ONTARIO GEOTHERMAL ASSOCIATION INTERROGATORIES

ON EVIDENCE OF ENBRIDGE GAS DISTRIBUTION

Ontario Energy Board Community Expansion Proceeding

EB-2016-0004

1. [p. 7] Please confirm that a Stage 2 analysis should, in Enbridge's proposal, include

    a. the economic impacts on all customers outside of the new communities of the subsidies they are providing,
    b. the economic impacts on the local communities of any subsidies provided by the municipalities,
    c. the economic impacts across the province of any provincial funding,
    d. the impacts on the Ontario electricity system,
    e. quantification of the environmental costs and benefits of the expansion relative to:
        i. Status quo, and
        ii. Other options for provision of energy functionality to the community.

    If any of the above are not proposed to be included, please explain why they should be excluded.

2. [p. 12] Attached is a journal article dated April 22, 2014 authored by Professor Robert Howarth of Cornell University. Please advise whether Enbridge agrees with the conclusion of the author that, in addition to carbon dioxide emissions from combustion of natural gas, natural gas upstream and downstream methane emissions are equivalent to 3.8% of conventional gas, and 5.8% of unconventional gas including shale gas. Please advise the forecast mix of conventional vs. unconventional gas in years 10, 20, and 30 of its gas forecasts. Please provide a calculation of equivalent carbon dioxide emissions reflecting the upstream and downstream methane emissions. Please advise the total equivalent carbon dioxide emissions (including CO_2 equivalent of methane from upstream and downstream emissions) for each cubic metre of natural gas expected to be burned in the expansion communities.

3. [p. 12] Please provide all studies, reports, analyses and other documents or information in the possession of Enbridge dealing in whole or in part with the implications of Ontario's greenhouse gas reduction goals on Enbridge's business, including, without limitation, any estimates of the reductions in natural gas throughput volumes that will be required to meet those goals.

4. [p. 12] Please confirm that, in most communities in Ontario, the timing of the load for electric heating and water heating is not consistent with natural gas being the marginal electricity generation fuel at those times.

5. [p. 12] Please advise whether Enbridge agrees that the Board's decision with respect to community expansion policies should be consistent with the provincial government's published climate change strategy.

6. [p. 15] Please provide detailed calculations, with sources, for the annual average energy cost savings of $1,700 and the average cost of conversion of $3,500.

7. [p. 15] Please add ground source heat pumps to Table 1.

8. [p. 19] Please provide the full PI calculations for each of the ten largest Enbridge projects. Please include in the response the customer class breakdown for each of the communities, the assumptions with respect to conversion rates, and all other assumptions necessary to review the PI calculations.

9. [p. 19] For all of the Enbridge projects in aggregate, please provide the total cost, the number of customers by year by rate class, the total revenues by year, the incremental throughput by year, the incremental operating costs by year, and the forecast cost of carbon by year.

10. [p. 20] Please explain how and to what extent Enbridge believes the Board's rules with respect to DSM should be applicable to uneconomic community expansions.

11. [p. 25] Please recalculate Tables 4 through 6 to include in the PI for each project a) the cost of all related reinforcements, and b) the cost of carbon.

12. [p. 29] Please provide details of what subsidies are included, and what subsidies are not included, in each of the columns relating to subsidies.

13. [p. 30] Please confirm that Table 7 does not include subsidies, tax increment relief, contributions in aid of construction, or any other such amounts (e.g. no SES, ITE or CIAC). If any such amounts are included, please restate Table 7 with no such amounts.

14. [p. 31] Please provide the full calculations behind Table 10. Please in addition provide the full calculation of the figure of $351 million, and the calculation of the reduction due to cap and trade.

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PERSPECTIVE

A bridge to nowhere: methane emissions and the greenhouse gas footprint of natural gas

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Keywords
Greenhouse gas footprint, methane emissions, natural gas, shale gas

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Abstract

In April 2011, we published the first peer-reviewed analysis of the greenhouse gas footprint (GHG) of shale gas, concluding that the climate impact of shale gas may be worse than that of other fossil fuels such as coal and oil because of methane emissions. We noted the poor quality of publicly available data to support our analysis and called for further research. Our paper spurred a large increase in research and analysis, including several new studies that have better measured methane emissions from natural gas systems. Here, I review this new research in the context of our 2011 paper and the fifth assessment from the Intergovernmental Panel on Climate Change released in 2013. The best data available now indicate that our estimates of methane emission from both shale gas and conventional natural gas were relatively robust. Using these new, best available data and a 20-year time period for comparing the warming potential of methane to carbon dioxide, the conclusion stands that both shale gas and conventional natural gas have a larger GHG than do coal or oil, for any possible use of natural gas and particularly for the primary uses of residential and commercial heating. The 20-year time period is appropriate because of the urgent need to reduce methane emissions over the coming 15–35 years.

Introduction

Natural gas is often promoted as a bridge fuel that will allow society to continue to use fossil energy over the coming decades while emitting fewer greenhouse gases than from using other fossil fuels such as coal and oil. While it is true that less carbon dioxide is emitted per unit energy released when burning natural gas compared to coal or oil, natural gas is composed largely of methane, which itself is an extremely potent greenhouse gas. Methane is far more effective at trapping heat in the atmosphere than is carbon dioxide, and so even small rates of methane emission can have a large influence on the greenhouse gas footprints (GHGs) of natural gas use.

Increasingly in the United States, conventional sources of natural gas are being depleted, and shale gas (natural gas obtained from shale formations using high-volume hydraulic fracturing and precision horizontal drilling) is rapidly growing in importance: shale gas contributed only 3% of United States natural gas production in 2005, rising to 35% by 2012 and predicted to grow to almost 50% by 2035 [1]. The gas held in tight sandstone formations is another form of unconventional gas, also increasingly obtained through high-volume hydraulic fracturing and is growing in importance. In 2012, gas extracted from shale and tight-sands combined made up 60% of total natural gas production, and this is predicted to increase to 70% by 2035 [1]. To date, shale gas has been almost entirely a North American phenomenon, and largely a U.S. one, but many expect shale gas to grow in global importance as well.

In 2009, I and two colleagues at Cornell University, Renee Santoro and Tony Ingraffea, took on as a research challenge the determination of the GHG of unconventional gas, particularly shale gas, including emissions of methane. At that time, there were no papers in the peer-reviewed literature on this topic, and there were relatively few papers even on the contribution of methane to the GHG of conventional natural gas [2–4]. At the end of 2009, the U.S. Environmental Protection Agency (EPA) still did not distinguish between conventional gas and shale gas, and they estimated methane emissions for the natural gas industry using emission factors from a 1996 study conducted jointly with the industry [5]; shale gas is not mentioned in that report, which is not surprising since significant shale gas production only started in the first decade of the 2000s.

