# Assessing the greenhouse impact of natural gas

L. M. Cathles, June 6, 2012

## 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 substituting gas for coal and some oil to the reduction which could be achieved by instead substituting zero carbon energy sources. We show that substitution of natural gas reduces global warming by 40% of that which could be attained by the substitution of zero carbon energy sources. At methane leakage rates that are ~1% of production, which is similar to today's probable leakage rate of ~1.5% of production, the 40% benefit is realized as gas substitution occurs. For short transitions the leakage rate must be more than 10 to 15% of production for gas substitution not to reduce warming, and for longer transitions the leakage must be much greater. But even if the leakage was so high that the substitution was not of immediate benefit, the 40%-of-zero-carbon benefit would be realized shortly after methane emissions ceased because methane is removed quickly form the atmosphere whereas $CO_2$ is not. The benefits of substitution are unaffected by heat exchange to the ocean. $CO_2$ emissions are the key to anthropogenic climate change, and substituting gas reduces them by 40% of that possible by conversion to zero carbon energy sources. Gas substitution also reduces the rate at which zero carbon energy sources must be eventually introduced.

## 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) have taken issue with Howarth et al. 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 the use of metrics such as GWP factors seems to complicate rather than simplify the analysis. 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 goes back to the fundamental equation and does not use simplified GWP metrics. Because it is a null analysis it avoids the complications of $SO_2$, carbon black, and the complexities of $CO_2$ removal from the atmosphere. It shows that the substitution of natural gas for coal and some oil would realize ~40% of the greenhouse benefits that could be had by replacing fossil fuels with low carbon energy sources such as wind, solar, and nuclear. In the long term this gas substitution benefit does not depend on the speed of the transition or the methane leakage rate. If the transition is faster, greenhouse warming is less. If the leakage is less, the reduction of warming during the substitution period is greater, but regardless of the rate of leakage or the speed of substitution, natural gas achieves ~40% of the benefits of low carbon energy substitution a few decades after methane emissions associated with gas production cease. 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, the equilibrium global temperature change is computed by multiplying the sum of these forcings by the equilibrium sensitivity factor currently favored by the IPCC, and the increments of equilibrium temperature change are converted to transient temperature changes using a two layer ocean thermal mixing model.

## Emission Scenarios

Greenhouse warming is driven by the increase in the atmospheric levels of $CO_2$, $CH_4$ and other greehouse gases that result from 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. In the year 2005 six and a half billion people consumed ~440EJ (EJ= exajoules = $10^{18}$ joules, 1 joule = 1.055 Btu; EIA, 2011) of energy. Oil and gas supplied 110 EJ each, coal 165EJ, and other sources (hydro, nuclear, and renewables such a wind and solar) 55 EJ (MiniCAM scenario, Clark, 2007). 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 kW $p^{-1}$, global energy consumption in 2100 would be 2300 EJ per year (74 TW). We start with the fuel consumption pattern at 2005 AD and grow it exponentially so that it reaches 2300 EJ per year at the end of a "transition" period. At the end of the transition the energy is supplied almost entirely by low carbon sources in all cases, but in the first half of the transition, which we call the growth period, hydrocarbon consumption either increases on the current trajectory (the "business-as-usual" scenario), increases at the same equivalent rate with gas substituted for coal and oil (a "substitute-gas scenario), or declines immediately (the low-carbon-fast scenario). Coal use is phased out at exactly the same rate in the substitute-gas and low-carbon-fast scenarios, so that the reduction of $SO_2$ and carbon black emissions is exactly the same in these two scenarios and therefor is not a factor when we compare the reduction in greenhouse warming for the substitute-gas and the low-carbon-fast scenarios.

Figure 1 shows the three fuel scenarios considered for a 100 year transition:

- In first half (growth period) of the *business- as-usual* scenario (A in Figure 1), fossil fuel consumption increases 2.9 fold from 440 EJ/yr in 2005 to 1265 EJ/yr over the

50 year growth period, and then declines to 205.6 EJ/yr after the full transition. The mix of hydrocarbons consumed at the end of the transition produces $CO_2$ emissions at the same 4.13 GtC/yr rate as at the end of the other scenarios. The total energy consumption grows at 2.13 % per year in the growth period, and at 1.2% over the decline period. The growth period is a shifted (to start in 2005), slightly simplified, exponential version of the MiniCAM scenario in Clark (2007). We increase the hydrocarbon consumption by the same factors as in the MiniCAM scenario, and determine the renewable growth by subtracting the hydrocarbon energy consumption from this total. The growth-decline combination is similar to the base scenario used by Wigley(2011).

- In the *substitute-gas* scenario (B in Figure 1), gas replaces coal and new oil consumption over the growth period, and is replaced by low carbon fuels in the decline period. Gas replaces coal on an equal electricity-generation basis ($\Delta H_{gas}=\Delta H_{coal} R_{coal}/R_{gas}$ = 234 EJ $y^{-1}$, see Table 1), and gas replaces new oil (165 EJ $y^{-1}$) on an equal heat content basis. Gas use at the end of the growth period is thus 729 EJ $y^{-1}$, rather than 330 EJ y-1in the business-as-usual scenario. The growth of renewable energy consumption is greater than in (A). Over the ensuing decline period, oil consumption drops to 75 EJ $y^{-1}$ and gas to 175 EJ $y^{-1}$.
- In the *low-carbon-fast* scenario (C in Figure 1), low carbon energy sources replace coal, new gas, and new oil over the growth period, and gas use grows and oil use decreases so that the consumption at the end is the same as in the substitute-gas scenario.

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 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.

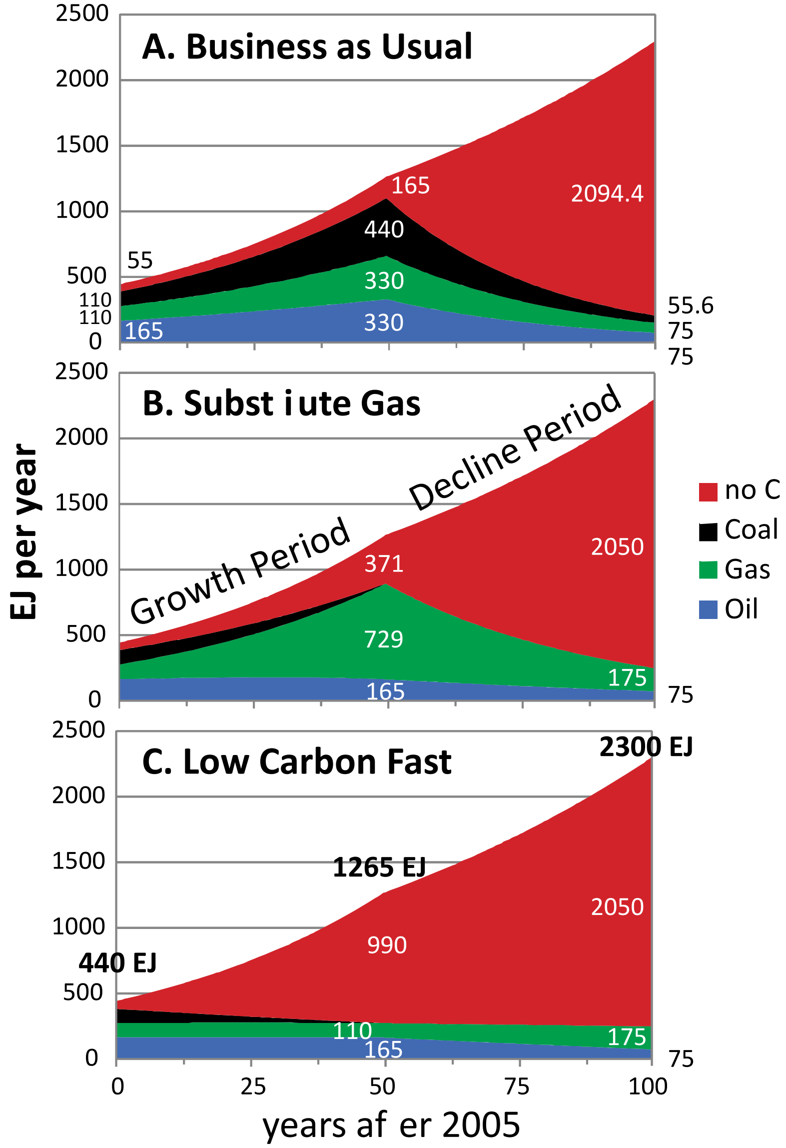


**Figure 1 Three fuel consumption scenarios compared in this paper: (A) Fossil fuel use in the business-as-usual scenario continues the present growth in fossil fuel consumption in the initial 50 year growth period before low carbon energy sources replace fossil fuels in the decline period. (B) In the substitute-gas scenario, gas replaces coal such that the same amount of electricity is generated, and substitutes for new oil on an equal heat energy basis. (C) In the low-carbon-fast scenario, low carbon energy sources immediately substitute for coal and new oil and gas in the growth period, and gas use declines and substitutes for oil in the decline period. Numbers indicate the consumption of the fuels in EJ per year at the start, midpoint, and end of the transition period. The total energy use is the same in all scenarios and is indicated at the start, midpoint, and end by the bold black numbers in (C).**

**Table 1. Parameters used in the calculations.** ***I*** **is the energy content of the fuel,** ***R*** **the efficiency of conversion to electricity, and** ***ξ*** **and** ***ζ*** **the carbon and methane emissions factors. See text for discussion.**

| | $I$[EJ $Gt^{-1}$] | $R$[$EJ_e$ $EJ^{-1}$] | $\xi$ [$Gt_C$ $EJ^{-1}$] | $\zeta$[$Gt_{CH4}$ $EJ^{-1}$] |
|---|---|---|---|---|
| **Gas** | 55 | 0.6 | 0.015 | $1.8 \times 10^{-4}$ for a leakage of 1% of production |
| **Oil** | 43 | | 0.020 | |
| **Coal** | 29 | 0.32 | 0.027 | $1.2 \times 10^{-4}$ for $5 m^3/t$ |

## Computation Method and Parameters

Table 1 summarizes the parameters used in the calculations. $I$[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 values we use are from http://www.natural-gas.com.au/about/references.html. The energy density of coal varies from 25-37 GJ/t, depending on the rank of the coal, but 29 GJ/t is considered a good average value for calculations.

