Assessing the greenhouse impact of natural gas

L. M. Cathles, January 7, 2011 (Submitted to G³)

Abstract

The global warming impact of substituting natural gas for coal and oil is currently in debate. We address this question here by comparing the reduction of greenhouse warming that would result from substitution of gas for coal and oil to the reduction which could be achieved by immediately substituting low carbon energy sources. This comparison shows that if the leakage rate of natural gas is ~1% or less (as it could be now and certainly could be made to be), the substitution of natural gas reduces global warming by 40% of that which could be attained by the immediate transition to low carbon energy sources. This 40% benefit does not depend on the duration of the transition period; it is the same whether the transition is over 20 or 100 years. The comparison avoids complexities of SO_2 and CO_2 removal from the atmosphere, and illustrates clearly that at low gas leakage rates the greenhouse warming from the use of fossil fuels is associated solely with the amount of CO_2 introduced into the atmosphere: the less CO_2, the less warming. Fast transitions to low carbon energy sources reduce greenhouse gas forcing more and are therefore desirable, but the substitution of natural gas is always of substantial benefit if the leakage rates are low because significantly less CO_2 is emitted to the atmosphere.

Introduction

In a recent controversial paper, Howarth et al. (2011) suggested that, because methane is a far more potent greenhouse gas than carbon dioxide, the leakage of natural gas makes its greenhouse forcing as bad and possibly twice as bad as coal, and they concluded that this undermines the potential benefit of natural gas as a transition fuel to low carbon energy sources. Others (Hayhoe et al., 2009; Wigley, 2011) have pointed out that the warming caused by reduced SO_2 emissions as coal electrical facilities are retired will compromise some of the benefits of the CO_2 reduction. Wigley (2011) has suggested that because the impact of gas substitution for coal on global temperatures is small and there would be some warming as SO_2 emissions are reduced, the decision of fuel use should be based on resource availability and economics, not greenhouse gas considerations.

Some of these suggestions have been challenged. For example Cathles et al. (2012) among others have taken issue with Howarth et al.'s for comparing gas and coal in terms of the heat content of the fuels rather than their electricity generating capacity (coal is used only to generate electricity), for exaggerating the methane leakage by a factor of 3.6, and for using an inappropriately short (20 year) global warming potential factor (GWP). Nevertheless it remains difficult to see in the published literature precisely what benefit might be realized by substituting gas for coal and what period is appropriate in selecting a

GWP factor. This paper seeks to remedy these deficiencies by comparing the benefits of natural gas substitution to those of immediately substituting low-carbon energy sources. The comparative analysis avoids the complications of SO_2 and the complexities of CO_2 removal from the atmosphere, and shows that, provided the gas leakage rate is 1% of production or less (which it could be now and in any case could easily be made to be), the substitution of natural gas for coal and some oil would realize >40% of the greenhouse benefits that could be had by rapidly replacing fossil fuels with low carbon energy sources such as wind, solar, and nuclear. This gas substitution benefit does not depend on the speed of the transition. If the transition is faster, greenhouse warming is less, but regardless of the rate of transition substituting natural gas achieves >40% of the benefits of low carbon energy substitution. The benefit of natural gas substitution is a direct result of the decrease in CO_2 emissions it causes.

The calculation methods used here follow Wigley (2011), but are computed using programs of our own design from the equations and parameters given below. Parameters are defined that convert scenarios for the yearly consumption of the fossil fuels to the yearly production of CO_2 and CH_4. These greenhouse gases are then introduced into the atmosphere and removed using accepted equations. Radiative forcings are calculated for the volumetric gas concentrations as they increase, and the global temperature change is computed by multiplying the sum of these forcings by the equilibrium sensitivity factor currently favored by the IPCC.

The computational results we obtain agree with other models. What is new is the simplification of the comparative approach taken. The complicated removal of gases from the atmosphere cancels out because the proportions of CO_2 added are not changed by its removal. The small warming (few tenths of a degree centigrade, e.g., Wigley, 2011) caused by the reduction of sulfur emission as coal use declines is the same no matter which fuel replaces coal, and thus cancels in our comparisons. The comparative approach shows that what counts is simply the reduction of CO_2 put into the atmosphere.

Greenhouse gas sources

Greenhouse warming is driven by the rate at which CO_2 and CH_4 are introduced into the atmosphere by the burning of fossil fuels. Between 1970 and 2002, world energy consumption from all sources (coal, gas, oil, nuclear, hydro and renewables) increased at the rate of 2.1% per year (Figure 1). In the year 2000 the world population of six billion people consumed ~400EJ (EJ= exajoules = 10^{18} joules, 1 joule = 1.055 Btu) of energy. Oil and gas supplied 100 EJ each, coal 150EJ, and other sources (hydro, nuclear, and renewables such a wind and solar) 50 EJ. In 2100 the world population is projected to plateau at ~10.5 billion. If the per person consumption then is at today's European average of 7.2 kW p^{-1}, global energy consumption in 2100 would be 2300 EJ per year (75 TW).

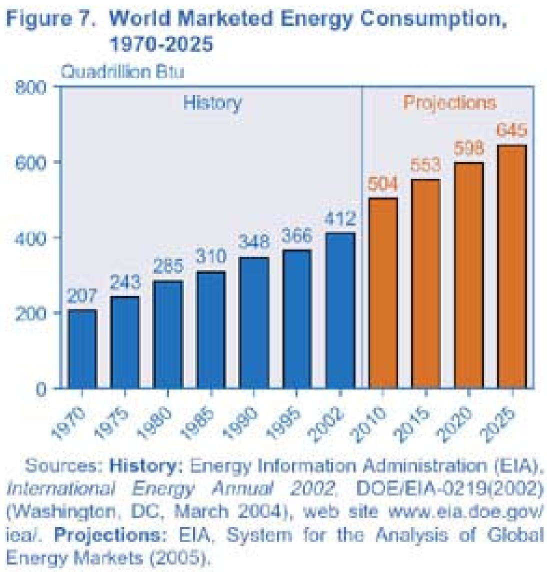

Figure 1 World energy consumption has been growing at a rate of ~2.1% per year over the last 32 years. http://bio.freelogy.org/wiki/Image:EIAenergy.jpg .

We start with the fuel consumption pattern at 2000 AD and grow the overall consumption linearly to reach 2200 EJ some "transition" period of time later (Figure 2). At the end of our transition period everyone in the world will have access to energy at the 7.2 kW p^{-1} rate enjoyed today by the average European, and, except for a small amount of gas and oil, the energy will be supplied by low carbon sources.