We began giving public lectures on our analysis in March 2010, and these attracted media attention. One of our points was that it seemed likely that complete life cycle methane emissions from shale gas (from well development and hydraulic fracturing through delivery of gas to consumers) were greater than from conventional natural gas. Another preliminary conclusion was that the EPA methane emission estimates (as they were reported in 2009 and before, based on [5]) seemed at least two- to three-fold too low. In response to public attention from our lectures, the EPA began to reanalyze their methane emissions [6], and in late 2010, EPA began to release updated and far higher estimates of methane emissions from the natural gas production segment [7]. In April 2011, we published our first paper on the role of methane in the GHG of shale gas [8]. We concluded that (1) the amount and quality of available data on methane emissions from the natural gas industry were poor; (2) methane emissions from shale gas were likely 50% greater than from conventional natural gas; and (3) these methane emissions contributed significantly to a large GHG for both shale gas and conventional gas, particularly when analyzed over the timescale of 20-years following emission. At this shorter timescale – which is highly relevant to the concept of natural gas as a bridge or transitional fuel over the next two to three decades – shale gas appeared to have the largest greenhouse warming consequences of any fossil fuel (Fig. 1). Because our conclusion ran counter to U.S. national energy policy and had large implications for climate change, and because the underlying data were limited and of poor quality, we stressed the urgent need for better data on methane emissions from natural gas systems. This need has since been amplified by the Inspector General of the EPA [9].

Our paper received immense media coverage, as evidenced by Time Magazine naming two of the authors

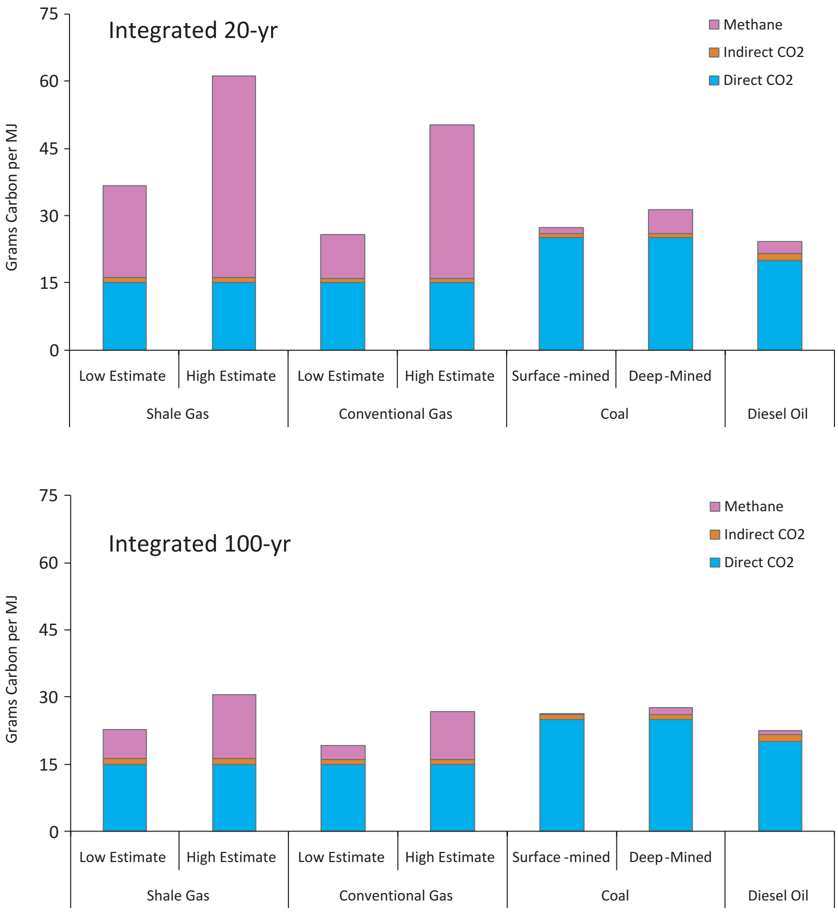

Figure 1. Comparison of the greenhouse gas footprint of shale gas, conventional natural gas, coal, and oil to generate a given quantity of heat. Two timescales for analyzing the relative warming of methane and carbon dioxide are considered: an integrated 20-year period (top) and an integrated 100-year period (bottom). For both shale gas and conventional natural gas, estimates are shown for the low- and high-end methane emission estimates from Howarth et al. [8]. For coal, estimates are given for surface-mined and deep-mined coal, since methane emissions are greater for deeper mines. Blue bars show the direct emissions of carbon dioxide during combustion of the fuels; the small red bars show the indirect carbon dioxide emissions associated with developing and using the fuels; and the magenta bars show methane emissions converted to g C of carbon dioxide equivalents using period-appropriate global warming potentials. Adapted from [8].

(Howarth and Ingraffea) "People who Mattered" to the global news in the December 2011 Person of the Year Issue [10]. The nine months after our paper was published saw a flurry of other papers on the same topic, a huge increase in the rate of publication on the topic of methane and natural gas compared to prior years and decades. While some of these offered support for our analysis, most did not and were either directly critical of our work, or without referring to our analysis reached conclusions more favorable to shale gas as a bridge fuel. Few of these papers published in the 9 months after our April 2011 paper provided new data; many simply offered different interpretations of previously presented information (as is reviewed briefly below). However, in 2012 and 2013 many new studies were published with major new insights and sources of data. In this paper, I briefly review the work on methane and natural gas published between April 2011 and February 2014, concentrating on those studies that have produced new primary data.

There are four components that are central to evaluating the role of methane in the GHG footprint of natural gas: (1) the amount of carbon dioxide that is directly emitted as the fuel is burned and indirectly emitted to obtain and use the fuel; (2) the rate of methane emission from the natural gas system (often expressed as a fraction of the lifetime production of the gas well, normalized to the amount of methane in the gas produced); (3) the global warming potential (GWP) of methane, which is the relative effect of methane compared to carbon dioxide in terms of its warming of the global climate system and is a function of the time frame considered after the emission of the methane; and (4) the efficiency of use of natural gas in the energy system. The GHG is then determined as:

$$\text{GHG footprint} = [\text{CO}_2\,\text{emissions} + (\text{GWP} \times \text{methane emissions})]/\text{efficiency}$$

There is widespread consensus on the magnitude of the direct emissions of carbon dioxide, and the indirect emissions of carbon dioxide used to obtain and use natural gas (for example, in building and maintaining pipelines, drilling and hydraulically fracturing wells, and compressing gas), while uncertain, are also relatively small [8]. In this paper, I separately consider each of the other three factors (methane emissions, GWP, and efficiency of use) in the context of our April 2011 paper [8] and the subsequent literature.