$R$[$EJ_e$ $EJ^{-1}$] is the efficiency with which gas and coal can be converted to electricity in exajoules of electrical energy per exajoule of heat. Gas can generate electricity with much greater efficiency than coal because it can drive a gas turbine whose effluent heat can then be used to drive a steam generator. Looking forward, older low efficiency coal plants will likely be replaced by higher efficiency combined cycle gas plants of this kind. The electrical conversion efficiencies we adopt in Table 1 are those selected by Hayhoe et al. (2002, their Table II).

The carbon emission factors in gigatons of carbon released to the atmosphere per exajoule of combustion heat, $\xi$ [$Gt_C$ $EJ^{-1}$], listed in the fourth column of Table 1 are the factors compiled by the EPA(2005) and used by Wigley (2011).

Finally, the methane emission factors, $\zeta$[$Gt_{CH4}$ $EJ^{-1}$] in the last column of Table 1 are computed from the fraction of methane that leaks during the production and delivery of natural gas and the volume of methane that is released to the atmosphere during mining and transport of coal:

$$\xi_{gas}[\mathrm{Gt_{CH4}\ EJ^{-1}}] = L[\mathrm{Gt_{CH4\text{-}vented}\ Gt^{-1}_{CH4\text{-}burned}}] / I[\mathrm{EJ\ Gt^{-1}_{CH4\text{-}burned}}] \qquad (1a)$$

$$\xi_{coal}[\mathrm{Gt_{CH4}\ EJ^{-1}}] = V[\mathrm{m^3_{CH4}\ t^{-1}_{coal\text{-}mined}}]\rho_{\mathrm{CH4}}[t_{CH4}\ \mathrm{m^{-3}_{CH4}}] / I[\mathrm{EJ\ Gt^{-1}_{coal\text{-}burned}}] \quad . \qquad (1b)$$

The density of methane in (1b) $\rho_{CH4}$= 0.71x10$^{-3}$ tons per m$^3$. We treat the methane vented to the atmosphere during the production and distribution of natural gas, *L*, parametrically in our calculations. The natural gas leakage, L, is defined as the mass fraction of natural gas that is burned.

We assume in our calculations that 5 m$^3$ of methane is released per ton of coal mined. The leakage of methane during coal mining has been reviewed in detail by Howarth et al. (2011) and Wigley (2011). Combining leakages from surface and deep mining in the proportions that coal is extracted in these two processes, they arrive at 6.26 m$^3$/t and 4.88 m$^3$/t respectively. The value we use lies between these two estimates, and appears to be a reasonable estimate (e.g., see Saghafi et al., 1997), although some have estimated much higher values (e.g, Hayhoe et al., 2002, suggest ~23 m$^3$/t).

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

$$Q_C[\mathrm{Gt_C\, y^{-1}}] = H[\mathrm{EJ\ y^{-1}}]\xi[\mathrm{Gt_C\ EJ^{-1}}] \qquad (2a)$$

$$Q_{CH4}[\mathrm{Gt_C y^{-1}}] = H[\mathrm{EJ\ y^{-1}}]\zeta[\mathrm{Gt_{CH4}\ EJ^{-1}}] \qquad (2b)$$

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

$$\Delta X_{CO2}(t_i)[\,ppmv\ y^{-1}] = \frac{Q_C[\mathrm{Gt_C y^{-1}}]10^{15}\dfrac{W_{CO2}}{W_C}\dfrac{W_{air}}{W_{CO2}}\dfrac{V_{CO2}}{V_{air}}}{M_{atm}[t]} \qquad (3a)$$

$$\Delta X_{CH4}(t_i)[\,ppbv\ y^{-1}] = \frac{Q_{CH4}[\mathrm{Gt_{CH4} y^{-1}}]10^{18}\dfrac{W_{air}}{W_{CH4}}\dfrac{V_{CH4}}{V_{air}}}{M_{atm}[t]} \,. \qquad (3b)$$

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:

$$\begin{aligned} \Delta X_{CO2}(t_i + t) &= \Delta X_{CO2}(t_i) f_{CO2}(t) \\ f_{CO2}(t) &= 0.217 + 0.259 e^{-t/172.9} + 0.338 e^{-t/18.51} + 0.186 e^{-t/1.186} \end{aligned} \tag{4a}$$

$$\begin{aligned} \Delta X_{CH4}(t_i + t) &= \Delta X_{CH4}(t_i) f_{CH4}(t) \\ f_{CH4}(t) &= e^{-t/12} \end{aligned} \quad , \tag{4b}$$

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 in (4b) is a perturbation lifetime that takes into account chemical reactions that increase methane's lifetime according to the IPCC (2007, §2.10.3.1). The decay of $CO_2$ described by (4a) does not account for changes with time in the carbonate-bicarbonate equilibrium (such as decreasing $CO_2$ solubility as the temperature of the ocean surface waters increases) which become important at higher concentrations of atmospheric $CO_2$ (see NRC, 2011; Eby et al., 2009). Equation (4a) thus probably understates the amount of $CO_2$ that will be retained in the atmosphere when warming has become substantial.

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

$$\begin{aligned} X_{CO2}(t_i) &= \Delta X_{CO2}(t_i) + \sum_{j=1}^{i-1} \Delta X_{CO2}(t_j) f_{CO2}(t_i - t_j) \\ X_{CH4}(t_i) &= \Delta X_{CH4}(t_i) + \sum_{j=1}^{i-1} \Delta X_{CH4}(t_j) f_{CH4}(t_i - t_j) \end{aligned} \quad , \tag{5}$$

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 terms on the right hand sides does not contribute unless $i \geq 2$.

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

$$
\begin{aligned}
&\Delta F_{CO2}\left[W\,m^{-2}\right] = 5.35 \ln \frac{X_{CO2}(t_i) + X_{CO2}(t=0)}{X_{CO2}(t=0)} \\
&\Delta F_{CH4}\left[W\,m^{-2}\right] = 0.036\,\Psi_{CH4}\left(\left(\sqrt{X_{CH4}(t_i) + X_{CH4}(0)} - \sqrt{X_{CH4}(0)}\right) - \left(f\left(\left(X_{CH4}(t_i) + X_{CH4}(0)\right), N_o\right) - f\left(X_{CH4}(0)\right), N_o\right)\right) \\
&f(M,N) = 0.47 \ln\left(1 + 2.01\times10^{-5}(MN)^{-5} + 5.31\left(MN^{-15}\right) + M(NM)^{1.52}\right)
\end{aligned}
\tag{6}
$$

We start our calculations with the atmospheric conditions in 2005: $X_{CO2}[t=0]$=379 ppmv, $X_{CH4}[t=0]$=1774 ppbv, and the $N_2O$ concentration, $N_o$ =319 ppbv. $\psi_{CH4}$ is a factor that magnifies the direct forcing of $CH_4$ to take into account the indirect interactions caused by increases in atmospheric methane. The IPCC(2007) suggests these indirect interactions increase the direct forcing first by 15% and then by an additional 25%, with the result that $\psi_{CH4}$ = 1.43. Shindell et al. (2009) have suggested additional indirect interactions which increase $\psi_{CH4}$ to ~1.94. There is continuing discussion of the validity of Shindell et al.'s suggested additional increase (see Hultman et al., 2011). We generally use $\psi_{CH4}$ =1.43 in our calculations, but consider the impact of $\psi_{CH4}$ to ~1.94 where it could be important.

The radiative forcing of the greenhouse gas additions in (6) drives global temperature change. The ultimate change in global temperature they cause is:

$$\Delta T^{equil} = \Delta T_{CO2} + \Delta T_{CH4} = \lambda_S^{-1}\left(\Delta F_{CO2} + \Delta F_{CH4}\right), \tag{7}$$

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

The heat capacity of the ocean delays the surface temperature response to greenhouse forcing. Assuming, following Solomon et al (2011), a two layer ocean where the mixed layer is in thermal equilibrium with the atmosphere:

$$
\begin{aligned}
C_{mix}\frac{\partial \Delta T_{mix}}{\partial t} &= \lambda_s\left(\Delta T_{mix}^{equil} - \Delta T_{mix}\right) - \gamma\left(\Delta T_{mix} - \Delta T_{deep}\right) \\
C_{deep}\frac{\partial \Delta T_{mix}}{\partial t} &= \gamma\left(\Delta T_{mix} - \Delta T_{deep}\right)
\end{aligned} \quad . \qquad (8)
$$

Here $\gamma$ is the heat transfer coefficient for the flow of heat from the mixed layer into the deep layer in W K$^{-1}$ m$^{-2}$, and $\lambda_s$ is the heat transfer coefficient into the mixed layer from the atmosphere (and the inverse of the equilibrium climate sensitivity). $C_{mix}$ and $C_{deep}$ are the heat storage capacities per unit surface area of the mixed and deep layers in J K$^{-1}$ m$^{-2}$.
Defining $\Delta T'_{mix} = \Delta T_{mix}^{equil} - \Delta T_{mix}$, $\Delta T'_{deep} = \Delta T_{mix}^{equil} - \Delta T_{deep}$, $\bar{t} = t/\tau_{mix}$, and $\tau_{mix} = C_{mix}\lambda_s^{-1}$, we can write:

$$
\frac{\partial}{\partial \bar{t}}\begin{pmatrix} \Delta T'_{mix} \\ \Delta T'_{deep} \end{pmatrix} = \begin{pmatrix} -\left(\gamma\lambda_s^{-1}+1\right) & \gamma\lambda_s^{-1} \\ \gamma\lambda_s^{-1} C_{mix}C_{deep}^{-1} & -\gamma\lambda_s^{-1} C_{mix}C_{deep}^{-1} \end{pmatrix}\begin{pmatrix} \Delta T'_{mix} \\ \Delta T'_{deep} \end{pmatrix}. \qquad (9)
$$

For the imposition of a sudden increase in greenhouse forcing that will ultimately produce an equilibrium temperature change of $\Delta T_{mix}^{equil}$ as described by (7), the solution to (8) is:

$$
\Delta T_{mix} = \Delta T_{mix}^{equil}\left\{1 - \left(a\exp\left(-t\big/e_m^{-1}\tau_{mix}\right) + (1-a)\exp\left(-t\big/e_d^{-1}\tau_{mix}\right)\right)\right\}. \qquad (10)
$$

Here $e_m$ and $e_d$ are the magnitudes of the eigenvalues of the matrix in (9), and the coefficient, $a$, is determined by the initial condition that the layers are not thermally perturbed before the increment of greenhouse forcing is imposed.