Figure 2 and Table 1 show the three fuel scenarios that are considered:

- In the first half (growth period) of the *business- as-usual* scenario (A in Figure 2), overall fossil fuel consumption increases 2.9 fold but there is a relative decline in oil and rise in coal consumption. In the second half of the transition (decline period) low carbon energy sources replace the fossil fuels so that the rate of consumption of fossil fuels at the end of the transition period is the same as at the start. Our growth period is a simplified version of the MiniCAM scenario in Clark (2007), and the growth-decline combination is similar to the base scenario used by Wigley(2011).
- In the *substitute-gas* scenario (B in Figure 2), gas replaces coal and new oil consumption over the growth period, and then in the decline period is replaced by low carbon fuels to the point that the combined use of gas and oil is the same (on a heat content basis) at the start and end of the transition.
- In the *low-carbon-fast* scenario (C in Figure 2), low carbon energy sources replace coal, new gas, and new oil over the growth period, and gas grows so that it replaces half of oil consumption in the decline period.

These scenarios are intended to provide a simple basis for assessing the benefits of substituting gas for coal; they are intended to be instructive and realistic enough to be relevant to our future societal decisions. The question they pose is: How far will substituting gas for coal and some oil take us toward the greenhouse benefits of an immediate and rapid conversion to low carbon energy sources.

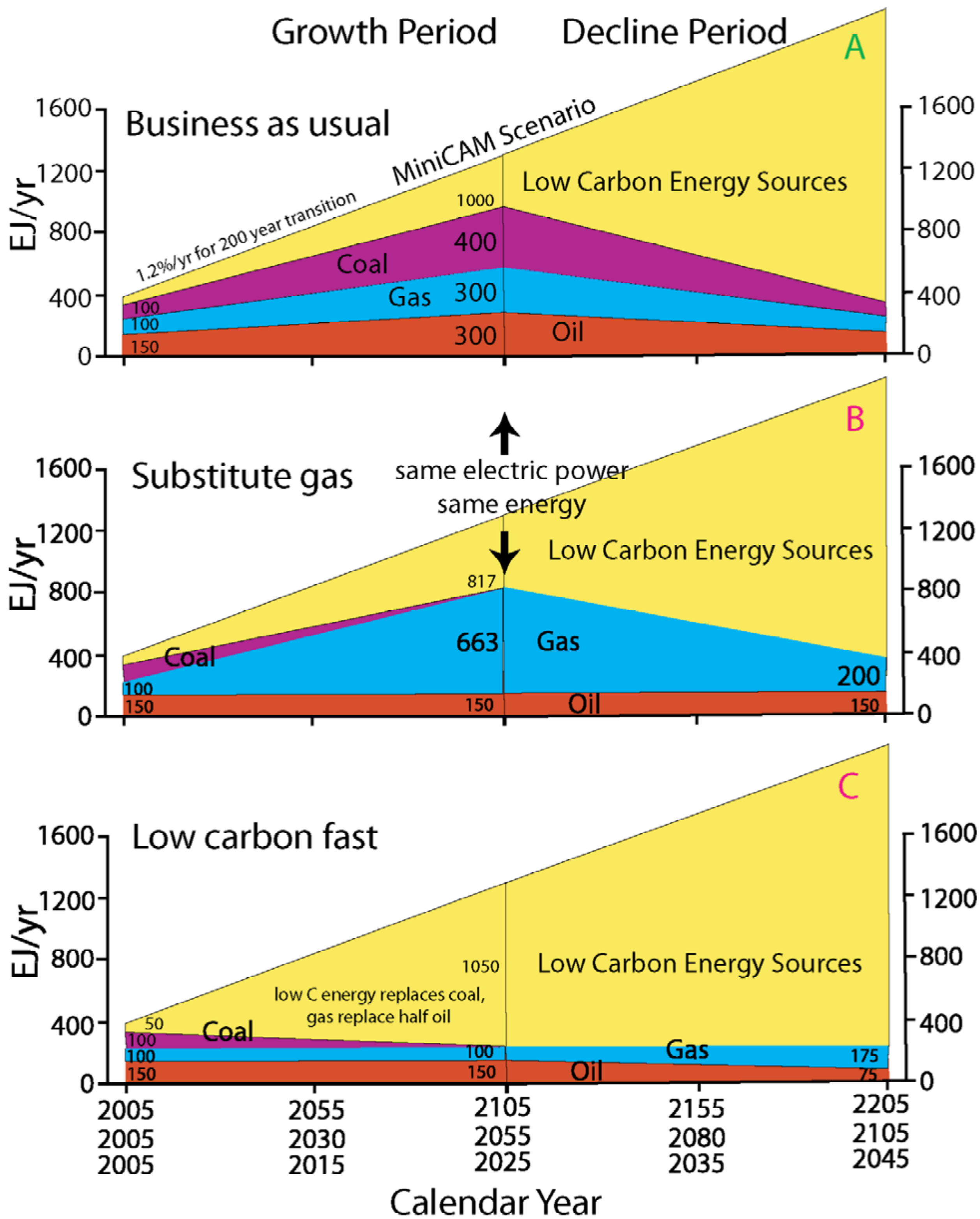

Figure 2 Three fuel consumption scenarios compared in this paper. Gas replaces coal such that the same amount of electricity is generated. Gas replaces oil on an equal heat energy basis. These scenarios are tabulated in Table 1.

Table 1 Heat energy in exajoules produced each year by the burning of various fossil fuels or supplied by low carbon energy sources, H[EJ y^{-1}] is tabulated at the start, midpoint, and end of the scenarios shown in Figure 2 The heat input in intervening years is obtained by linear extrapolation between these times. In the substitute-gas scenario, gas replaces coal on an equal electricity-generation basis ($\Delta H_{gas}=-\Delta H_{coal} R_{coal}/R_{gas}$ = 213 EJ y^{-1}, see Table 2), and gas replaces new oil (150 EJ y^{-1}) on an equal heat content basis. Gas use thus increases from 300 to 663 EJ y^{-1}. Over the ensuing decline period, oil consumption is kept flat and low carbon fuels replace 463 EJ y^{-1} of gas. In the low-carbon-fast scenario coal, new oil, and new gas are replaced by low carbon energy sources over the growth period, and gas replaces half the oil consumption over the decline period.