How Much Methane is Emitted by Natural Gas Systems?

We used a full life cycle analysis in our April 2011 paper, estimating the amount of methane emitted to the atmosphere as a percentage of the lifetime production of a gas well (normalized to the methane content of the natural gas), including venting and leakages at the well site but also during storage, processing, and delivery to customers. For conventional natural gas, we estimated a range of methane emissions from 1.7% to 6% (mean = 3.8%), and for shale gas a range of 3.6% to 7.9% (mean = 5.8%) [8]. We attributed the larger emissions from shale gas to venting of methane at the time that wells are completed, during the flowback period after high-volume hydraulic fracturing, consistent with the findings of the EPA 2010 report [7]. We assumed all other emissions were the same for conventional and shale gas. We estimated that downstream emissions (emissions during storage, long-distance transport of gas in high-pressure pipelines, and distribution to local customers) were 1.4–3.6% (mean = 2.5%) of the lifetime production of a well, and that the upstream emissions (at the well site and for gas processing) were in the range of 0.3–2.4% (mean = 1.4%) for conventional gas and 2.2–4.3% (mean = 3.3%) for shale gas (Table 1).

Table 1. Full life cycle-based methane emission estimates, expressed as a percentage of total methane produced in natural gas systems, separated by upstream emissions for conventional gas, upstream emissions for unconventional gas including shale gas, and downstream emissions for all natural gas. Studies are listed chronologically, and our April 2011 study is boldfaced.

	Upstream conventional gas	Upstream unconventional gas	Downstream
EPA 1996 [5]	0.2%	–	0.9%
Hayhoe et al. [2]	1.4	–	2.5
Jamarillo et al. [4]	0.2	–	0.9
Howarth et al. [8]	**1.4**	**3.3**	**2.5**
EPA [11]	1.6	3.0	0.9
Ventakesh et al. [12]	1.8	–	0.4
Jiang et al. [13]	–	2.0	0.4
Stephenson et al. [14]	0.4	0.6	0.07
Hultman et al. [15]	1.3	2.8	0.9
Burnham et al. [16]	2.0	1.3	0.6
Cathles et al. [17]	0.9	0.9	0.7

Total emissions are the sum of the upstream and downstream emissions. Studies are listed chronologically by time of publication. Dashes indicate no values provided. The full derivation of the estimates shown here is provided elsewhere [18, 19].

Although there were no prior papers on methane emissions from shale gas when our paper was published, we can compare our estimates for conventional natural gas with earlier literature (Table 1). Our mean estimates for both upstream and downstream emissions were identical to the "best estimate" of Hayhoe et al. [2], although that paper presented a wider range of estimates for both upstream and downstream. It is important to note that we used several newer sources of information not available to Hayhoe et al. [2], making the agreement all the more remarkable. The Howarth et al. [8] estimates were substantially higher than the emission factors used by the EPA through 2009 based on the 1996 joint EPA-industry study [5], which were only 1.1% for total emissions, 0.2% for upstream emissions, and 0.9% for downstream emissions. In the only other peer-reviewed paper on life cycle methane emissions from conventional gas published in the decade or two before our paper, Jamarillo et al. [4] relied on these same EPA emission factors, although new data on downstream emissions had already shown these emission factors to be too low [3].

Through late 2010 and the first half of 2011, the EPA provided a series of updates on their methane emission factors from the natural gas industry, giving estimates for shale gas for the first time as well as substantially increasing their estimates for conventional natural gas. These are discussed in detail by us elsewhere [18, 19]. Note that the EPA did not and still has not updated their estimates for downstream emissions, still using a value of 0.9% from a 1996 study [5]. For upstream emissions, the revised EPA estimates gave emission factors of 1.6% (an increase from their earlier value of 0.2%) for conventional natural gas and 3.0% for shale gas [18, 19]. Note that the EPA estimates for upstream emissions presented in 2011 [11] were 14% higher than ours for conventional gas and 10% lower than ours for shale gas. Total emissions were more divergent, due to the large difference in downstream emission estimates (Table 1).

In addition to the revised EPA emission factors, many other papers presented life cycle assessments of methane emissions from shale gas, conventional gas, or both in the immediate 9 months after April 2011 (Table 1). We and others have critiqued these publications in detail elsewhere [18–20]. Here, I will emphasize four crucial points:

1 For the upstream emissions in Table 1, all studies relied on the same type of poorly documented and highly uncertain information. These poor-quality data led us in Howarth et al. [8] to call for better measurements on methane fluxes, conducted by independent scientists. Several such studies have been published in the past 2 years, as is discussed further below, and these provide a more robust approach for estimating methane emissions.

2 At least some of the differences among values in Table 1 are due more to different assumptions about the lifetime production of a shale gas well than to differences in emissions per well [18, 20]. Note that the upstream life cycle emissions are scaled to the lifetime production of a well (normalized to the methane content of the gas produced for the estimates given in Table 1), and this was very uncertain in 2011 since shale gas development is such a new phenomenon [21]. A subsequent detailed analysis by the U.S. Geological Survey has demonstrated that the mean lifetime production of unconventional gas wells is in fact lower than any of papers in Table 1 assumed [22], meaning that upstream shale gas emissions per production of the well from all of the studies should be higher, in some cases substantially so [18, 20].

3 The downstream emissions in Table 1 are particularly uncertain, as highlighted by both Hayhoe et al. [2] and Howarth et al. [8]. Note that all of the other papers listed in Table 1 base their downstream emissions on the EPA emission factors from 1996 [5], and none are higher than those EPA estimates, even though a 2005 paper in *Nature* demonstrated higher levels of emission from long-distance pipelines in Europe [3]. Several of the papers in Table 1 have downstream emissions that are lower than the 1996 EPA values, as they are focused on electric power plants and assume that these plants are drawing on gas lines that have lower emissions than the average, which would include highly leaky low-pressure urban distribution lines [12–14, 16]. Some recent papers have noted a high incidence of leaks in natural gas distribution systems in two U.S. east coast cities [23, 24], but these new studies have yet placed an emission flux estimate on these leaks. Another study demonstrated very high methane emissions from fossil fuel sources in Los Angeles but could not distinguish between downstream natural gas emissions and other sources [25]. Given the age of gas pipelines and distribution systems in the United States, it should come as no surprise that leakage may be high [8, 18, 19]. Half of the high-pressure pipelines in the United States are older than 50 years [18], and parts of the distribution systems in many northeastern cities consist of cast-iron pipes laid down a century ago [24].