Insight is provided by noting that the eigenvalues and parameter $a$ in (10) are functions of the ratios of heat transfer and heat storage parameters $\gamma\lambda_s^{-1}$ and $C_{deep}C_{mix}^{-1}$ only, and can be approximated to within ±10%:

$$
\begin{aligned}
a &= 0.483 + 0.344\left(1-\gamma\lambda_s^{-1}\right),\ 0.2 < \gamma\lambda_s^{-1} \le 1 \\
e_m^{-1} &= \left(1+\gamma\lambda_s^{-1}\right)^{-1} \\
e_d^{-1} &= 2C_{deep}C_{mix}^{-1}\Big/\left(\gamma\lambda_s^{-1}\right)^{0.7}
\end{aligned} \quad . \qquad (11)
$$

It is unlikely that that heat will be transferred out the base of the mixed layer more efficiently than it is into the top of the mixed layer because the transfer will be mostly driven by winds and cooling of the ocean surface. For this reason the heat transfer coefficient ratio $\gamma\lambda_s^{-1}$ is almost certainly ≤1 and the reduction of temperature is greatest for $\gamma\lambda_s^{-1} = 1$. For $\gamma\lambda_s^{-1} = 1$, the initial temperature change in the mixed layer will be about half the change that will occur when the ocean layers are fully warmed, and the response time required to reach this equilibrium change (the time required to reach 2/3$^{\text{rds}}$ of the equilibrium value) will be about ½ of the response time of the mixed layer (e.g., $e_{mix}^{-1} = 1/2$). For $\gamma\lambda_s^{-1} = 1$, the response time of the deep layer is twice the heat storage capacity ratio times the response time of the mixed layer: $2C_{deep}C_{mix}^{-1}\tau_{mix}$.

The transient temperature change can be computed from the equilibrium temperature change in (7) by convolving in a fashion similar to what was done in (5):

$$T(t_i) = \sum_{j=1}^{i-1} \Delta T^{equil}(t_j)\left\{1 - \left(a \exp\left(\frac{-(t_i - t_j)}{e_m^{-1}\tau_{mix}}\right) + (1-a)\exp\left(\frac{-(t_i - t_j)}{e_d^{-1}\tau_{mix}}\right)\right)\right\} \quad , \qquad (12)$$

where $i \geq j$. We do not use the approximations of equation (11) when we carry out the convolution in (12). Rather we solve for the actual values of the eigenvalues and parameter *a* from the matrix in (9) at each yearly increment in temperature change. For $\tau_{mix}$ = 5 years, $\Delta T_{mix}$ will reach 0.483 $\Delta T_{mix}^{equil}$ with a decay time of 2.5 years and rise to $\Delta T_{mix}^{equil}$ with a decay time of 200 years.

The current consensus seems to be that $\gamma\lambda_s^{-1} = 1$ and the transient thermal response is about half the full equilibrium forcing value (NRC, 2011, §3.3). The ratio of the heat storage capacity of the deep to mixed layer, $C_{deep}C_{mix}^{-1}$ is probably at least 20, a value adopted by Solomon et al. (2011). Schwartz (2007) estimated the thermal response time of the mixed layer at ~5 years from the temporal autocorrelation of sea surface temperatures. This may be the best estimate of this parameter, but Schwartz notes that estimates range from 2 to 30 years. Fortunately the moderation of temperature change by the oceans does not impact the benefit of substituting gas for coal and oil at all. It is of interest in defining the cooling that substitution would produce, however. We calculate the transient temperature changes for the full range of ocean moderation parameters.

Equations (1) to (10) plus (12), together with the parameters just discussed define completely the methods we use to calculate the global warming caused by the fuel use scenarios in Figure 1.

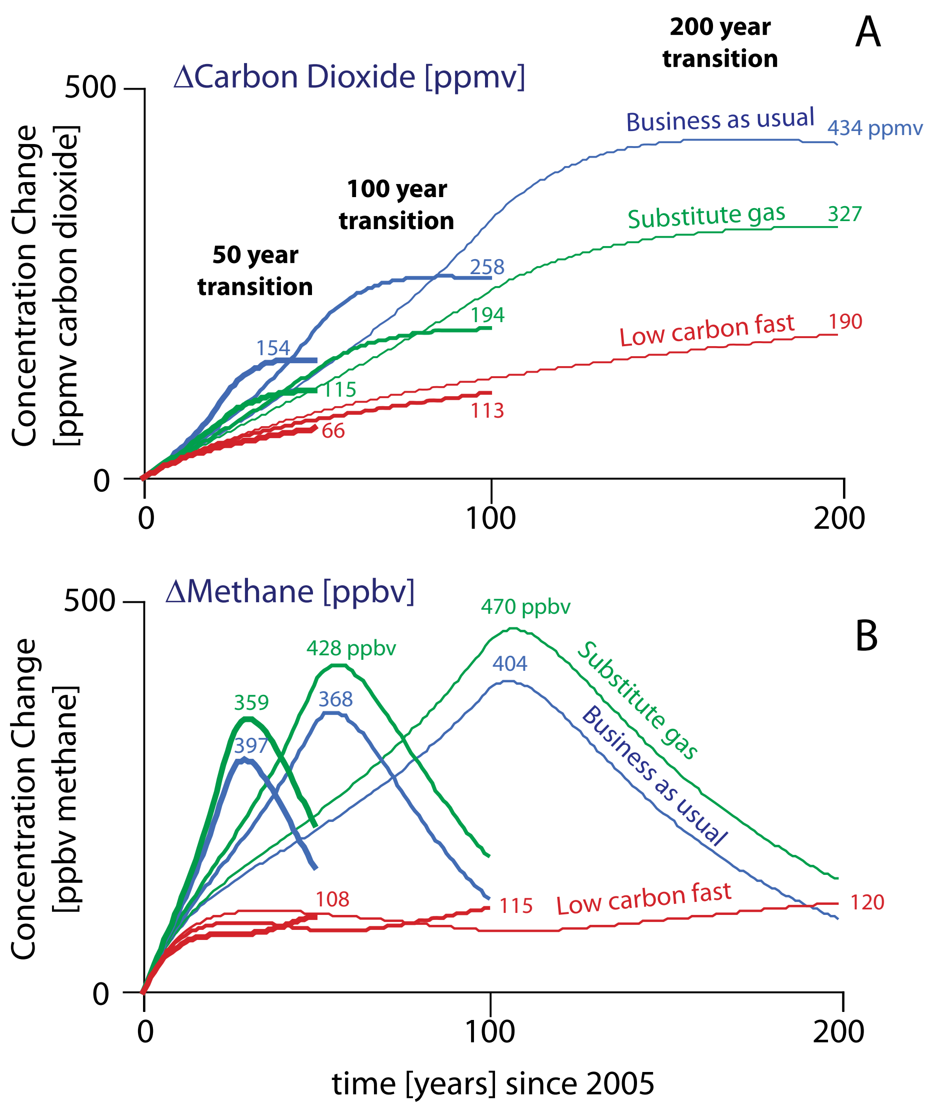


**Figure 2 Changes in (A) carbon dioxide and (B) methane concentrations computed for the three fuel scenarios shown in Figure 1 and three different transition intervals (50 100 and 200 years). In this and subsequent figures the blue curves indicate the business-as-usual fuel use scenario, the green curves indicate the substitute-gas scenario, and the red curves the low-carbon-fast scenario. The numbers indicate the change in concentrations of**

$CO_2$ and methane from the 379 ppmv for $CO_2$ and 1774 ppbv for $CH_4$ levels present in the atmosphere in 2005. The calculation is based on L= 1% of gas consumption and V= 5 m$^3$ methane per ton of coal burned.

## Results

Figure 2 shows the additions of $CO_2$ in ppmv and methane in ppbv that occur for the different fuel consumption scenarios show in Figure 1 for the three transition periods (50, 100 and 200 years). The methane leakage is assumed to be 1% of consumption. Five cubic meters of methane are assumed to leak to the atmosphere for each ton of coal mined. The atmospheric methane concentrations track the pattern of methane release quite closely because methane is removed quickly from the atmosphere with an exponentially decay constant of 12 years (equation 4b). On the other hand, because only a portion of the $CO_2$ introduced into the atmosphere by fuel combustion is removed quickly (see equation 4a), $CO_2$ accumulates across the transition periods and, as we will show below, persists for a long time thereafter.

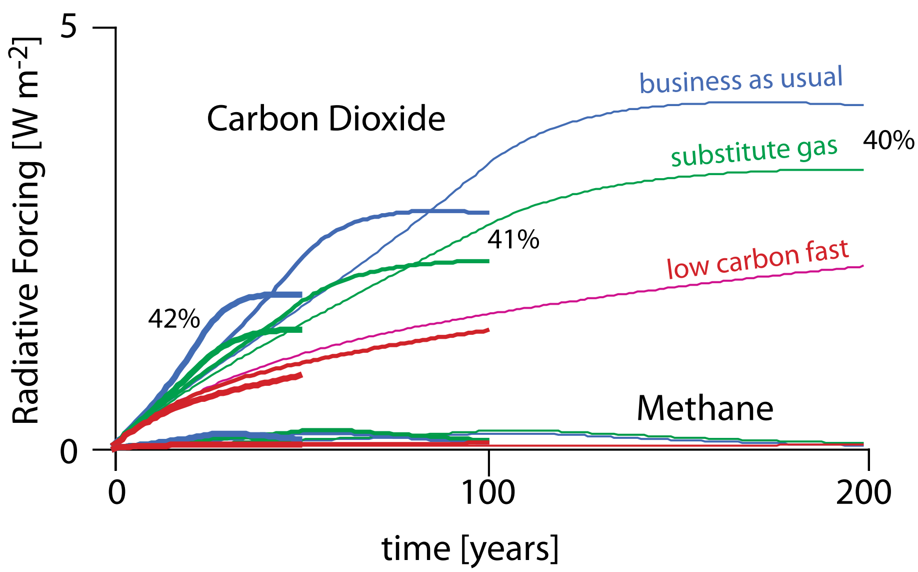


**Figure 3 Radiative forcings calculated for the carbon dioxide and methane additions shown in Figure 2 using equation (6) and assuming $\Psi_{CH4}$=1.43. The blue curves indicate the business as usual scenario for the 50, 100 and 200 year transition periods, the green the substitute-gas scenario, and the red the low-carbon-fast scenario. The numbers indicate the reduction in $CO_2$ forcing achieved by substituting gas, expressed as a percentage of the reduction achieved by the low-carbon-fast scenario.**

Figure 3 shows the radiative forcings corresponding to the atmospheric gas concentrations shown in Figure 2 using equation (6). The methane forcing is a few percent of the $CO_2$ forcing, and thus is unimportant in driving greenhouse warming for a gas leakage rate of 1%.

