage is the value for zero year lag. It is the period immediately after the release, and when there is no advantage to methane from the disappearance of methane from the atmosphere. For that reason, we think the emphasis on this number, not in the paper by Alvarez et al., but in the focus put on it by policy makers is misguided. In their paper, Alvarez et al. also give the leakages that would achieve equivalence for longer periods. For example, in their Fig. 2C, they show that a 7% pulse of leakage would achieve equivalence to coal in about 45 years. It is important to note that what they mean by this result is that the *average* over 45 years is equal to that of coal. After 45 years (over 5 half-lives) 97% of the leaked methane is gone. It is easy to misread the Alvarez et al. results to think that methane has a long legacy.

8. CHINA, INDIA, AND THE DEVELOPING WORLD

When considering energy policies in the US, the UK, or Europe, it is important to consider how insignificant the West is in the future of global warming. The future rise in global temperatures will come primarily from China, India, and the rest of the developing world. The developed world can hope to set an example that the developing nations can then follow, but it needs to be an example that they can afford.

As a specific example, suppose that the US were to replace half of its coal-powered stations immediately, today, with zero-carbon power plants. About 20% of the total US energy use comes from coal; let's assume that 30% of its

[24] Z. Hausfather, Bounding the Climate Viability of Natural Gas as a Bridge Fuel, published in Energy Policy, vol. 86, pp. 286-294 (2015); doi:10.1016/j.enpol.2015.07.012.

CO_2 comes from this. A cut in half would amount to a 15% cut in the CO_2 from the US. Let's also assume that China reduces its emission growth to the promised level of 6% per year. Since China's emissions are now double those of the US, China's growth would negate the reduction in the US in 15 months.

Thus even the unrealistic scenario of cutting US coal use by 50% would result in only a trivial delay in warming. If the goal is to prevent substantial additional global warming, the focus must be on the expected rise in emissions from the developing world. The West must help the developing world avoid new coal use.

China and India have an additional reason to switch from coal to natural gas: the fact that particulate air pollution can be reduced by a factor of 400 by doing so.[25] The poorer nations can't afford to subsidise carbon-free energy, so in general, economic concerns must be foremost. In much of the developing world, coal provides the primary source of electric power, and to the extent that natural gas can replace it, both greenhouse gas and air pollution emissions can be substantially reduced.

9. DISCUSSION

The benefits of natural gas for electricity production compared to that of coal are large, and the role it could play as a bridging fuel is significant. Our main concern is for the future, and that is why we assumed replacement of existing coal facilities with high efficiency combined cycle natural gas generators. Many currently existing natural gas plants don't have the high efficiency we assumed, and that reduces their "advantage" factor.

The threat of fugitive methane is low, and could be made even lower by addressing the small number of super emitters, primarily through regulations that require industry best practice at all wells. Because of the short 8.6-year half-life of methane in the atmosphere, the legacy danger of fugitive methane is tiny. If methane leakage proves to only be a temporary phenomenon. If we continue to use natural gas and sustain a high leakage rate over the full century, methane leakage has more of an impact, although still less than coal for any plausible leakage rate.

It is always worthwhile to emphasise that reduction of greenhouse emissions in the US, the UK, and Europe is a worthwhile goal, but it is the developing world that really counts. We need to set an example that China and the rest of the developing world can afford to follow.

[25] R. Muller and E. Muller, *Why Every Serious Environmentalist Should Favour Fracking,* Centre for Policy Studies (London, 2013), ISBN 978-1-906996-802, available at www.BerkeleyEarth.org/papers.

THE AUTHORS

Elizabeth Muller is co-founder and Executive Director of Berkeley Earth, a non-profit research organization. She has authored numerous scientific and policy papers, and Op Eds in the New York Times and the San Francisco Chronicle, and made numerous TV and radio appearances. Previously she was a director at Gov3 (now CS Transform) and Executive Director of the Gov3 Foundation. From 2000 to 2005 she was a policy advisor at the OECD (Organization for Economic Cooperation and Development). She has advised governments in over 30 countries, in both the developed and developing world, and has extensive experience with stakeholder engagement and communications, particularly regarding technical issues.

Richard A Muller has been Professor of Physics at the University of California, Berkeley since 1980. He is recognised as one of the world's leading climate scientists and is the co-founder and scientific director of Berkeley Earth, a non-profit organization that re-analysed the historic temperature record and addressed key issues raised by climate sceptics. He is the author of Physics for Future Presidents and Energy for Future Presidents and six other books. He has founded two projects that led to Nobel Prizes and was named by Foreign Policy as one of its 2012 Top 100 Global Thinkers.

ISBN 978-1-910627-17-4