4 While one of the papers in Table 1 by Cathles and his colleagues [17], characterized our methane emission estimates as too high and "at odds with previous studies," that in fact is not the case. As noted above, both our downstream and upstream estimates for conventional gas are in excellent agreement with one of the few previous peer-reviewed studies [2]. Furthermore, our upstream emissions are in good agreement with the majority of the papers published in 9 months after

ours: for conventional gas, our mean estimate of 1.4% compares with the mean for all the other studies in Table 1 of 1.33%; if we exclude the very low estimate from Stephenson et al. [14], which was based on an analysis of what the gas industry is capable of doing rather than on any new measurements, and also the relatively low estimate from Cathles et al. [17], which was based on the assumption that the gas industry would not vent gas for economic and safety issues (see critique of this in [18]), the mean of the other four studies is 1.7, or almost twice as high as the Cathles et al. [17] estimate and 20% higher than our estimate. For shale gas, again excluding Stephenson et al. [14] and Cathles et al. [17] as well as our estimate, the other four studies in Table 1 have a mean estimate of 2.3, a value 2.5-fold greater than that from Cathles et al. [17] and 30% less than our mean estimate. From this perspective, the estimates of Cathles et al. [17] appear to be greater outliers than are ours.

Since 2012, many new papers have produced additional primary data (Fig. 2). Two of these found very high upstream methane emission rates from unconventional gas fields (relative to gross methane production), 4% for a tight-sands field in Colorado [26] and 9% for a shale gas field in Utah [27], while another found emissions from a shale gas field in Pennsylvania to be broadly consistent with the emission factors we had published in our 2011 paper [28]. All three of these studies inferred rates from atmospheric data that integrated a large number of wells at the basin scale. The new Utah data [27] are much higher than any of the estimates previously published for upstream emissions from unconventional gas fields (Fig. 2), while the measurement for the Colorado tight-sands field [26] overlaps with our high-end estimate for upstream unconventional gas emissions in Howarth et al. [8]. The Utah and Colorado studies may not be representative of the typical methane emissions for the entire United States, in part, because they focused on regions where they expected high methane fluxes based on recent declines in air quality. But I agree with the conclusion of Brandt and his colleagues [29] that the "bottom-up" estimation approaches that we and all the other papers in Table 1 employed are inherently likely to lead to underestimates, in part, because some components of the natural gas system are not included. As one example, the recent Pennsylvania study, which quantified fluxes from discrete locations on the ground by mapping methane plumes from an airplane, found very high emissions from many wells that were still being drilled, had not yet reached the shale formation, and had not yet been hydraulically fractured [28]. These wells represented only 1% of the wells in the area but were responsible for 6–9% of the regional methane flux from all sources. One explanation is that the drill rigs encountered pockets of shallower gas and released this to the atmosphere. We, the EPA, and all of the papers in Table 1 had assumed little or no methane emissions from wells during this drilling phase.

Allen and colleagues [30] published a comprehensive study in 2013 of upstream emissions for both conventional and unconventional gas wells for several regions in the United States, using the same basic bottom-up approach as the joint EPA-industry study of 1996 used [5]. As with that earlier effort, this new study relied heavily on industry cooperation, and was funded largely by industry with coordination provided by the Environmental Defense Fund. For the United States as a whole at the

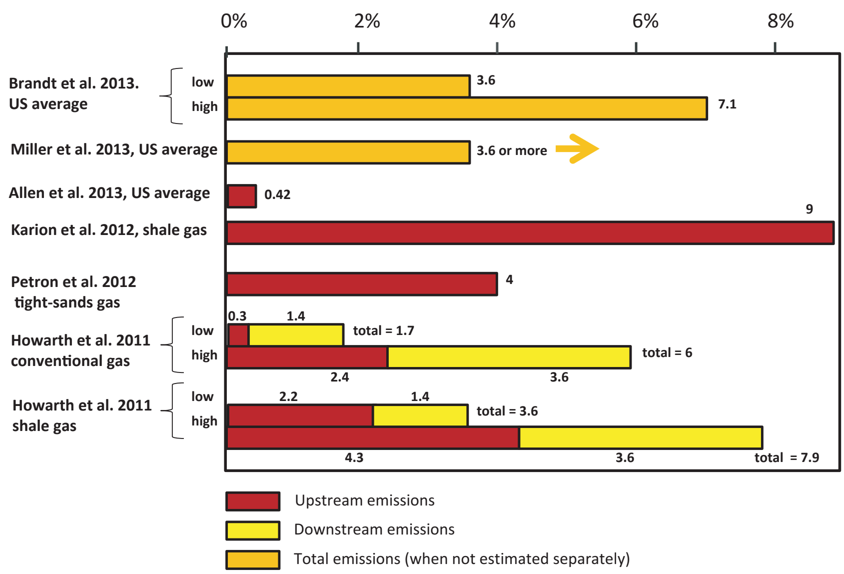

Figure 2. Comparison of recent new data on methane emissions compared to the estimates published in Howarth et al. [8]. Some of the new data are for upstream emissions, while others give only averages for natural gas systems in the United States. No new measurements for downstream emissions alone have been published since 2005 [8, 26, 27, 29, 30, 32].

time of their study, Allen et al. [30] concluded that upstream methane emissions were only 0.42% of the natural gas production by the wells (Fig. 2), a value at the low end of those seen in Table 1. Using the low-end estimates, "best-case" scenarios for upstream emissions from Howarth et al. [8] and the mix of shale gas and conventional gas produced in the United States in 2012, I estimate the U.S. national best-case emission rate would be 0.5%, or similar to that observed by Allen and colleagues. It should not be surprising that their study, in relying on industry access to their sampling points, ended up in fact measuring the best possible performance by industry.

In 2013, the EPA reduced their emission estimates for the oil and gas industry, essentially halving their upstream emissions for average natural gas systems from 1.8% to 0.88% for the year 2009 (with the mix of conventional and unconventional gas for that year) from what they had reported in 2011 and 2012; the EPA estimate for downstream emissions remained at 0.9%, giving a total national emission estimate of 1.8%. EPA took this action to decrease their emission factors for upstream emissions despite the publication in 2012 of the methane emissions from a Colorado field [26] and oral presentations at the American Geophysical Union meeting in December 2012 of the results subsequently published by Karion and colleagues [27] and Caulton and colleagues [28], all of which would have suggested higher emissions, perhaps spectacularly so. As is discussed by Karion et al. [27], the decrease in the upstream methane emissions by EPA in 2013 was driven by a non-peer-reviewed industry report [31] which argued that emissions from liquid unloading and during refracturing of unconventional wells were far lower than used in the EPA [11] assessment. At least in part in response to these changes by EPA, the Inspector General for the EPA concluded that the agency needs improvements in their approach to estimating emissions from the natural gas industry [9].