Figure 4 shows the global warming predicted from the radiative forcings in Figure 3 for various degrees of heat loss to the ocean. We take the equilibrium climate sensitivity $\lambda_s^{-1}$ = 0.8 (e.g., a doubling of CO2 causes a 3°C of global warming). The faster transitions produce less global warming because they put less $CO_2$ into the atmosphere. The thermal modulation of the oceans can reduce the warming by up to a factor of two. For example, Figure 4A shows the global warming that would result from the business-as-usual scenario if there were no heat losses to the ocean ranges from 1.5°C for the 50 year transition to 3.3°C for the 200 year transition. Figure 4C indicates that heat exchange to the oceans could reduce this warming by a factor of two for the long transitions and three for the 50 year transition. A warming reduction this large is unlikely because it assumes extreme parameter values: a deep ocean layer with a heat storage 50 times the shallow mixed layer, and a long mixing time for the shallow layer ($\tau_{mix}$ = 50 years). Figure 4B indicates the more likely ocean temperature change moderation based on mid-range deep layer storage ($C_{deep}C_{mix}^{-1}$=20) and mixed layer response time ($\tau_{mix}$ = 5 years) parameter values.

The important message of this figure for the purposes of this paper, however, is not the amount of warming that might be produced by the various fuel scenarios of Figure 1, but the indication that the reduction in greenhouse warming from substituting gas for coal and oil is not significantly affected by heat exchange with the ocean or by the duration of the transition period. The same percent reduction in global warming from substituting gas for coal and oil is realized regardless of the duration of the transition period or the degree of thermal moderation by the ocean. The benefit of substituting gas is a percent or so less for the short transitions, and the ocean moderation reduces the benefit by a percent or so, but the benefit in all circumstances remains ~38%. Heat loss into the oceans may reduce the warming by a factor of two, but the benefit of substituting gas is not significantly affected.

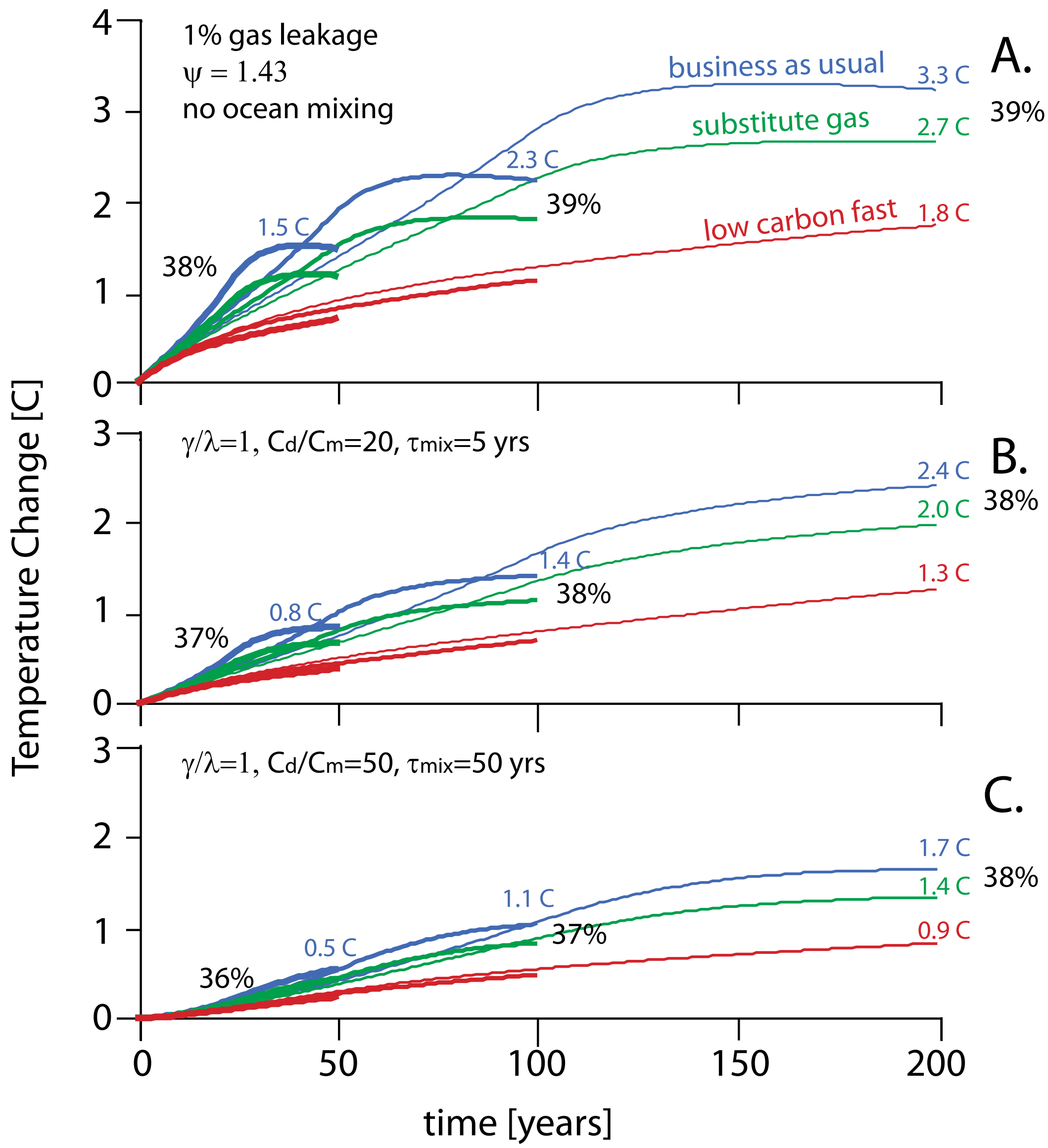


**Figure 4. Global warming produced by the forcings in Figure 3 computed using equations (7, 10, and 12). The blue curves indicate temperature changes under the business-as-usual scenario for 50, 100 and 200 year transition durations, and the green and red curves indicate the temperature changes for the substitute-gas and low-carbon-fast scenarios. The colored numbers indicate the temperature changes, and the black numbers the reduction in temperature achieved by the substitute-gas scenario expressed as a fraction of the temperature reduction achieved by the low-carbon-fast scenario. (A) The warming when there is no thermal interaction with the ocean (or the ocean layers thermally equilibrate very quickly). (B) Warming under a likely ocean interaction. (C) Warming with a very high ocean thermal interaction. The ocean mixing parameters are indicated in (B) and (C). All calculations assume gas leakage is 1% of consumption and the IPCC methane climate sensitivity.**

Figure 5 compares the methane forcing of the substitute-gas scenario to the $CO_2$ forcing of the business-as-usual scenario for the 50 and 100 year transition durations. The forcing for the 1% methane curves are the same as in Figure 3, but is continued out to 200 years assuming the fuel use remains the same as at the end of the of the transition period. Similarly the business-as-usual curve is the same as in Figure 3 continued out to 200 years. The figure shows that the methane forcing increases as the percent methane leakage increases, and becomes equal to the $CO_2$ forcing in the business-as usual scenario when the leakage is ~15% of consumption for the 50 year transition and 30% of consumption for the 100 year transition. At the end of the transition the methane radiative forcings fall to the level that can be steadily maintained by the constant methane leakage associated with the small continued natural gas consumption. The $CO_2$ forcing under the business-as-usual scenario fall a bit and then rise at a slow steady rate, reflecting the proscription that 26% of the $CO_2$ released to the atmosphere is only very slowly removed and 22% is not removed at all (equation 3a). This slow rise emphasizes that even very low releases of $CO_2$ can be of concern. The methane in the atmosphere would rapidly disappear in a few decades if the methane venting were stopped, whereas the $CO_2$ curves would flatten but not drop significantly. Finally, Figure 5A shows that the greater methane climate sensitivity proposed by Shindell et al (2009) ($\psi_{CH4}$=1.94) would make a 10% methane venting equivalent to a 15% venting with $\psi_{CH4}$=1.43 (the IPCC methane climate sensitivity).