Fuel	**Start**	**Midpoint**	**End**
Business- as-usual Scenario			
Low carbon	50	300	1850
gas	100	300	100
oil	150	300	150
coal	100	400	100
Total	400	1300	2200
Substitute-gas Scenario			
Low carbon	50	487	1850
gas	100	663	200
oil	150	150	150
coal	100	0	0
Total	400	1300	2200
Low-Carbon-Fast Scenario			
Low carbon	50	1050	1950
gas	100	100	175
oil	150	150	75
coal	100	0	0
Total	400	1300	2200

Computational Methods

Table 2 summarizes the parameters used in the calculations. The first factor, I[EJ Gt^{-1}], gives the heat energy produced when each fossil fuel is burned in exajoules (10^{18} joules) per gigaton (10^9 tons) of the fuel. The next factor, R[EJ_e EJ^{-1}], indicates the efficiency with which we assume gas and coal can be converted to electricity in exajoules of electrical energy per exajoule of heat. The third factor, ξ [Gt_C EJ^{-1}], indicates the gigatons of carbon released to the atmosphere per exajoule of combustion heat. The fourth factor, ζ[Gt_{CH4} EJ^{-1}], gives expressions for the methane released from mining coal and delivering natural gas in terms of the volume of methane released when the coal is mined and used, $V[m^3]$, and the fraction of natural gas vented to the atmosphere during its recovery and delivery to the customer, L.

Table 2 Parameters (defined in the text) that are used in the calculations. We take V=5 m^3 methane released per ton of coal, and L=1% in the calculations reported in the next section.

	I[EJ Gt^{-1}]	R[EJ_e EJ^{-1}]	ξ [Gt_C EJ^{-1}]	ζ[Gt_{CH4} EJ^{-1}]
Gas	55	0.6	0.015	$L[\mathrm{Gt}_{\text{CH4-vented}}\ \mathrm{Gt}^{-1}_{\text{CH4-consumed}}]/I[\mathrm{EJ\ Gt}_{\text{CH4-consumed}}]$
Oil	43		0.020	
Coal	39	0.32	0.027	$V[\mathrm{m}^3_{\text{CH4}}\ \mathrm{t}^{-1}_{\text{coal}}]\rho_{\text{CH4}}[t_{CH4}\ \mathrm{m}^{-3}_{\text{CH4}}]/I[\mathrm{EJ\ Gt}_{\text{CH4}}]$

The yearly discharge to the atmosphere of CO_2 (measured in tons of carbon)and CH_4, Q_C[Gt_C y^{-1}] and Q_{CH4}[Gt_{CH4} y^{-1}], are related to the heat produced in burning the fuels, H[EJ y^{-1}] in Table 1:

$$Q_C[\mathrm{Gt_C\,y^{-1}}] = H[\mathrm{EJ\ y^{-1}}]\xi[\mathrm{Gt_C\ EJ^{-1}}]$$
$$Q_{CH4}[\mathrm{Gt_C\,y^{-1}}] = H[\mathrm{EJ\ y^{-1}}]\varsigma[\mathrm{Gt_{CH4}\ EJ^{-1}}] \qquad (1)$$

The volume fractions of CO_2 and CH_4 added to the atmosphere in year t_i by (1) are:

$$\Delta X_{CO2}(t_i)[ppmv\ y^{-1}] = \frac{Q_C[\mathrm{Gt_C y^{-1}}]10^{15}\frac{W_{CO2}}{W_C}\frac{W_{air}}{W_{CO2}}\frac{V_{CO2}}{V_{air}}}{M_{atm}[t]}$$
$$\Delta X_{CH4}(t_i)[ppbv\ y^{-1}] = \frac{Q_{CH4}[\mathrm{Gt_{CH4} y^{-1}}]10^{18}\frac{W_{air}}{W_{CH4}}\frac{V_{CH4}}{V_{air}}}{M_{atm}[t]} \qquad (2)$$

Here M_{atm}[t] = 5.3 x 10^{15} tons is the mass of the atmosphere, W_{CO2} is the molecular weight of CO_2 (44 g/mole), and V_{CO2} is the molar volume of C_{O2}, etc. In (2a) the first molecular weight ratio converts the yearly mass addition of carbon to the yearly mass addition of CO_2, and the second mass fraction ratio converts this to the volume fraction of CO_2 in the atmosphere. We assume the gases are ideal and thus $V_{CO2}= V_{air}$.

Each yearly input of carbon dioxide and methane is assumed to decay with time as follows:

$$\Delta X_{CO2}(t_i+t) = \Delta X_{CO2}(t_i)f_{CO2}(t), \quad f_{CO2}(t) = 0.217 + 0.259e^{-t/172.9} + 0.338e^{-t/18.51} + 0.186e^{-t/1.186}$$
$$\Delta X_{CH4}(t_i+t) = \Delta X_{CH4}(t_i)f_{CH4}(t), \quad f_{CH4}(t) = e^{-t/12} \qquad , (3)$$

where t is time in years after the input of a yearly increment of gas at t_i. These decay rates are those assumed by the IPCC (2007, Table 2.14). The 12 year decay time for methane take into account methane's interactions with O_3 and OH (See IPCC, 2007, §2.10.3.1).

The concentration of carbon dioxide and methane as a function of time is computed by summing the additions each year and the decayed contributions from the additions in previous years:

$$
\begin{aligned}
X_{CO2}(t_i) &= \Delta X_{CO2}(t_i) + \sum_{j=1}^{i-1} \Delta X_{CO2}(t_j) f_{CO2}(t_i - t_j) \\
X_{CH4}(t_i) &= \Delta X_{CH4}(t_i) + \sum_{j=1}^{i-1} \Delta X_{CH4}(t_j) f_{CO2}(t_i - t_j)
\end{aligned}, \qquad (4)
$$

where $X_{CO2}(t_i)$ and $X_{CH4}(t_i)$ are volumetric concentration of CO_2 and CH_4 in *ppmv* and *ppbv* respectively, *i* runs from 1 to t_{tot}, where t_{tot} is the duration of the transition in years, and the sum term on the right hand sides does not contribute unless $i \geq 2$.

The radiative forcings for carbon dioxide and methane, ΔF_{CO2}[W m^{-2}] and ΔF_{CO2}[W m^{-2}] are computed using the following formulae given in the IPCC (2001, §6.3.5):

$$
\begin{aligned}
\Delta F_{CO2}\left[W\,m^{-2}\right] &= 5.35 \ln \frac{X_{CO2}(t_i) + X_{CO2}(t=0)}{X_{CO2}(t=0)} \\
\Delta F_{CH4}\left[W\,m^{-2}\right] &= 0.036\,\Psi_{CH4}\left(\left(\sqrt{X_{CH4}(t_i) + X_{CH4}(0)} - \sqrt{X_{CH4}(0)}\right) - \left(f\left(\left(X_{CH4}(t_i) + X_{CH4}(0)\right), N_o\right) - f\left(X_{CH4}(0)\right), N_o\right)\right) \\
f(M,N) &= 0.47 \ln\left(1 + 2.01\times10^{-5}(MN)^{-5} + 5.31\left(MN^{-15}\right) + M(NM)^{1.52}\right)
\end{aligned} \qquad (5)
$$

We start our calculations in 2005 when X_{CO2}[t=0]=379 ppmv, X_{CH4}[t=0]=1774 ppbv, and the NO_2 concentration, N_o =319 ppbv. ψ_{CH4} is a factor that magnifies the direct forcing of CH_4 to take into account the indirect interactions of methane with O_3 and OH. The IPCC(2007) suggests these indirect interactions increase the direct forcing first by 15% and then by an additional 25%, with the result that $\psi_{CH4} = 1.44$. We use this value in our calculations.