An important paper published late in 2013 [32] indicates the EPA made a mistake in reducing their emission estimates earlier in the year. In this analysis, the most comprehensive study to date of methane sources in the United States, Miller and colleagues used atmospheric methane monitoring data for 2007 and 2008 – 7710 observations from airplanes and 4984 from towers from across North America – together with an inverse model to assess total methane emissions nationally from all sources. They concluded that rather than reducing methane emission terms between their 2011 and 2013 inventories, EPA should have increased anthropogenic methane emission estimates, particularly for the oil and gas industry and for animal agriculture operations. They stated that methane emissions from the United States oil and gas industry are very likely two-fold greater or more than indicated by the factors EPA released in 2013 [32]. This suggests that total methane emissions from the natural gas industry were at least 3.6% in 2007 and 2008 (Fig. 2).

In early 2014, Brandt and his colleagues [29] reviewed the technical literature over the past 20 years on methane emissions from natural gas systems. They concluded that "official inventories consistently underestimate actual methane emissions," but also suggested that the very high estimates from the top–down studies in Utah and Colorado [26, 27] "are unlikely to be representative of typical [natural gas] system leakage rates." In the supplemental materials for their paper, Brandt et al. [29] state that methane emissions in the United States from the natural gas industry are probably greater than the 1.8% assumed by the EPA by an additional 1.8–5.4%, implying an average rate between 3.6% and 7.1% (mean = 5.4%) [33] (Fig. 2).

This recent literature suggests to me that the emission estimates we published in Howarth et al. [8] are surprisingly robust, particularly for conventional natural gas (Fig. 2). The results from two of the recent top–down studies [26, 27] indicate our estimates for unconventional gas may have been too low. Partly in response to our work and their own reanalysis of methane emissions from shale gas wells, EPA has now promulgated new regulations that will as of January 2015 reduce methane emissions at the time of well completions, requiring capture and use of the gas instead in most cases. Some wells are exempt, and the regulation does not apply to venting of methane from oil wells, including shale oil wells, which often have associated gas. Nonetheless, the regulations are an important step in the right direction, and will certainly help, if they can be adequately enforced. Even still, though, results such as those from the Pennsylvania flyover showing high rates of methane emission during the drilling phase of some shale gas wells [28] suggest that methane emissions from shale gas may remain at levels higher than from conventional natural gas.

The GWP of Methane

While methane is far more effective as a greenhouse gas than carbon dioxide, methane has an atmospheric lifetime of only 12 years or so, while carbon dioxide has an effective influence on atmospheric chemistry for a century or longer [34]. The time frame over which we compare the two gases is therefore critical, with methane becoming relatively less important than carbon dioxide as the timescale increases. Of the major papers on methane and the GHG for conventional natural gas published before our analysis for shale gas, one modeled the relative radiative forcing by methane compared to carbon dioxide continuously over a 100-year time period following emission [2], and two used the global warming approach (GWP) which compares how much larger the integrated global warming from a given mass of methane is over a specified period of time compared to the same mass of carbon dioxide. Of the two that used the GWP approach, one showed both 20-year and 100-year GWP analyses [3] while another used only a 100-year GWP time frame [4]. Both used GWP values from the Intergovernmental Panel on Climate Change (IPCC) synthesis report from 1996 [35], the most reliable estimates at the time their papers were published. In subsequent reports from the IPCC in 2007 [36] and 2013 [34] and in a paper in *Science* by workers at the NASA Goddard Space Institute [37], these GWP values have been substantially increased, in part, to account for the indirect effects of methane on other radiatively active substances in the atmosphere such as ozone (Table 2).

In Howarth et al. [8], we used the GWP approach and closely followed the work of Lelieveld and colleagues [3] in presenting both integrated 20 and 100 year periods, and in giving equal credence and interpretation to both timescales. We upgraded the approach by using the most recently published values for GWP at that time [37].

Table 2. Comparison of the timescales considered in comparing the global warming consequences of methane and carbon dioxide.

Publication	Timescale considered	20-year GWP	100-year GWP
IPCC [35]	**20 and 100 years**	**56**	**21**
Hayhoe et al. [2]	0–100 years	NA	NA
Lelieveld et al. [3]	20 and 100 years	56	21
Jamarillo et al. [4]	100 years	–	21
IPCC [36]	**20 and 100 years**	**72**	**25**
Shindell et al. [37]	**20 and 100 years**	**105**	**33**
Howarth et al. [8]	20 and 100 years	105	33
Hughes [20]	20 and 100 years	105	33
Venkatesh et al. [12]	100 years	–	25
Jiang et al. [13]	100 years	–	25
Wigley [38]	0–100 years	NA	NA
Stephenson et al. [14]	100 years	–	25
Hultman et al. [15]	20 and 100 years	72, 105	25, 44
Skone et al. [39]	100 years	–	25
Burnham et al. [16]	100 years	–	25
Cathles et al. [17]	100 years	–	25
Alvarez et al. [40]	0–100 years	NA	NA
IPCC [34]	**10, 20, and 100 years**	**86**	**34**
Brandt et al. [29]	100 years	–	25

Studies are listed chronologically by time of publication. Values for the global warming potentials at 20 and 100 years given, when used in the studies. NA stands for not applicable and is shown when studies did not use the global warming potential approach. Dashes are shown for studies that did not consider the 20-year GWP. Studies that are bolded provided primary estimates on global warming potentials, while other studies are consumers of this information.

These more recent GWP values increased the relative warming of methane compared to carbon dioxide by 1.9-fold for the 20-year time period (GWP of 105 vs. 56) and by 1.6-fold for the 100-year time period (GWP of 33 vs. 21; Table 2). Our conclusion was that for the 20-year time period, shale gas had a larger GHG than coal or oil even at our low-end estimates for methane emission (Fig. 1); conventional gas also had a larger GHG than coal or oil at our mean or high-end methane emission estimates, but not at the very low-end range for methane emission (the best-case, low-emission scenario). At the 100-year timescale, the influence of methane was much diminished, yet at our high-end methane emissions, the GHG of both shale gas and conventional gas still exceeded that of coal and oil (Fig. 1).