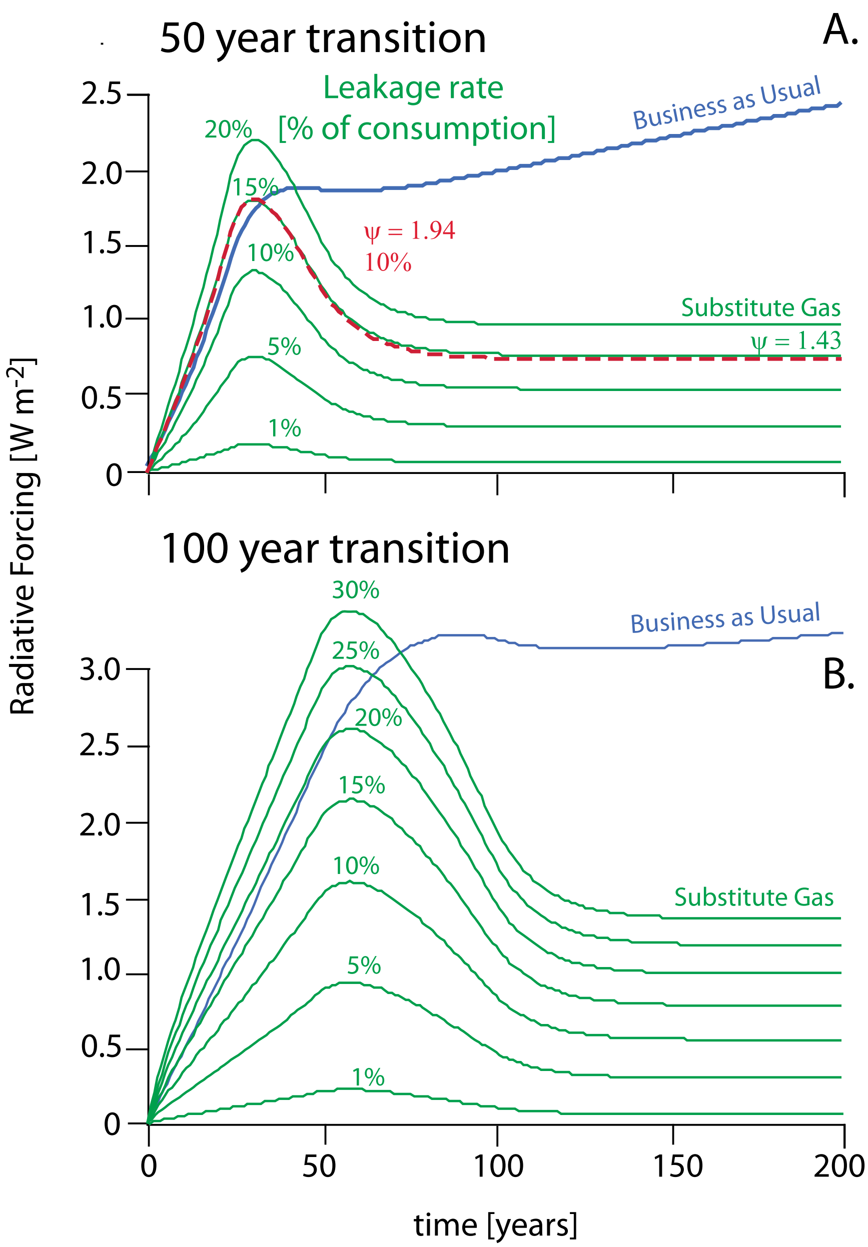


**Figure 5. Radiative forcings of $CO_2$ for the business as usual scenario (blue curves) and for $CH_4$ for various gas leakage rates in the substitute-gas scenario (green curves). The 1% methane curves and the business as usual curves are the same as in Figure 3 except the vertical scale is expanded and the curves are extended from the end of the transition to 200 years assuming the gas emissions are the same as at the end of the transition past 100 years. The methane forcings plateau at the levels corresponding to the atmospheric concentration supported by the steady $CH_4$ emissions. The $CO_2$ forcing increases because an appreciable fraction of the $CO_2$ emissions are removed slowly or not at all from the atmosphere. The methane forcings all assume the IPCC methane climate sensitivity ($\psi_{CH4}$=1.43) except the single red curve, which assumes the methane climate sensitivity suggested by Shindell et al. (2009) ($\psi_{CH4}$=1.94).**

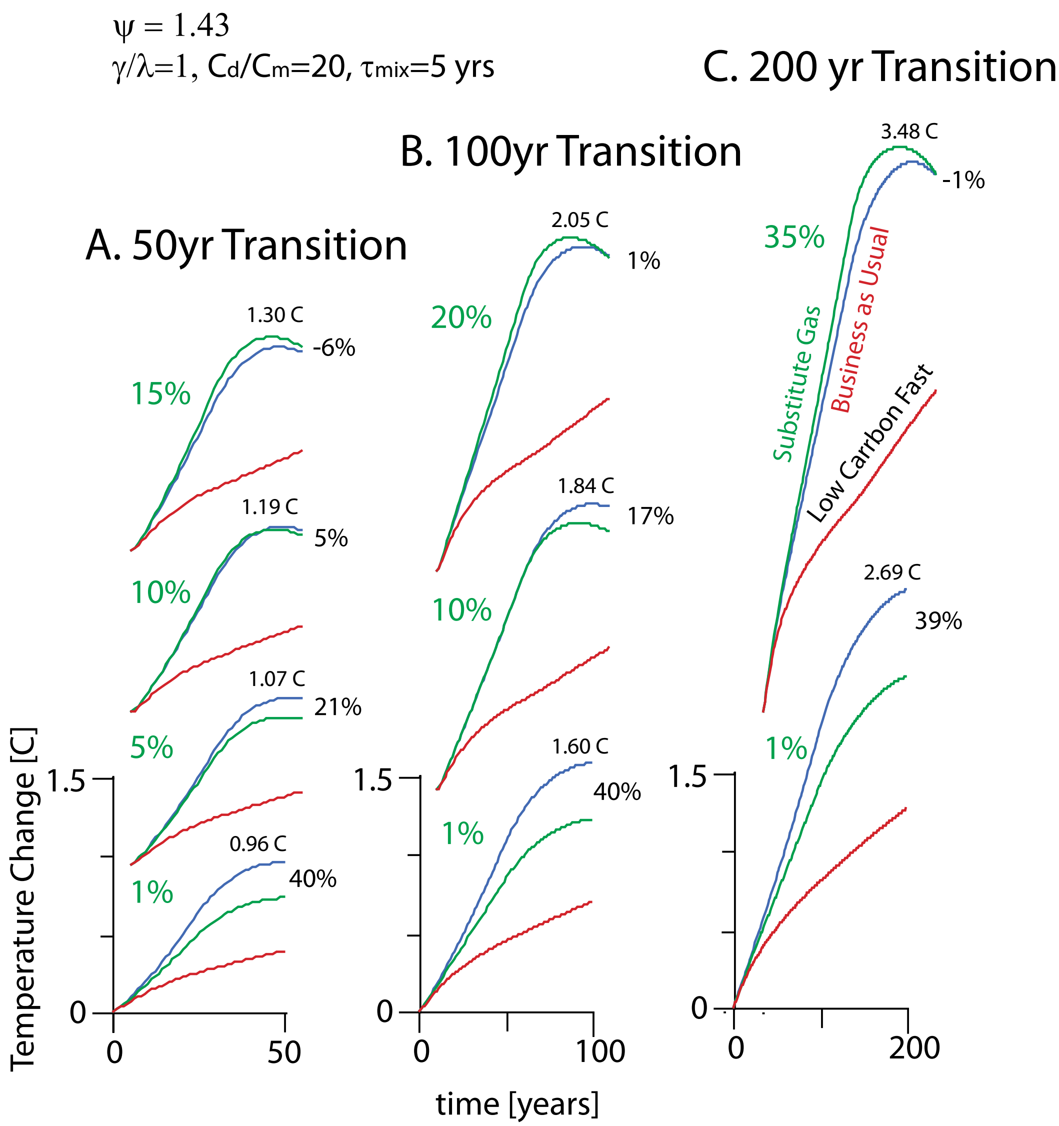


**Figure 6. Impact of methane leakage on global warming for transition periods of (A) 50, (B) 100, and (C) 200 years. As the leakage rate (green percentage numbers) increase, the warming of the substitute-gas scenario (green curves) increases, the blue business-as-usual and green substitute-gas curves approach one another and then cross, and the percentage of the warming reduction attained by the fast substitution of low carbon energy sources decrease and then become negative. The warmings assume the same exchange with the ocean as in Figure 4B.**

Figures 6 illustrates how the benefits of substituting gas for coal and oil disappear as the methane leakage increases above 1% of total methane consumption. The figure shows the global warming calculated for the ocean heat exchange show in Figure 4B. As the methane leakage increases, the green substitute-gas scenario curves rise toward and then exceed the blue business-as-usual curves, and the benefit of substituting gas disappears. The gas leakage at which substituting gas for oil and coal warms the earth more than the business-as-usual scenario is smallest (L~10%) for the 50 year transition period and largest (L~35%) for the 200 year transition period.

Figure 7 summarizes how the benefit of gas substitution depends on the gas leakage rate. For the IPCC methane climate sensitivity ($\psi_{CH4}$=1.43), the benefit of substituting gas goes to zero when the gas leakage is 44% of consumption (30% of production) for the 200 year transition, 24% of consumption (19% of production) for the 100 year transition, and 13% of consumption (12% or production) for the 50 year transition. For the Shindell et al. climate sensitivity corresponding to $\psi_{CH4}$=1.94, the crossover for the 50 year transition occurs at a gas leakage of ~9% of consumption, and reasonable ocean thermal mixing reduces this slightly to ~8% of consumption (7.4% of production). This last is approximately the cross-over discussed by Howarth et al. (2011 and 2012). In their papers they suggest a methane leakage rate as high as 8% of production is possible, and therefor that natural gas could be as bad (if compared on the basis of electricity generation) or twice as bad (if compared on a heat content basis) as coal over a short transition period. As discussed in the next section, a leakage rate as high as 8% is difficult to justify. Figure 7 thus shows the significance of Shindell's higher methane climate sensitivity to Howarth's proposition. Without it, an even less plausible methane leakage rate of 13% would be required to make gas as bad or twice as bad as coal in the short term. Over the longer term, substitution of gas is beneficial even at high leakage rates- a point completely missed by Howarth et al.

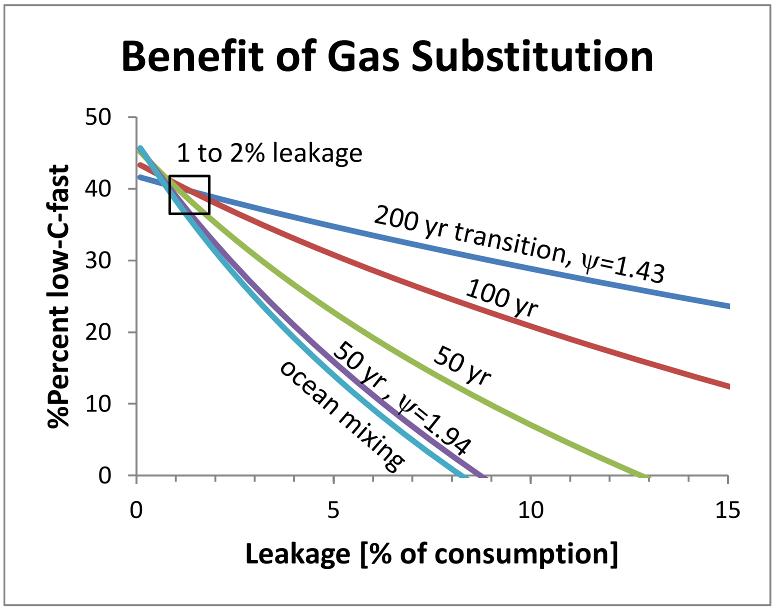


**Figure 7. The reduction of greenhouse warming attained by substituting natural gas for coal and oil (substitute-gas scenario), expressed as a percentage of the reduction attained by immediately substituting low carbon fuels (low-C-fast scenario), plotted as a function of the gas leakage rate. At leakage rates less than ~1%, the benefit of substituting natural gas is >40% that of immediately substituting low carbon energy sources. The benefit declines more rapidly with leakage for short transitions. The top three curves assume an IPCC methane climate sensitivity ($\psi_{CH4}$=1.43). The bottom two show the impact of the greater methane climate sensitivity suggested by Shindell et al (2009) ($\psi_{CH4}$=1.94). The ocean mixing curve adds the small additional impact of thermal exchange with the oceans at the rate shown in Figure 4B to the $\psi_{CH4}$=1.94 curve immediately above it.**

## What is the gas leakage rate

The most extensive syntheses of data on fugitive gases associated with unconventional gas recovery is an industry report to the EPA commissioned by The Devon Energy Corporation (Harrison, 2012). It documents gas leakage during the completion of 1578 unconventional (shale gas or tight sand) gas wells by 8 different companies with a reasonable representation across the major unconventional gas development regions of the U.S. Three percent of the wells in the study vented methane to the atmosphere. Of the 1578 unconventional (shale gas or tight sand) gas wells in the Devon study, 1475 (93.5%) were *green completed* - that is they were connected to a pipeline in the pre-initial production stage so there was no need for them to be either vented or flared. Of the 6.5% of all wells that were not green completed, 54% were flared. Thus 3% of the 1578 wells studied vented methane into the atmosphere.