Finally the change in global temperature caused by the greenhouse gas additions is:

$$
\Delta T = \Delta T_{CO2} + \Delta T_{CH4} = \lambda^{-1}\left(\Delta F_{CO2} + \Delta F_{CH4}\right), \qquad (6)
$$

where λ^{-1} is the equilibrium climate sensitivity. We adopt the IPCC, 2007 value of $\lambda^{-1} = 0.8$, which is equivalent to assuming that a doubling of atmospheric CO_2[ppmv] causes a 3°C global temperature increase.

Equations (1) to (6) and the parameters specified define completely the method we use to calculate the global warming caused by the fuel use scenarios in Figure 2 and Table 1.

Results

Table 3 shows the gigatons of carbon as CO_2 (GtC) and the megatons of CH_4 introduced each year into the atmosphere at the turning points of our three scenarios, assuming a natural gas leakage rate of 1% and a release of 5 m^3 of methane per ton of coal burned.

Table 3 Rates of carbon (as CO_2) and methane introduced to the atmosphere each year in the various scenarios indicated in Figure 2 and Table 1. The gas fluxes tabulated assume a 1% leakage rate for natural gas and a methane release of 5 m^3/ton of coal mined. The fluxes are calculated for the fuel consumption scenarios in Table 2 using equation (1).

	Start	Midpoint	End
Business-as-usual			
EJ fossil fuels consumed per year	350	1000	350
GtC/year (as CO_2)	7.25	21.41	7.25
$GtCH_4$/yr	30	101	30
Swap-gas			
EJ fossil fuels consumed per year	350	813	350
GtC/year (as CO_2)	7.25	13.07	6.06
$GtCH_4$/yr	30	121	36
Low-C-fast			
EJ fossil fuels consumed per year	350	250	250
GtC/year (as CO_2)	7.25	4.55	4.16

Figure 3 to 5 show the changes in atmospheric chemistry, the radiative forcings, and the global warming predicted by equations (1)-(6) for three transition durations and the three scenarios in Figure 2 and Table 1.

Figure 3 shows the additions of CO_2 in ppmv and methane in ppbv that occur for the different fuel consumption scenarios and transition periods. Methane is removed from the atmosphere exponentially with a decay constant of 12 years. This is rapid enough that methane concentrations track the changing rate of methane introduction (Table 3) quite closely. On the other hand, because only a portion of the CO_2 introduced into the atmosphere is removed quickly (see equation 3a), CO_2 accumulates across the transition periods and persists for a long time thereafter (projections of truncated Δcarbon dioxide curves).

Figure 4 shows the radiative forcings corresponding to the atmospheric gas concentrations shown in Figure 3, computed using equations (5). The methane forcing is a few percent of the CO_2 forcing and thus is unimportant in driving greenhouse warming. Remember, however, that in these figures a gas leakage rate of only 1% is assumed.

Figure 5 shows the global warming that is predicted from the radiative forcings shown in Figure 4, assuming an equilibrium climate sensitivity of λ^{-1} = 0.8 (e.g., a doubling of CO2 causes a 3°C of global warming). Global warming is less for the shorter transition periods because the amount of CO_2 released to the atmosphere is proportional to the length of the transition period. For all periods of transition, however, swapping gas for coal and oil achieves 40% of the reduction in greenhouse warming that could be achieved by meeting the same energy goals with the fast substitution of low carbon energy sources and no growth in fossil fuel consumption.

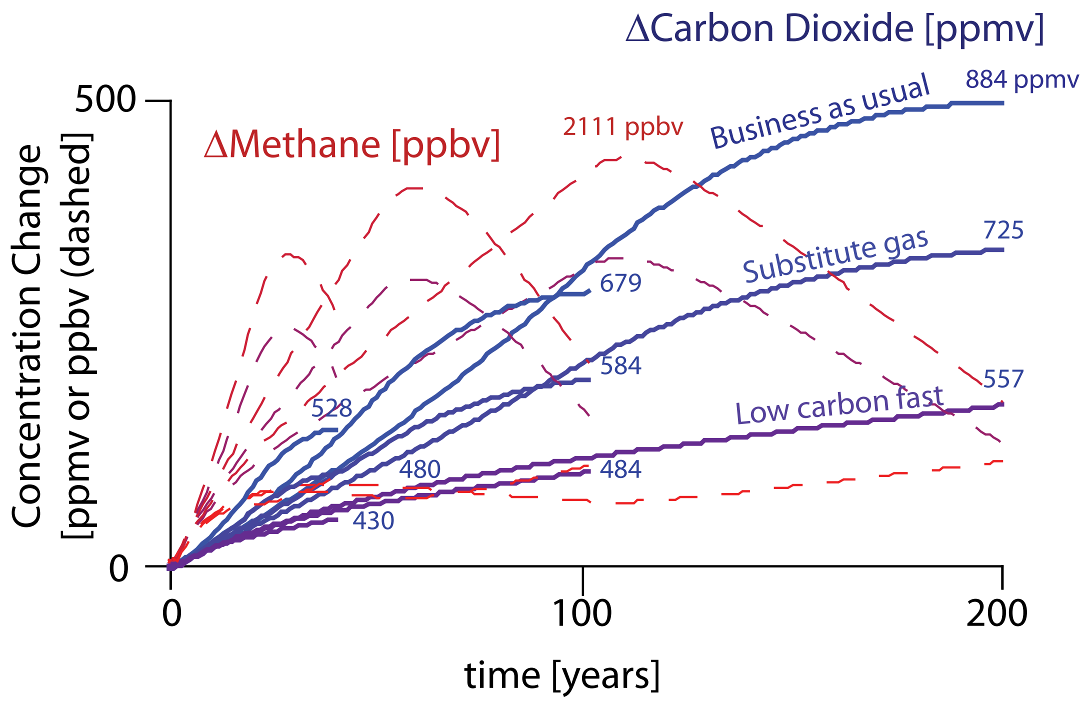

Figure 3 Changes in methane and carbon dioxide concentrations computed for the three fuel scenarios shown in Figure 1 and Table 2 for three transition periods (40, 100 and 200 years). In this figure and the two that follow, he top curve in each set of three is the business-as-usual scenario, the middle curve the substitute-gas scenario, and the lower curve the low-carbon-fast scenario. In all three figures a 1% methane leakage rate, 5 m^3 methane released per ton of coal burned, and that indirect couplings increase the greenhouse forcing of methane by a factor Ψ_{CH4}=1.43 (the IPCC, 2007 estimate) are assumed. Also, the starting (t=0) concentrations are the 2005 values of 379 ppmv for CO_2 and 1774 ppbv for CH_4. The numbers indicate the total (initial plus change) concentrations of CO2 at the end of each transition period, and the number at the top of the business-as-usual 100 year methane curve is the maximum total methane at the peak of that curve.