Of nine new reports on methane and natural gas published in 9 months after our April 2011 paper [8], six only considered the 100-year time frame for GWP, two used both a 20- and 100-year time frame, and one used a continuous modeling of radiative forcing over the 0–100 time period (Table 2). Of the six papers that only examined the 100-year time frame, all used the lower GWP value of 25 from the 2007 IPCC report rather than the higher value of 33 published by Shindell and colleagues in 2009 that we had used; this higher value better accounts for the indirect effects of methane on global warming. Many of these six papers implied that the IPCC dictated a focus on the 100-year time period, which is simply not the case: the IPCC report from 2007 [36] presented both 20- and 100-year GWP values for methane. And two of these six papers criticized our inclusion of the 20-year time period as inappropriate [14, 17]. I strongly disagree with this criticism. In the time since April 2011 I have come increasingly to believe that it is essential to consider the role of methane on timescales that are much shorter than 100 years, in part, due to new science on methane and global warming presented since then [34, 41, 42], briefly summarized below.

The most recent synthesis report from the IPCC in 2013 on the physical science basis of global warming highlights the role of methane in global warming at multiple timescales, using GWP values for 10 years in addition to 20 and 100 years (GWP of 108, 86, and 34, respectively) in their analysis [34]. The report states that "there is no scientific argument for selecting 100 years compared with other choices," and that "the choice of time horizon …. depends on the relative weight assigned to the effects at different times" [34]. The IPCC further concludes that at the 10-year timescale, the current global release of methane from all anthropogenic sources exceeds (slightly) all anthropogenic carbon dioxide emissions as agents of global warming; that is, methane emissions are more important (slightly) than carbon dioxide emissions for driving the current rate of global warming. At the 20-year timescale, total global emissions of methane are equivalent to over 80% of global carbon dioxide emissions. And at the 100-year timescale, current global methane emissions are equivalent to slightly less than 30% of carbon dioxide emissions [34] (Fig. 3).

This difference in the time sensitivity of the climate system to methane and carbon dioxide is critical, and not widely appreciated by the policy community and even some climate scientists. While some note how the long-term momentum of the climate system is driven by carbon dioxide [15], the climate system is far more immediately responsive to changes in methane (and other short-lived radiatively active materials in the atmosphere, such as black carbon) [41]. The model published in 2012 by Shindell and colleagues [41] and adopted by the United Nations [42] predicts that unless emissions of methane and black carbon are reduced immediately, the Earth's average surface temperature will warm by 1.5°C by about 2030 and by 2.0°C by 2045 to 2050 whether or not carbon dioxide emissions are reduced. Reducing methane and black carbon emissions, even if carbon dioxide is not controlled, would significantly slow the rate of global warming and postpone reaching the 1.5°C and 2.0°C marks by 15–20 years. Controlling carbon dioxide as well as methane and black carbon emissions further slows the rate of global warming after 2045, through at least 2070 [41, 42] (Fig. 4).

Why should we care about this warming over the next few decades? At temperatures of 1.5–2.0°C above the 1890–1910 baseline, the risk of a fundamental change in the Earth's climate system becomes much greater [41–43], possibly leading to runaway feedbacks and even more global warming. Such a result would dwarf any possible benefit from reductions in carbon dioxide emissions over the next few decades (e.g., switching from coal to natural gas, which does reduce carbon dioxide but also increases methane emissions). One of many mechanisms for such catastrophic change is the melting of methane clathrates in the oceans or melting of permafrost in the Arctic. Hansen and his colleagues [43, 44] have suggested that warming of the Earth by 1.8°C may trigger a large and rapid increase in the release of such methane. While there is a wide range in both the magnitude and timing of projected carbon release from thawing permafrost and melting clathrates in the literature [45], warming consistently leads to greater release. This release can in turn cause a feedback of accelerated global warming [46].

To state the converse of the argument: the influence of today's emissions on global warming 200 or 300 years into the future will largely reflect carbon dioxide, and not

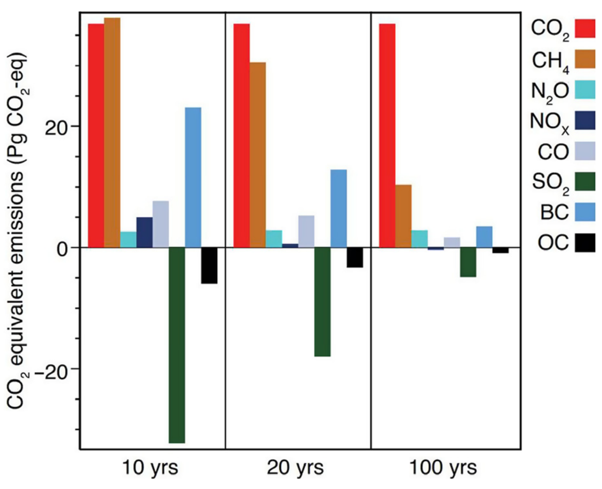

Figure 3. Current global greenhouse gas emissions, as estimated by the IPCC [34], weighted for three different global warming potentials and expressed as carbon dioxide equivalents. At the 10-year time frame, global methane emissions expressed as carbon dioxide equivalents actually exceed the carbon dioxide emissions. Adapted from [34].

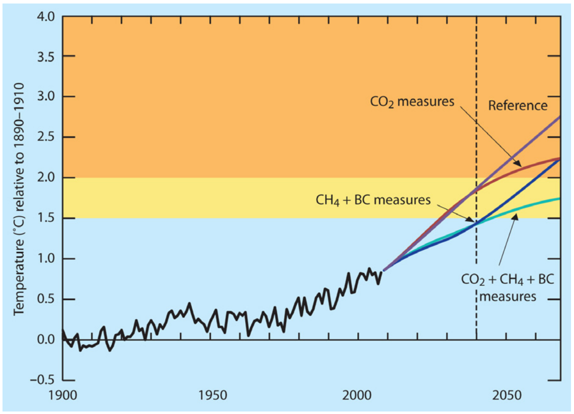

Figure 4. Observed global mean temperature from 1900 to 2009 and projected future temperature under four scenarios, relative to the mean temperature from 1890 to 1910. The scenarios include the IPCC [36] reference, reducing carbon dioxide emissions but not other greenhouse gases ("CO_2 measures"), controlling methane, and black carbon emissions but not carbon dioxide ("CH_4 + BC measures"), and reducing emissions of carbon dioxide, methane, and black carbon ("CO_2 + CH_4 + BC measures"). An increase in the temperature to 1.5–2.0°C above the 1890–1910 baseline (illustrated by the yellow bar) poses risk of passing a tipping point and moving the Earth into an alternate state for the climate system. The lower bound of this danger zone, 1.5° warming, is predicted to occur by 2030 unless stringent controls on methane and black carbon emissions are initiated immediately. Controlling methane and black carbon shows more immediate results than controlling carbon dioxide emissions, although controlling all greenhouse gas emissions is essential to keeping the planet in a safe operating space for humanity. Adapted from [42].

methane, unless the emissions of methane lead to tipping points and a fundamental change in the climate system. And that could happen as early as within the next two to three decades.