The wells that vented methane to the atmosphere did so at the rate of 765 Mcsf/completion. The maximum gas that could be vented from the non-green completed wells was estimated by calculating the sonic venting rate from the choke (orifice) size and source gas temperature of the well, using a formula recommended by the EPA. Since many wells might vent at sub-sonic rates, which would be less, this is an upper bound on the venting rate. The total vented volume was obtained by multiplying this venting rate by the known duration of venting during well completion. These vented volumes ranged from 340 to 1160 Mscf, with an average of 765 Mscf. The venting from an average unconventional shale gas well indicated by the Devon study is thus ~23 Mscf (= 0.03 x 765 Mscf), which is similar to the 18.33 Mcf EPA (2010) estimates is vented during well completion of a conventional gas well (half vented and half flared). Since venting during well completion and workover conventional gas wells is estimated at 0.01% of production (e.g., Howarth et al., 2011), this kind of venting is insignificant for both unconventional and conventional wells.

The unconventional gas leakage rate indicated by the Devon data is very different from the 4587 Mscf the EPA(2010) inferred was vented during well completion and workover for unconventional gas wells from the amount of gas captured in a very limited number of "green completions" reported to them by industry through their GasSTAR program. In their 2010 background technical support document the EPA assumed that this kind of "green" capture was very rare, and that the gas was usually either vented or flared. Assuming further that the gas was vented 50% of the time, the EPA concluded that 4587 Mscf was vented to the atmosphere and that unconventional wells vent 250 times (=4587/18.3) more methane during well completion and workover than conventional gas wells. The EPA (2010) study is a "Background Technical Support Document" and not an official report. It was probably never intended to be more than an outline of an approach and an initial estimate, and the EPA has since cautioned that they have not reviewed their analysis in detail and continue to believe that natural gas is better for the environment than coal (Fulton, 2011). Nevertheless the EPA(2010) report suggested to many that the leakage during well completion and workover for unconventional gas wells could be a substantial percentage (~2.5%) of production, and many accepted this suggestion without further critical examination despite the fact that the safety implications of the massive venting implied by the EPA numbers should have raised questions (e.g., Cathles et al., 2012a,b).

Once a well is in place, the leakage involved in routine operation of the well site and in transporting the gas from the well to the customer is the same for an unconventional well as it is from a conventional well. What we know about this leakage is summarized in Table 2. Routine site leaks occur when valves are opened and closed, and leakage occurs when the gas is processed to removing water and inert components, during transportation and storage, and in the process of distribution to customers. The first major assessment of these leaks was carried out by the Gas Research Institute (GRI) and the EPA in 1997 and the results are shown in the second column of Table 2. Appendix A of EPA(2010) gives a detailed and very specific accounting of leaks of many different kinds. These numbers are summed into the same categories and diaplayed in column 3 of Table 2. EPA(2011) found similar leakage rates (column 4). Skone (2011) assessed leakage from 6 classes of gas wells. We show his results for unconventional gas wells in the Barnett Shale in column 5 of Table 2. His other well classes are similar. Venkatish et al (2011) carried out an independent assessment that is given in column 6. There are variations in these assessments, but overall a leakage of ~1.5% of production is suggested. Additional discussion of this data and its compilation can be found in Cathles et al. (2012) and Cathles (2012).

**Table 2. Leakage of natural gas that is common to both conventional and unconventional gas wells in perent of gas production.**

| | **GRI-EPA (1997)** | **EPA (2010)** | **EPA (2011)** | **Skone (2011)** | **Venkatish et a. (2011)** |
|---|---|---|---|---|---|
| **Routine site leaks** | 0.37% | 0.40% | 0.39% | | |
| **Processing** | 0.15% | 0.12% | 0.16% | 0.21% | 0.42% |
| **Transportation & storage** | 0.48% | 0.37% | 0.40% | 0.40% | 0.26% |
| **Distribution** | 0.32% | 0.22% | 0.26% | | 0.22% |
| **Totals** | 1.32% | 1.11% | 1.21% | | |

Based on the above review the natural gas leakage rate appears to be no different during the drilling and well preparation of unconventional (tight shales drilled horizontally and hydrofractured ) gas wells than for conventional gas wells, and the overall leakage from gas wells is probably <1.5% of gas production. In their controversial paper suggesting that gas could be twice as bad a coal from a greenhouse warming perspective, Howarth et al (2011, 2012) suggested routine site leaks could be up to 1.9% of production, leakage during transportation, storage, and distribution could be up to 3.6% or production, and gas leakage from unconventional gas wells during well completion and workover could be 1.9% of production. Adding 0.45% leakage for liquid unloading and gas processing, the suggested gas leakage could be 7.9% of production, enough to "undercut the logic of its use as a bridging fuel in the coming decades, if the goal is to reduce global warming."

The basis given by Howarth et al. (2011) for their more than 5 fold increase in leakage during transportation, storage, and distribution is: (a) a leakage in Russian pipelines that occurred during the breakup of the Soviet Union which is irrelevant to gas pipelines in the U.S., and (b) a debate on the accounting of gas in Texas pipelines that concerns royalties and tax returns (Percival, 2010). Howarth et al. suggest in this Texas case that the industry is seeking to hide methane losses of more than 5% of the gas transmitted, but the proponents in the article state "We don't think they're really losing the gas, we just think they're not paying for it". In their 5 fold increase in routine gas leaks (from the average level in Table 2 of 0.38% to 1.9%), Howarth's et al. (2011) cite a GAO study of venting from wells in onshore and offshore government leases that does not distinguish venting from flaring. Lacking this distinction, it is not surprising that it conflicts dramatically with the summaries in Table 2. We have already discussed leakage during well completion and workover and noted that the Devon data indicate Howarth et al.'s 1.9% leakage at this stage is hugely exaggerated (the Devon data indicates the leakage is ~0.01% and similar to that from conventional gas well completions and workovers).

There have been a number of papers published recently that offer support for Howarth's high leakage estimates. Hughes (2011) re-interpreted data presented in a widely distributed NETL powerpoint analysis by Skone (2011). By lowering Skone's Estimated Ultimate Recoveries (EUR) for the Barnell Shale from 3 Bcf to 0.84 Bcf while keeping the same estimate of leakage during well completion and gas delivery, Hughes increased Skone's leakage estimates from 2 to 6% of production- a level which falls midway between Howarth's low and high gas leakage estimates. However leakage is a fraction of well production (a well that does not produce cannot emit), and thus is it bogus to reduce the EUR (the denominator) without also reducing the numerator (the absolute leakage of the well). Skone's data must be evaluated on its own terms, not simply adjusted to fit someone else's conclusions.

Petron et al. (2012) analyzed air samples at the 300 m high Bolder Atmospheric Observatory (BAO) tower when the wind was toward it from across the Denver-Julesburg Basin (DJB). Gases venting from condensate (condensed gas from oil and wet gas wells) stock tanks in the DJB are rich in propane relative to methane, whereas the raw natural gas venting from gas wells in the DJB contain very little propane. From the intermediate ratio of propane to methane observed at the BAO tower and estimates of leakage from the stock tanks, Petrone et al. calculate that to dilute the propane leaking from the stock tanks to the propane/methane ratio observed at the tower, ~4% of methane produced by gas wells in the DJB must vent into the atmosphere. The air sampled at the BAO tower is certainly not simply a mix of raw natural gas and stock tank emissions from the DJB as Petron et al. assume, however. If this were the case there would be no oxygen in the air at the BAO tower location. The background atmosphere must certainly mix in with these two (and perhaps other) gas sources. Background air in the Denver area contains ~1800 ppb methane and very little propane. Mixing with the background atmosphere could dilute the stock tank emissions to the propane/methane ratio observed at the BAO tower with no leakage from gas wells in the DJB required at all. Contrary to their suggestion, the BAO tower data reported by Petrone et al. place no constraints at all on the gas leakage rates in the DJB what so ever. More details are in Cathles (2012).

Certainly there is more we could learn about natural gas leakage rates. The issue is complicated because gas is used in the transmission process so shrinkage of product does not equate to venting. In addition there are conventions and practices that make scientific assessment difficult. Despite the difficulties, however, it appears that the leakage rate is less than 2% of production.

## Discussion

We have verified our computations by comparing them to predictions by Wigley's (2011) publically available and widely used MAGICC program. Although there are some internal differences, Table 3 shows that the ~40% reduction in greenhouse warming we predict is also predicted by MAGICC when scenarios similar to the one we consider here are input to both MAGICC and our programs. The MAGICC calculations start at 1990 AD so we consider the temperature increases from 2000 to the end of the period. Fuel use is increased and reduced linearly rather than exponentially, and the fuel use at the start, midpoint, and end of the transition simulations are slightly different than in Figure 1. The temperature changes for the 200 year cycle agree very well. Wigley's MAGICC temperature change predictions become progressively lower than ours as the transition interval is shortened. This may be because MAGICC includes a small ocean thermal interaction, whereas the calculations we report in Table 3 do not.