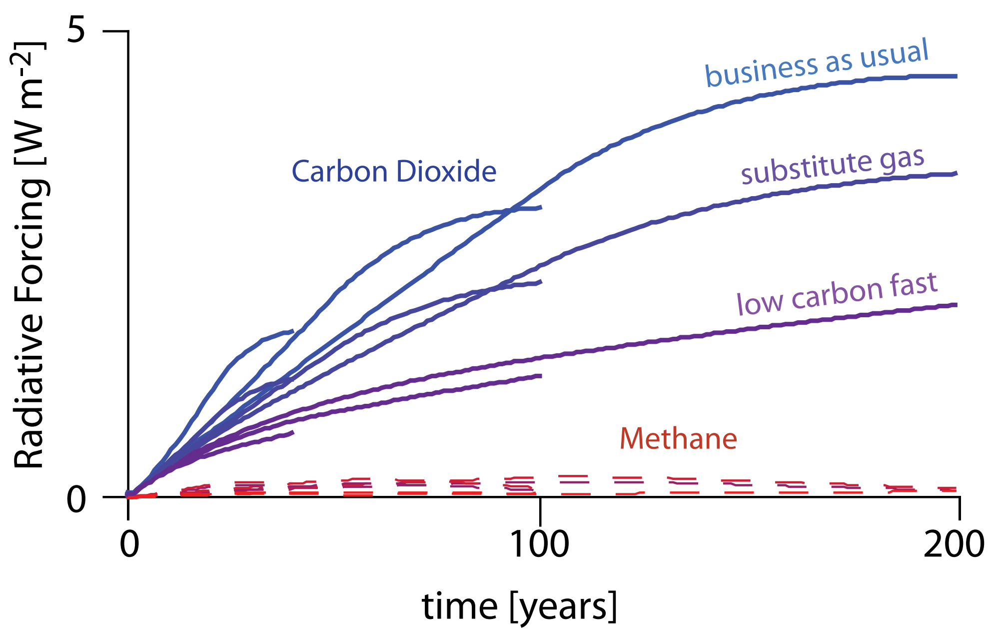

Figure 4 Radiative forcings calculated for the carbon dioxide and methane additions to the atmosphere shown in Figure 3. The curve conventions and model parameters are as described in the caption of Figure 3 and in the text.

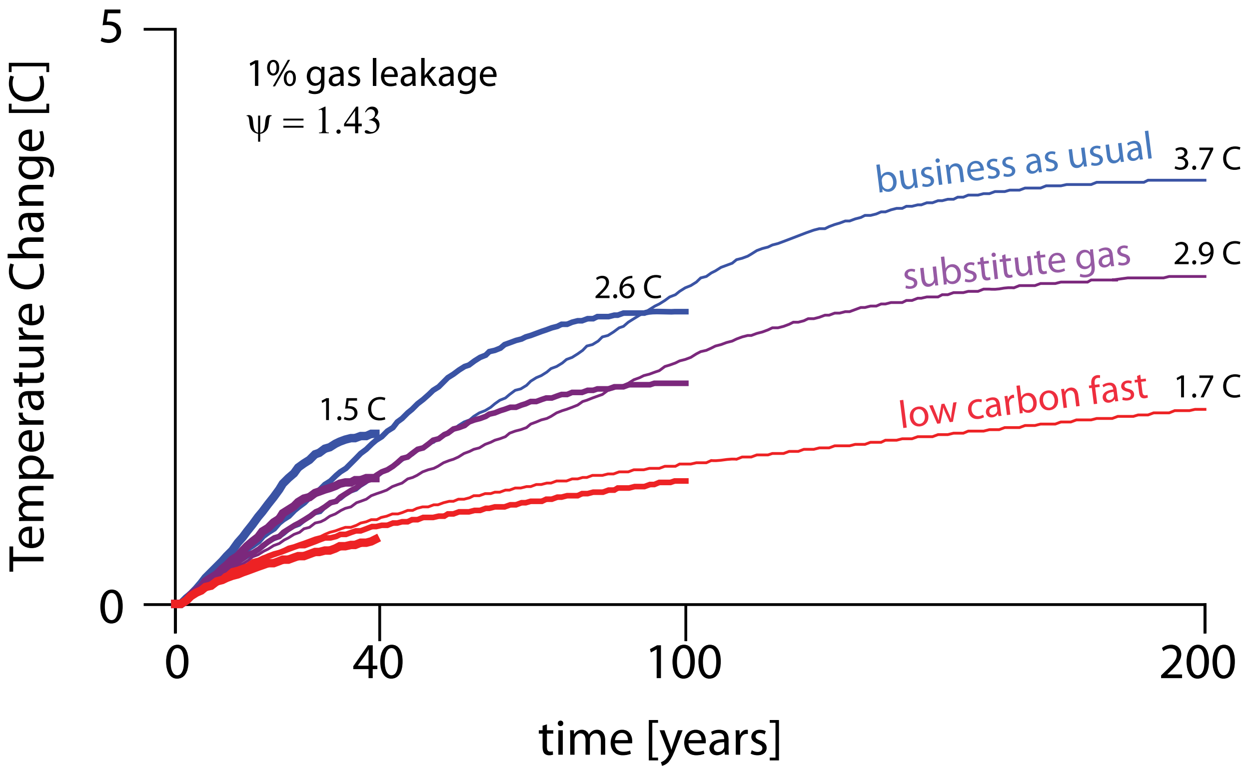

Figure 5 Global warming computed for three transition periods (40, 100 and 200 years) and the three fuel scenarios shown in Figure 2 and Table 2, assuming a 1% gas leakage rate and that indirect couplings increase the greenhouse forcing of methane by 43% (the IPCC AR4 estimate). The faster transitions produce less the global warming because less CO2 is put into the atmosphere. For low leakage rates, natural gas decreases global warming by about 40% of that which could be achieved by the fast substitution of low carbon fuels. The curve conventions and model parameters are as described in the caption of Figure 3 and in the text.