An increasing body of science is developing rapidly that emphasizes the need to consider methane's influence over the decadal timescale, and the need to reduce methane emissions. Unfortunately, some recent guidance for life cycle assessments specify only the 100-year time frame [47, 48], and the EPA in 2014 still uses the GWP values from the IPCC 1996 assessment and only considers the 100-year time period when assessing methane emissions [49]. In doing so, they underestimate the global warming significance of methane by 1.6-fold compared to more recent values for the 100-year time frame and by four to fivefold compared to the 10- to 20-year time frames [34, 37].

Climate Impacts of Different Natural Gas Uses

In Howarth et al. [8], we compared the greenhouse gas emissions of shale gas and conventional natural gas to those of coal and oil, all normalized to the same amount of heat production (i.e., g C of carbon dioxide equivalents per MJ of energy released in combustion). We also noted that the specific comparisons will depend on how the fuels are used, due to differences in efficiencies of use, and briefly discussed the production of electricity from coal versus shale gas as an example; electric-generating plants on average use heat energy from burning natural gas more efficiently than they do that from coal, and this is important although not usually dominant in comparing the GHGs of these fuels [8, 18–20]. We presented our main conclusions in the context of the heat production (Fig. 1), though, because evaluating the GHGs of the different fossil fuels for all of their major uses was beyond the scope of our original study, and electricity production is not the major use of natural gas. This larger goal of separately evaluating the GHGs of all the major uses of natural gas has not yet been taken on by other research groups either.

In Figure 5 (left-hand panel), I present an updated comparison of the GHGs of natural gas, diesel oil, and coal based on the best available information at this time (April 2014). Values are expressed as g C of carbon dioxide equivalents per MJ of energy released as in our 2011 paper [8] and Figure 1. The methane emissions in Figure 5 are the mean and range of estimates from the recent review by Brandt and colleagues [29] (see Fig. 2), normalized to carbon dioxide equivalents using the 20-year mean GWP value of 86 from the latest IPCC assessment [34]. As noted above, I believe the 20-year GWP is

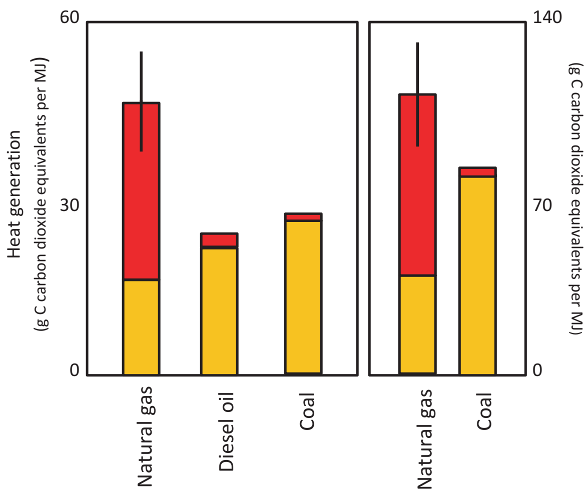

Figure 5. Comparison of the greenhouse gas footprint for using natural gas, diesel oil, and coal for generating primary heat (left) and for using natural gas and coal for generating electricity (right). Direct and indirect carbon dioxide emissions are shown in yellow and are from Howarth et al. [8], while methane emissions shown as g C of carbon dioxide equivalents using the 2013 IPCC 20-year GWP [34] are shown in red. Methane emissions for natural gas are the mean and range for the U.S. national average reported by Brandt and colleagues [29] in their supplemental materials. Methane emissions for diesel oil and for coal are from Howarth et al. [8] For the electricity production, average U.S. efficiencies of 41.8% for gas and 32.8% for coal are assumed [20]. Several studies present data on emissions for electricity production in other units. One can convert from g C of CO_2-equivalents per MJ to g CO_2-equivalents per kWh by multiplying by 13.2. One can convert from g C of CO_2-equivalents per MJ to g C of CO_2-equivalents per kWh by multiplying by 3.6.

an appropriate timescale, given the urgent need to control methane emissions globally. Estimates for coal and diesel oil are from our 2011 paper [8], using data for surface-mined coal since that dominates the U.S. market [20]. The direct and indirect emissions of carbon dioxide are combined and are the same values as in Howarth et al. [8] and Figure 1. Direct carbon dioxide emissions follow the High Heating Value convention [2, 8]. Clearly, using the best available data on rates of methane emission [29], natural gas has a very large GHG per unit of heat generated when considered at this 20-year timescale.

Of the studies listed in Tables 1 and 2 published after our 2011 paper [8], most focused just on the comparison of natural gas and coal to generate electricity, although one also considered the use of natural gas as a long-distance transportation fuel [40]. For context, over the period 2008–2013 in the United States, 31% of natural gas has been used to generate electricity and 0.1% as a transportation fuel [50]. None of the studies listed in Tables 1 and 2, other than Howarth et al. [8], considered the use of natural gas for its primary use: as a source of heat. In the United States over the last 6 years, 32% of natural gas has been used for residential and commercial heating and 28% for industrial process energy [50]. The focus on electricity is appropriate if the only question at hand is "how does switching out coal for natural gas in the generation of electricity affect greenhouse gas emissions?" However, policy approaches have pushed other uses of natural gas – without any scientific support – as a way to reduce greenhouse gas emissions, apparently on the mistaken belief that the analysis for electricity generation applied to these other uses. Before exploring some of these other uses of natural gas, I would like to further explore the question of electricity generation.

Many of the papers listed in Tables 1 and 2 concluded that switching from coal to natural gas for generating electricity has a positive influence on greenhouse gas emissions. Note, though, that for almost all of these papers, the conclusion was driven by a focus on only the 100-year timescale [4, 12–14, 16, 17, 29, 39], on a very low assumed level of methane emission [4, 12–14, 17, 39], or both. The differences in efficiency of use in electric power plants, comparing either current average plants or best possible technologies, are relatively small compared to the influence of the GWP on the calculation [8, 18, 20, 40]. Using a 20-year GWP framework and the methane emission estimates from Howarth et al. [8], the GHG from generating electricity with natural gas is larger than that from coal [8, 18–20]. Alvarez and colleagues [40] concluded that for electricity generation, the GHG of using natural gas was less than for coal for all time frames only if the rate of methane leakage was less than 3.2%. Their analysis used the estimates for the radiative forcing of methane from the IPCC 2007 synthesis [36], and if we correct their estimate for the data in the 2013 IPCC assessment [34], this "break-even point" becomes 2.8%. If we further consider the uncertainty in the radiative forcing of methane of 30% or more [34], this "break-even" value becomes a range of 2.4–3.2%.