**Table 3. Temperature changes predicted by Wiglely's(2011) MAGICC program for linear changes in fuel use similar to the scenarios in Figure 1 compared to equilibrium (no ocean thermal interaction) global warming predictions by the program described and used in this paper. The first three rows compare the temperature changes of the two programs. 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% |

Incorporation of the indirect contributions to methane's radiative forcing through $\psi_{CH4}$ in equation (6) was validated by comparing values of GWP computed by (13) to published values summarized in Table 4.

$$GWP = \frac{\Psi_{CH4} \dfrac{\partial \Delta F_{CH4}}{\partial C_{CH4}[ppbv]} MW_{CO2} \int_{t=0}^{t} f_{CH4}\, dt}{\dfrac{\partial \Delta F_{CO2}}{\partial C_{CO2}[ppbv]} MW_{CH4} \int_{t=0}^{t} f_{CO2}\, dt} \qquad (13)$$

GWP is the relative global warming impact of a kg of CH4 compared to a kg of $CO_2$ added to the atmosphere, when considered over a period of time t. The radiative forcings ($\Delta F$) are defined by (6), the removal of the gases from the atmosphere ($f$) by (4a and b), and $MW_{CO2}$ is the molecular weight of $CO_2$. The $\psi_{CH4}$ factor of 1.43 in the second column of Table 4 combines the indirect forcing caused by $CH_4$-induced production of ozone (25% according to IPCC, 2007) and water vapor in the stratosphere (additional 15% according to the IPCC, 2007). With this factor the GWP listed in Table 2.14 of the IPCC (2007) are replicated as shown in the second row of Table 4. The $\psi_{CH4}$ factor of 1.94 in the second column was determined by us such that it approximately predicts the increased forcings suggested by Shindell et al. (2009) as shown in the bottom row of Table 4. We do not use GWPs in our analysis and use them here only to justify the values of $\psi_{CH4}$ used in our calculations.

**Table 4 The GWP calculated from (6 and 13) for the value of $\psi_{CH4}$ in column 2 are compared to GWP (in parentheses) given by the IPCC (2007) and Shindell et al. (2009).**

| | $\psi_{CH4}$ | t=20 years | t=100 years | t=500 years |
|---|---|---|---|---|
| Direct methane forcing from (6) | 1 | 51.5 | 17.9 | 5.45 |
| IPCC (2007, §2.10.3.1, Table 2.14) | 1.43 | 73.5 (72) | 25.8(25) | 7.8 (7.6) |
| Shindell et al. (2009) | 1.94 | 99(105) | 35(33) | 10.5 |

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 4). For methane leakages of ~1% of total consumption, 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 ~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 3), and only the $CO_2$ input counts. The reduction in $CO_2$ vented between the business-as-usual and the substitute-gas scenarios is 44.1% 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 50 years or 200 years. Because the losses of $CO_2$ from the atmosphere (equation 4a) 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. Thus the fractional substitute-gas reduction in CO2 in the atmosphere at the end of all the transition intervals remains 44.1% although there are some variations in the second decimal place. The curves shown in Figure 7 intersect the y-axis (0% gas leakage) at fractions slightly different from 44.1% because the radiative forcing is non-linear with respect to $CO_2$ concentration (equation 5a). The longer transition periods show larger non-linear effects because they put more $CO_2$ into the atmosphere. 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, a point made by Allen (2009).

The global warming reduction from swapping gas for the other fossil fuels of course decreases as methane leakage increases. But at low leakage rates, the benefit of substituting natural gas remains close to 40%. In the context of swapping gas for coal, the extra methane emitted by low levels of leakage has such a trivial climate effect that it need not be considered at all.

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. In the real world the "aerosol benefit" of coal must be removed eventually (unless we are to burn coal forever), and the sooner it is removed the better both because the small warming its removal will cause will have less impact when temperatures are cooler, and, much more importantly, because replacing coal soon will reduce $CO_2$ emissions and lead to much less global warming in the longer term.

Wigley's (2011) decrease in greenhouse warming for the natural gas substitution he defines is similar to that we compute 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 ~0.62°C for 0% leakage. Our cooling is greater than his at least in part because our gas substitution scenario reduces the $CO_2$ emissions more than his. From nearly the same start, our gas substitution reduces $CO_2$ emissions from the business-as-usual 200 year transition cycle by 743 GtC whereas Wigley reduces $CO_2$ by 425 GtC.

There are of course uncertainties in the kind of calculations carried out here, but these uncertainties are unlikely to change the conclusions reached. Carbon dioxide is almost certainly not removed from the atmosphere exactly as described by equation (3). The uptake of $CO_2$ may well slow as the climate warms. Carbon dioxide is less soluble in warm water and the haline circulation may slow as the sea surface temperature increases. The increase in terrestrial $CO_2$ uptake from $CO_2$ fertilization may be reduced by nitrogen limitations. A good discussion of these issues is provided in NRC(2011). Eby et al. (2009) have suggested based on sophisticated coupled global models that ~50% of the introduced $CO_2$ may be removed with a time constant of 130 years and 50% with an exponential time constant of 2900 years. Modifications of equation (3) that reduce $CO_2$ uptake as the climate warms will make the benefits of not putting $CO_2$ into the atmosphere, for example by substituting gas for coal, even greater, and the arguments presented here stronger.

The transmission of heat from the mixed to the deep layer of the oceans is an unknown which has a strong impact on transient global warming. For example, if heat entered the deep layer with 10% of the ease with which it enters it from the atmosphere so that $\gamma\lambda_s^{-1}$ ~0.1, the deep layer would largely loose its cooling effectiveness (e.g., *a* in equation 11 would have a value of 0.91). The transient response to $CO_2$ forcing would be rapid (occur at 0.91 $\tau_{mix}$), and the ocean would reduce the equilibrium global temperature change by only 9%. The relative rates at which heat is transferred into the mixed layer and out of it into the deep layer would appear to be an important area for further investigation, especially because it impacts our ability to infer proper values in the equilibrium climate forcing (see discussion in NRC, 2011). Ocean heat exchange does not affect the comparative benefit of substituting gas, so uncertainties in the ocean heat exchange aer not of concern to the conclusions we reach here.

The calculations made here avoid the use of GWP factors. The deficiencies in the GWP approach are discussed well by Solomon et al. (2011). As is apparent from (13), the GWP metric requires that the time period of comparison be specified. For a short time period, a short lived gas like methane has a high GWP (e.g., it is 72 times more potent in terms of global warming than $CO_2$ when compared over a 20 year). The notion that methane emissions have 72 times the global warming impact of $CO_2$ would tempt eliminating methane emissions immediately, and worrying about reducing $CO_2$ emissions later. On the other hand for a 500 year period, the global warming impact of a kilogram of vented methane is only 7.6 that of a kilogram of $CO_2$ ($GWP_{CH4}$=7.6, see Table 4), and this low impact would suggest dealing with $CO_2$ emissions first and the methane emissions later, perhaps even substituting gas for coal and oil. As Solomon et al. point out the GWP metric speaks only to the time period for which it is calculated and sheds no light on the whether $CO_2$ or $CH_4$ should be reduced first.

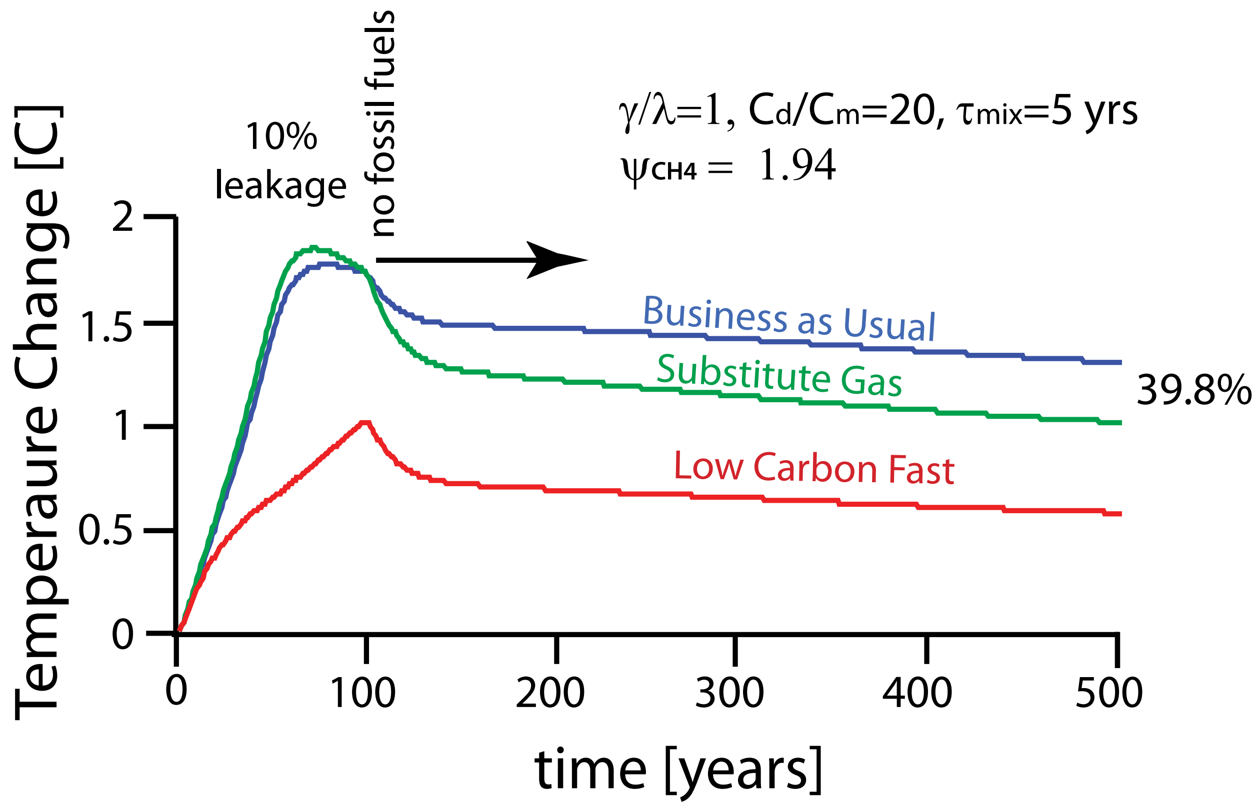


**Figure 8. Temperature change for scenarios in Figure 1 when a transition period is 100 years is followed by a 400 year period with no burning of fossil fuels. Methane leakage in the transition is 10% of gas consumption and Shindell's greater methane forcing and heat exchange with the ocean are included. Extra methane venting in the substitute-gas scenario produces warming greater than the business-as-usual scenario up to almost the end of the transition, but the benefits of reducing carbon emissions by substituting gas emerge very quickly thereafter.**

Figure 8 illustrates the fundamental dilemma. It shows that even when methane leakage is so large (L=10% of consumption) that substituting gas for coal and oil increases global warming in the short term, the benefit of gas substitution returns in the long term. The short term heating caused by methane leakage rapidly dissipates after emissions of $CO_2$ and $CH_4$ cease at 100 years. $CH_4$ is rapidly removed from the atmosphere, but $CO_2$ is not. The result is that 50 years or so after the termination of venting (beyond 150 years in Figure 8), the benefit of gas emerges unscathed. At a 10% leakage rate and a 100 year transition period, the substitute-gas scenario produces a small amount more warming than the business-as-usual scenario at 70 years, but after 150 years the gas substitution reduces global warming much more because it has reduced the amount of $CO_2$ vented to the atmosphere. Figure 8 shows how dangerous a metric such as GWP can be. Even for methane emissions of 9% of production and Shindell's forcings, substituting gas for coal is worthwhile in the long term. Analyses that rely only on GWP factors, such as that of Howarth et al. (2011), miss this mix of impacts completely, and see only the damage of extra methane emissions in the short term or the benefits of gas substitution in the long term, depending on the GWP interval selected. Fortunately it is very easy to carry out the necessary convolution integrals (equations 5 and 11) as done here and avoid GWP metrics altogether. As stated by Solomon et al. (2011) and others who they cite, GWP factors should simply not be used to evaluate fuel consumption scenarios.