Figures 6 to 8 show what happens when methane leakage is greater than 1% of total methane production. Figure 6 and 7 show that for the short transition of 40 years, substitution of natural gas for coal and oil reduces greenhouse warming so long as the leakage rate is less than ~10.7%. Figure 7 shows the benefit of swapping gas for coal and oil as a percentage of the benefit of rapid substitution of low carbon energy sources. At low leakage rates the benefit is >40% for short as well as long transition periods. In fact it is slightly higher for short transition periods because of the non-linear dependence of radiative forcing on atmospheric gas concentration. Figure 8 shows the reduction in warming from the business-as-usual scenario afforded by substitution of gas over the three transition periods. The benefit of substituting gas is less for the shorter transition periods (even though the percent reduction is nearly the same) because less CO_2 is vented in the shorter transition intervals.

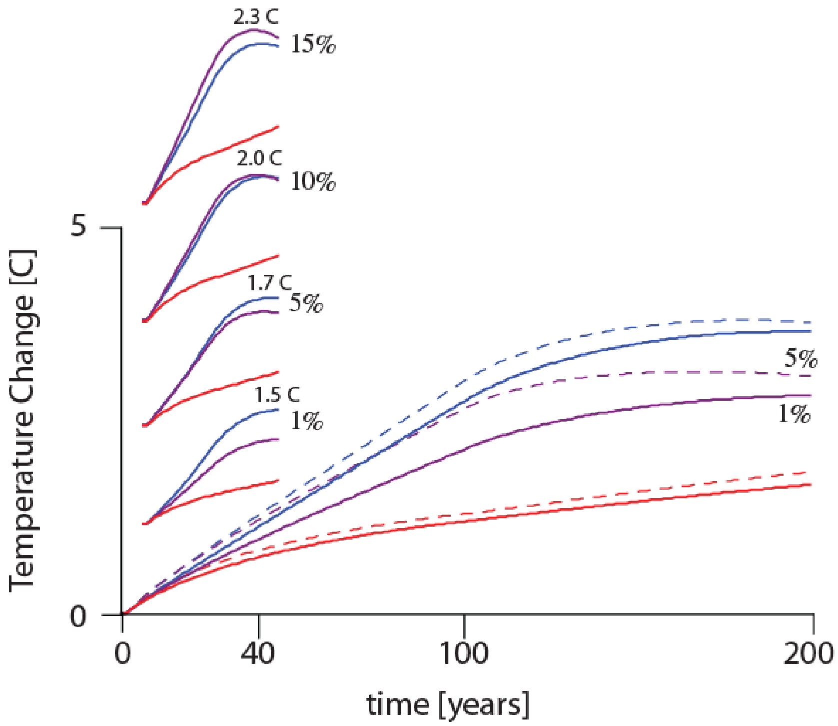

Figure 6 Sensitive to gas leakage. Substitution of natural gas for coal and oil is beneficial so long as methane leakage is less than ~10% of total production. The curve conventions and model parameters are as described in the caption of Figure 3 and in the text.

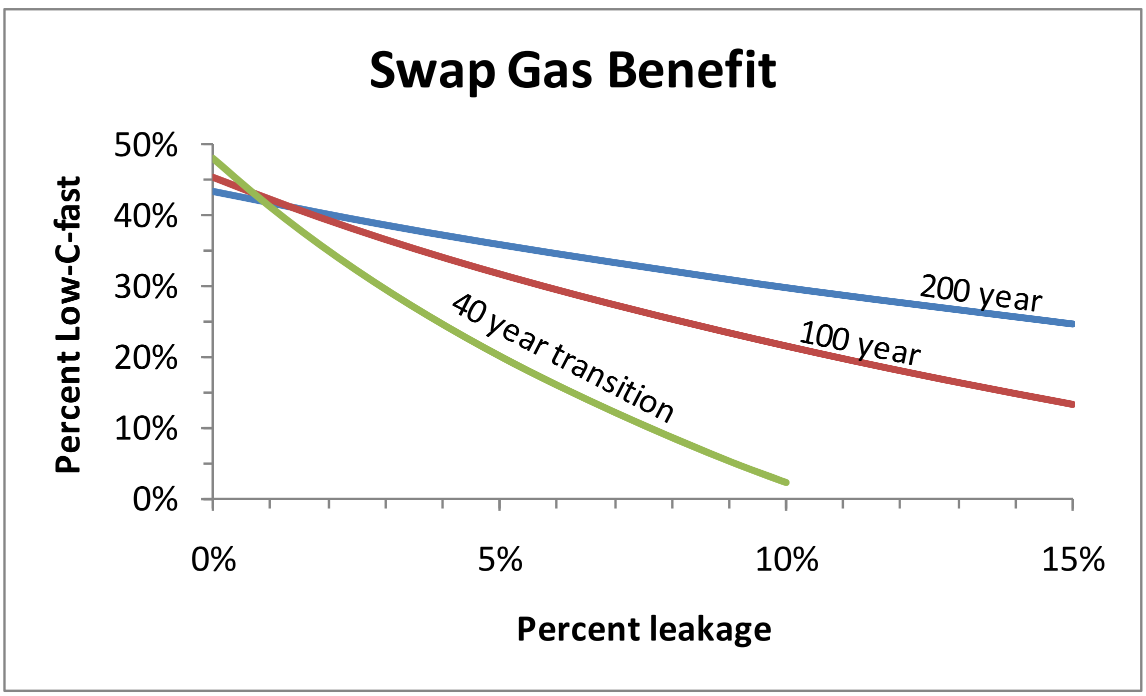

Figure 7 The reduction of greenhouse warming attained by substituting natural gas for coal and oil (substitute-gas scenario) expressed as a percentage of the greenhouse warming reduction produced by substituting of low carbon fuels for all fossil fuels (low-C-fast scenario) is plotted as a function of the gas leakage rate. Substitution of natural gas for fossil fuels is beneficial to leakages rates of 10.7% for the 40 year transition, to leakage rates of 25% in the 100 year transition, and to leakage rates of 49% in the 100 year transition.