In Figure 5 (right-hand panel), I compare the GHGs of natural gas and coal when used to generate electricity, again using the High Heating Value convention [2, 8], the latest IPCC value for the 20-year GWP [34] and the range of methane emission estimates reported by Brandt and colleagues [29]. No distinction is made for less downstream emissions for the pipelines that feed electric power plants, as is assumed in several other studies [12–14, 16], simply because no data exist with which to tease apart downstream emissions specific for electric power generation [51]. This analysis uses the average efficiency for electric power plants currently operating in the United States, 41.8% for gas and 32.8% for coal [20]. The emissions per unit of energy produced as electricity are higher than for the heat generation alone, due to these corrections for efficiency. Although the difference in the footprints for using the two fuels is less for the electricity comparison than for the comparison for heat generation, at this 20-year timescale the GHG of natural gas remains greater than that of coal, even at the low-end methane emission estimate. This conclusion still holds when one compares the fuels using the best available technologies (50.2% efficiency for natural gas and 43.3% for coal [20]); the emissions per unit of electricity generated decrease for both by approximately the same amount.

For the dominant use of natural gas – heating for water, domestic and commercial space, and industrial process energy – the analysis we presented in our 2011 paper [8] and shown in Figure 1 remains the only published study before this new analysis shown in Figure 5 (left-hand panel). The updated version shown here compellingly indicates natural gas is not a climate-friendly fuel for these uses. However, the greenhouse gas consequences may in fact be worse than Figure 5 or Howarth et al. [8] indicate, as I discuss next.

A recent study supported by the American Gas Foundation promoted the in-home use of natural gas over electricity for appliances (domestic hot water, cooking) because of a supposed benefit for greenhouse gas emissions [52]. The report argues that an in-home natural gas appliance will have a higher efficiency in using the fuel (up to 92%) compared to the overall efficiency of producing and using electricity ("only about 40%," according to this study). However, they did not include methane emissions in their analysis, nor did they consider the extremely high efficiencies available for some electrical appliances, such as in-home air-sourced heat pumps for domestic hot water. For a given input of electricity, such heat pumps can produce 2.2-times more heat energy, since they are harvesting and concentrating heat from the local environment [53]. In a comparison of using in-home gas-fired water heaters or in-home high-efficiency electric heat pumps, with the electricity for the heat pumps generated by burning coal, the heat pumps had a lower GHG than did in-home use of gas if the emission rate for methane was greater than 0.7% for a 20-year GWP or 1.3% for a 100-year GWP [51]. Using the mean methane emission estimate from Howarth et al. [8] for conventional natural gas (Fig. 2) and a 20-year GWP, the in-home natural gas heater had a GHG that was twice as large as that of the heat pump [51]. Of course, an in-home heat pump powered by electricity from renewable sources such as wind and solar would have a far smaller GHG yet [54].

What about other uses of natural gas? The "Natural Gas Act," a bill introduced in the United States Congress in 2011 with bipartisan support and the backing of President Obama, would have provided tax subsidies to encourage the replacement of diesel fuel by natural gas for long-distance trucks and buses; the bill did not pass, in part because conservatives opposed it as “market distorting” [55, 56]. In Quebec, industry has claimed that this replacement of diesel by shale gas would reduce greenhouse gas emissions by up to 30% [57]. However, in contrast to a possible advantage in replacing coal with natural gas for electricity generation (if methane emissions can be kept low enough), using natural gas to replace diesel fuel as a long-distance transportation fuel would greatly increase greenhouse emissions [29, 40]. In part, this is because the energy of natural gas is used with less efficiency than diesel in truck engines. Furthermore, although methane emissions from transportation systems have not been well measured, one could imagine significant emissions during refueling operations for buses and trucks, as well as from venting of on-vehicle natural gas tanks to keep gas pressures significantly safe during warm weather. Despite the findings of Alvarez and colleagues published in 2012 [40], the EPA continues to indicate that switching buses from diesel fuel to natural gas reduces greenhouse gas emissions [58].

Concluding Thoughts

By 1950, which is about the time I was born, human activity had contributed enough greenhouse gases to the atmosphere to cause a radiative forcing – the driving factor behind global warming – of 0.57 watts m^{-2} compared to before the industrial revolution [34]. Thirty years later, in 1980 when I taught my first course on the biosphere and global change, this human influence had doubled the anthropogenic radiative forcing, to 1.25 watts m^{-2} [34]. And another 30 years later, the continued release of greenhouse gases by humans has again doubled the forcing, now at 2.29 watts m^{-2} or fourfold greater than just 60 years ago [34]. The temperature of the Earth continues to rise in response at an alarming rate, and the climate scientists tell us we may reach dangerous tipping points in the climate system within just a few decades [34, 41, 42]. Is it too late to begin a serious reduction in greenhouse gas emissions? I sincerely hope not, although surely society has been very slow to respond to this risk. The use of fossil fuels is the major cause of greenhouse gas emissions, and any genuine effort to reduce emissions must begin with fossil fuels.

Is natural gas a bridge fuel? At best, using natural gas rather than coal to generate electricity might result in a very modest reduction in total greenhouse gas emissions, if those emissions can be kept below a range of 2.4–3.2% (based on [40], adjusted for the latest information on radiative forcing of methane [34]). That is a big “if,” and one that will require unprecedented investment in natural gas infrastructure and regulatory oversight. For any other foreseeable use of natural gas (heating, transportation), the GHG is larger than if society chooses other fossil fuels, even with the most stringent possible control on methane emissions, if we view the consequences through the decadal GWP frame. Given the sensitivity of the global climate system to methane [41, 42], why take any risk with continuing to use natural gas at all? The current role of methane in global warming is large, contributing 1.0 watts m^{-2} out of the net total 2.29 watts m^{-2} of radiative forcing [34].

Am I recommending that we continue to use coal and oil, rather than replace these with natural gas? Not at all. Society needs to wean itself from the addiction to fossil fuels as quickly as possible. But to replace some fossil fuels (coal, oil) with another (natural gas) will not suffice as an approach to take on global warming. Rather, we should embrace the technologies of the 21st Century, and convert our energy systems to ones that rely on wind, solar, and water power [59, 60, 61]. In Jacobson et al. [54], we lay out a plan for doing this for the entire state of New York, making the state largely free of fossil fuels by 2030 and completely free by 2050. The plan relies only on technologies that are commercially available at present, and includes modern technologies such as high-efficiency heat pumps for domestic water and space heating. We estimated the cost of the plan over the time frame of implementation as less than the present cost to the residents of New York from death and disease from fossil fuel caused air pollution [54]. Only through such technological conversions can society truly address global change. Natural gas is a bridge to nowhere.

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Conflict of Interest

None declared.

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