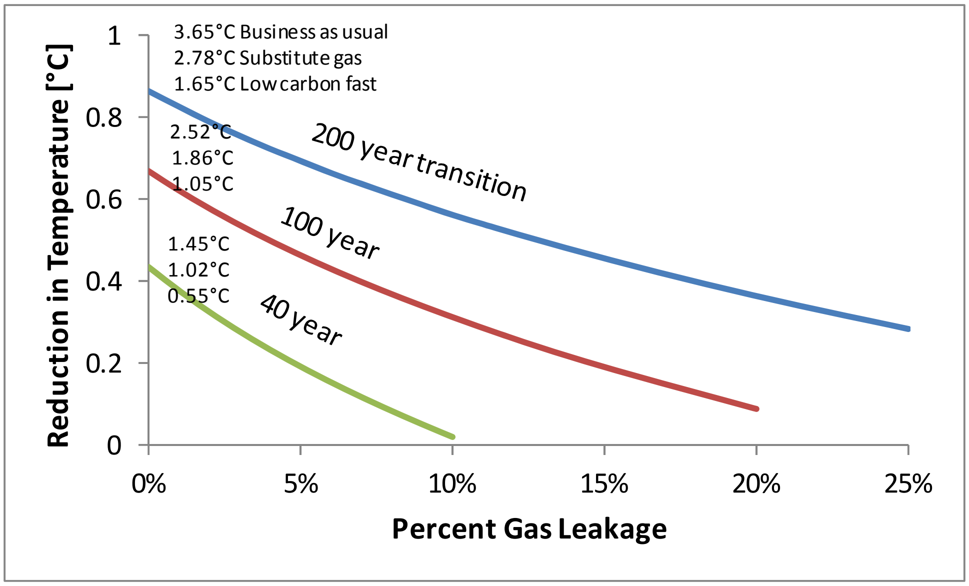

Figure 8 The reduction of greenhouse warming at the end of the transition period attained by substituting natural gas for coal and oil (substitute-gas scenario) expressed as the degrees centigrade reduction in average global temperature. The numbers next to each curve at the y-axis indicate the business-as-usual warming (top number), the substitute-gas warming (middle number), and the low-carbon-fast warming (bottom number) at 0% leakage. For example with no methane leakage the warming at 2205 AD under the business-as-usual scenario is 3.65°C, swapping gas reduces this warming by 0.87°C to 2.78°C, and this reduction is 43% of the 2°C reduction (to 1.65°C) offered by substituting low carbon fuels immeidately. The warming decreases as the transition period decreases because less CO_2 is put into the atmosphere in the shorter transitions. Because the warming is less, the reduction in warming by substituting gas or low carbon energy sources is also less.

Discussion

The most important message of the calculations reported here is that substituting natural gas for coal and oil is a significant way to reduce greenhouse forcing regardless of how long (within a feasible range) the substitution takes (Figure 5). For methane leakages of ~1% of total production, replacing coal used in electricity generation and 50% of the oil used in transportation with natural gas (very feasible steps that could be driven by the low cost of methane alone with no government encouragement) would achieve at least 40% of the greenhouse warming reduction that could be achieved by transitioning immediately to low carbon energy sources such as wind, nuclear, or solar. A faster transition to low-carbon energy sources would decrease greenhouse warming further, but the substitution of natural gas for the other fossil fuels is equally beneficial in percentage terms no matter how fast the transition.

The basis for the ~40% reduction in greenhouse forcing is simply the reduction of the CO_2 put into the atmosphere. When gas leakage is low, the contribution of methane to greenhouse warming is negligible (Figure 4), and only the CO_2 input counts. The mass of CO_2 vented under the various scenarios and time periods is easily computed from the start, midpoint, and end venting rates in Table 3 (e.g., it equals one quarter the total transition period times the sum of the production rates at the endpoints plus twice that at the midpoint). The reduction of CO_2 vented between the business-as-usual to the substitute-gas scenario is 48.6% of the reduction between the business-as-usual to the low-carbon-fast scenarios. This fraction is independent of the transition period; it is the same whether the transition occurs over 40 years or 200 years.

Because the losses of CO_2 from the atmosphere (equation 3a) are proportional to the amount of CO_2 in the atmosphere, the relative amounts of CO_2 at the end of the transition are similar to the proportions added. For the same transition interval almost the same proportional amounts of CO_2 are removed for all scenarios. The fraction of the CO2 introduced into the atmosphere that remains in the atmosphere at the close of the transition periods is 56±1.9% for the 40 year transition period, 45±1% for the 100 year transition period, and 38±0.7% for the 200 year transition period. The ± percentages indicate the variation between the three scenarios. For example for the 40 year transition cycle, the percentage of introduced CO2 is 57.1% (1.4% above the mean) for the business as usual scenario, 56.6% (0.5% above the mean) for the substitute gas scenario, and 55.2% (1.9% below the mean) for the low-carbon-fast scenario. Because the fractions of CO2 removed for all the scenarios are so similar, the 48.6% reduction in introduced CO2 by the substitute-gas scenario is reflected in the ppmv concentrations of CO_2 in the atmosphere at the end of the periods shown in Figure 3. The curves shown in Figure 7 intersect the y-axis (0% gas leakage) at fractions slightly different from 48.6% because the radiative forcing is slightly non-linear with respect to CO_2 concentration (equation 5a). The longer transition periods depart more from 48.6% because they put more CO_2 into the atmosphere. The global warming reduction from swapping gas for the other fossil fuels of course also decreases as methane leakage increases. But at low leakage rates, the benefit of substituting natural gas remains well above 40%, and the nearly direct relationship between reductions in the mass of CO_2 vented and the decrease in global warming is a powerful conceptual simplification that is particularly useful because it is so easy to calculate. Warming is related to the amount of CO_2 put into the atmosphere, period.

Sulfur dioxide additions are not a factor in our analysis because the substitute-gas and low-carbon-fast scenarios reduce the burning of coal over the growth period in an identical fashion. Thus both introduce SO_2 identically, and the small warming effects of the SO_2, which will occur no matter how coal is retired, cancel in the comparison.

We have verified out computations by comparing them to predictions by publically available and widely used programs. Although there are some internal differences, Table 4 shows that the ~40% reduction in greenhouse warming we predict is also predicted by Wigley's MAGICC program, when the same scenarios we consider are input to his program.

Table 4 Wiglely's MAGICC program, run with the CO_2 and CH_4 inputs shown in Table 3, replicates the reductions in global warming that our calculations predict. The MAGICC calculations start at 1990 AD so we consider the temperature increases from 2000 to the end of the period. The first three rows compare the temperature increases predicted. The last row shows the reduction in greenhouse warming achievable by substituting natural gas for coal and oil as a percentage of the reduction that would be achieved by the rapid substitution of all fossil fuels with low carbon energy sources.

	200 year cycle		**100 year cycle**		**40 year cycle**	
Program	MAGICC	This paper	MAGICC	This paper	MAGICC	This paper
B-as-usual	3.85	3.68	2.3	2.56	1.05	1.5
Swap gas	2.85	2.85	1.65	1.94	0.80	1.12
Low C fast	1.7	1.70	0.85	1.09	0.38	0.58
% reduction	42%	42%	45%	42%	37%	41%

Wigley's (2011) decrease in greenhouse warming for the natural gas substitution he defines is compatible with the calculations presented here. At 0% leakage, Wigley(2011, his Figure 3) calculates a 0.35°C cooling which would be a 0.45°C cooling absent the reduced SO_2 emissions he considers. We calculate a cooling of ~0.87°C for 0% leakage. Our cooling is almost twice his because our gas substitution scenario reduces the CO_2 emissions by about twice his. From nearly the same base, our gas substitution reduces CO_2 emissions from the business-as-usual 200 year transition cycle by 31% (894 GtC) whereas Wigley's reduces CO_2 by 15% (425 GtC). Wigley's scenario may be more realistic in terms of what might be practically achieved, but it understates the potential value of natural gas substitution, which is our interest in this paper.

There are of course uncertainties in the kind of calculations carried out here, but these uncertainties are unlikely to change the conclusions reached. The equilibrium climate forcing could be 30% less or 50% more (IPCC, 2007), for example. This would make reducing CO_2 emissions somewhat less or more urgent, but would not change the relative impact of substituting gas. Carbon dioxide is almost certainly not removed from the atmosphere exactly as described by equation (3), and the radiative forcing of CO_2 may not be exactly as specified in equation (5), but reasonable modifications should not be significant. Climate could change for reasons other than changing atmospheric CO_2. For example Milankovitch cycles, and changes in cloud cover could change average global temperatures. Cloud cover changes could be related to anthropogenic aerosols, multi-decadal ocean-atmosphere oscillations, or solar wind modulation of the cosmic ray flux. Our comparison ignors other factors such as these.

At the longer 100 and 200 year transition times, our substitute-gas and low-carbon-fast scenarios require oil and gas supplies greater than conventional resource estimates. These scenarios therefore assume that unconventional resources such as shale oil, shale gas, and hydrates will become available. Resource availability is another factor that could encourage a more rapid transition to low carbon energy sources whose supply is either very large (nuclear) or infinite (wind and solar).

The calculations made here indicate the global warming potential (GWP) factor is useful, but also indicate that the relationship between transition period and the GWP time period is not linear.   For example, with Schindell et al.'s (2009) methane forcing, ψ = 1.94, and a 40 year transition, the warming under the substitute-gas scenario exceeds that under the business-as-usual scenario when the leakage rate exceeds 7.3%.   This is close to the 7.9% transition leakage calculated by Howarth et al. (2011) for a 20 year GWP of 105. For a 100 year transition, we calculate the warming under the substitute-gas scenario exceeds that under the business-as-usual scenario when the leakage exceeds 16% of production. This is similar to the 18% crossover leakage calculated for a 100 year GWP of 33 by Cathles et al. (2012).   The 20 year GWP is thus appropriate for our 40 year transition, whereas a 100 year GWP is appropriate for our 100 year transition. The duration chosen for the GWP is thus only roughly similar to the transition period considered, but methods based on GWP factors are still useful. This is an aside in the context of this paper because we have not used GWP approximations. It is of interest to note that a 20 year GWP would be appropriate in analysis of a 20 year transition and would give results similar to obtained here, but the point here is that regardless of the rate of transition substitution of natural gas is beneficial.

The methods used in this paper should not be controversial. The benefit of substituting natural gas hinges only on its leakage rate. If gas can be substituted for coal and oil over a 20 year period as shown in the 40 year transition in Figure 2 (which seems too fast to be practical), the substitution has greenhouse benefit provided the leakage is less than 7.3% (for the high methane forcing of Schindell). If gas is substituted over a more reasonable 50 year growth period, the substitution has greenhouse benefit if the leakage is less than 16%(for the high methane forcing of Schindell).

No one has suggested a leakage rate as high as 16%. The leakage rate today is probably less than ~2% of production, and possibly as low as 1% or production. Leakage during the completion of shale gas wells is probably less than ~0.2% of production (data reported to the EPA by Devon via letter of Moore, 2011; Cathles et al., 2012) and the leakage from conventional gas wells is even less. The leakage between the well and the customer is probably less than 2% and could be already, or in any case made to be, 1% of production (Cathles et al., 2012). Companies have every economic incentive to reduce leakage because no business likes to lose product on the way to the customer. If the leakage is ~1% of production, this paper shows that a ~40%-of-possible greenhouse benefit can be attained by substituting gas for coal and some oil. This is a very substantial greenhouse benefit.

Conclusions

The conclusions to be drawn from the calculations presented are:

1. For leakage rates ~1% or less, the substitution of natural gas for the coal used in electricity generation and half the oil used in transportation and heating achieves 40% of the reduction that could be attained by an immediate transition to low-carbon energy sources.

2. This 40% reduction does not depend on the duration of the transition. A 40% reduction is attained whether the transition is over 40 years or 200 years.

3. For leakage rates ~1% or less, the reduction of greenhouse warming is related directly to the mass of CO_2 put into the atmosphere. This means to reduce greenhouse forcing we must reduce the CO_2 put into the atmosphere. Complexities of how CO_2 is removed and reductions in SO_2 emissions do not change this simple imperative and should not be allowed to confuse the situation.

4. At low methane leakage rates, substituting natural gas is always beneficial from a greenhouse warming perspective, even for forcings as high as have been suggested by Shindell et al. (2009) and used by Howarth et al. (2011). Under the fastest transition that is probably feasible (our 40 year transition scenarios), substitution of natural gas will be beneficial is the leakage rate is less than about 7% of production. For a more reasonable transition of 100 years, substituting gas will be beneficial if the leakage rate is less than ~16%.

The policy implications of this analysis are: (1) reduce the leakage of natural gas from production to consumption so that it is 1% of production or less, (2) encourage the substitution of natural gas for coal and oil, and (3) encourage as rapid a conversion to low carbon sources of energy as possible. It would of course be better to replace coal electrical facilities with nuclear plants, but replacing them with natural gas stations will be faster and probably cheaper. Natural gas also has an important enabling role to play in the transition to low carbon wind of solar energy sources because it can provide the needed surge capacity when these sources fluctuate and backup when these sources wane.

Because of its availability and low cost, economic factors will encourage gas to replace coal in electricity generation and oil in segments of transportation. It is a fuel the US and many other countries need not import. There are strong greenhouse and economic reasons to encourage the displacement of other fossil fuels by natural gas and reducing its leakage to 1% of less. With low leakage, natural gas is a very attractive transition fuel to low carbon energy sources.

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