Finally, framing the fuel use scenarios in terms of exponential growth and decline as we have done here allows the feasibility of implementing the various scenarios to be examined in a preliminary fashion. Figure 9 shows the rate of growth of low carbon energy resources that is required by the fuel histories in Figure 1 for a 100 year transition. Growth at more than 5% per year would be challenging. Figure 9 shows that the low-carbon-fast scenario in Figure 1 requires an immediate ~16% per year (but rapidly declining) growth in low carbon energy sources. The growth rate of low carbon energy sources at the end of the growth period of the business-as-usual scenario is an even greater 24% per year. Because there is time to plan, this could be reduced by phasing in low carbon energy sources toward the end of the fossil fuel growth period. The substitute-gas scenario has a much lower growth requirement at this stage, which would make this scenario substantially easier to accommodate.

Any decision to substitute gas for coal and oil of course involves economic and social consideration, as well as climate analysis. Natural gas can enable the transition to wind or solar energy by providing the surge capacity when these sources fluctuate and backup when these sources wane. Because of its wide availability and low cost, economic factors will encourage gas replacing coal in electricity generation and oil in segments of transportation. It is a fuel the U.S. and many other countries need not import, so its development could increase employment, national security, and a more positive balance of payments. On the other hand, cheap and available gas might undermine the economic viability of low carbon energy sources and delay a transition to low carbon sources. From a greenhouse point of view it would be better to replace coal electrical facilities with nuclear plants, wind farms, or solar panels, but replacing them with natural gas stations will be faster, cheaper and achieve 40% of the low-carbon-fast benefit if the leakage is low. How this balance is struck is a matter of politics and outside the scope of this paper. What can be said here is that gas is a natural transition fuel that could represents the biggest available stabilization wedge available to us.

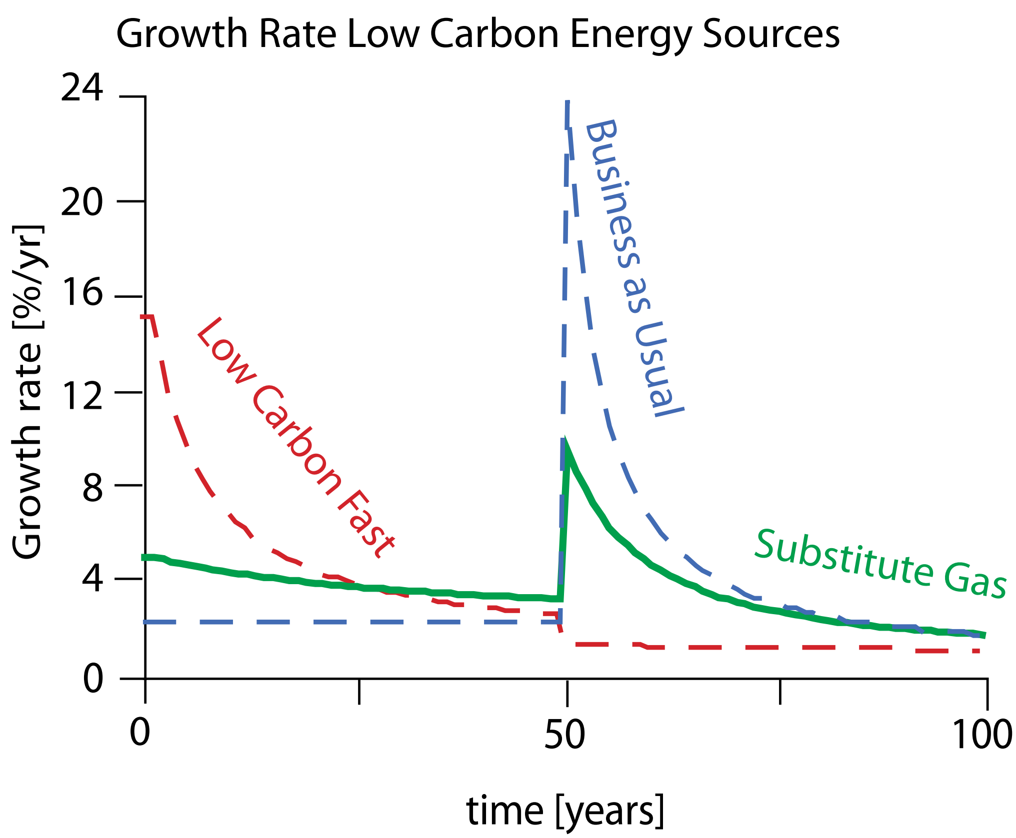


**Figure 9. The growth rate of low carbon energy sources deduced from Figure 1 plotted as a function of time for a 100 year transition. Growth rates more than 5% per year such will be challenging to achieve on a global basis.**

## Conclusions

The comparative approach taken in this paper shows that the benefit of substituting natural gas depends only on its leakage rate.

1. For leakage rates ~1% or less, the substitution of natural gas for the coal used in electricity generation and for 55% of 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 50 years or 200 years.

3. For leakage rates ~1% or less, the reduction of greenhouse warming at all times is related directly to the mass of $CO_2$ put into the atmosphere, and therefore to reduce greenhouse forcing we must reduce this $CO_2$ input. Complexities of how $CO_2$ is removed and reductions in $SO_2$ emissions and increases in carbon black and the like 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 50 year transition scenario), substitution of natural gas will be beneficial if 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 ~19% of production (Figure 7). The natural gas leakage rate appears to be presently less than 2% of production and probably ~1.5% of production.

5. Even if the natural gas leakage rate were high enough to increase greenhouse warming (e.g., the leakage was 10% of methane consumption or 9% of methane production), substituting gas would still have benefits because the reduction of $CO_2$ emissions would lead to a greater reduction in greenhouse warming later (Figure 8).

6. Gas is a natural transition fuel because its substitution reduces the rate at which low carbon energy sources must be later introduced (Figure 9) and because it can facilitate the introduction of low carbon energy sources.

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, (2) encourage the rapid substitution of natural gas for coal and oil, and (3) encourage as rapid a conversion to low carbon sources of energy as possible.

## Acknowledgements

This paper was greatly improved by three excellent reviews, two anonymous and one by Ray Pierrehumbert. Ray pointed out the importance of ocean mixing, suggested casting fuel use in terms of exponential growth and decline, and drew my attention to important references (as did the other reviewers). I am indebted to my prior co-authors in this subject (Milton Taam, Larry Brown, and Andrew Hunter) for continuing very helpful discussions, and to members of the gas industry who pointed out data and helped me understand the complexities of gas production. Milton Taam drew my attention to the MAGICC program and showed me how easy it was to use, and also pushed persistently for the broader view of methane substitution shown in Figure 8. The paper would not be what it is without the contribution of these individuals and I thank them for their input.

## References

Allen, MR, Frame DJ, HuntingforC, Jones CD, Lowe JA, Meinshause M, and Meinshausen N (2009) Warming caused by cumulative carbon emissions towards the trillionth tonne, Nature, 458 (7242), 1163–1166, doi:10.1038/nature08019.

Cathles LM, (2012) Perspectives on the Marcellus gas resource: What benefits and risks are associated with Marcellus gas development?, http://blogs.cornell.edu/naturalgaswarming/

Cathles LM, Brown L, Taam M, Hunter H (2012a) A commentary on "the greenhouse-gas footprint of natural gas in shale formations" by RW Howarth, R Santoro, and A Ingraffea, Climatic Change, DOI:10.1007/s10584-011-0333-0. http://www.springerlink.com/content/x001g12t2332462p/

Cathles LM, Brown L, Hunter A, and Taam M (2012b) Press release: response to Howarth et al.'s reply (February 29,2012), http://www.geo.cornell.edu/eas/PeoplePlaces/Faculty/cathles/Natural%20Gas/Response%20to%20Howarth's%20Reply%20Distributed%20Feb%2030,%202012.pdf

Clarke LE, Edmonds JA, Jacoby HD, Pitcher H, Reilly JM, Richels R (2007) Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations. Sub-report 2.1a of

Synthesis and Assessment Product 2.1. A Report by the Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC, 154pp

Eby M, Zickfeld K, Montenegro A, Archer D, Meissner K J, and Weaver AJ (2009) Lifetime of anthropogenic climate change: millennial time scales of potential CO2 and surface temperature perturbations. Journal of Climate 22 (10):2501-2511, DOI:10.1175/2008JCLI2554.1.

EIA(2011) International Energy Outlook 2011, World total energy consumption tables, http://www.eia.gov/oiaf/aeo/tablebrowser/#release=IEO2011&subject=1-IEO2011&table=1-IEO2011&region=0-0&cases=Reference-0504a_1630.

EPA (2005) Compillation of air pollution emission factors, vol. 1, Stationary point and and area sources: Report AP-42, Office of Air and Radiation, U. S. EPA, Research Triangel Park, NC 27711.

EPA (2010). Greenhouse Gas Emissions Reporting from the Petroleum and Natural Gas Industry. Background Technical Support Document. U.S. Environmental Protection Agency, Washington DC. http://www.epa.gov/climatechange/emissions/downloads10/Subpart-W_TSD.pdf

EPA (2011) Inventory of greenhouse gas emissions and sinks 1990-2009, EPA 430-R-11-005, 55 p, http://epa.gov/climatechange/emissions/usinventoryreport.html

Fulton M, Mellquist N, Kitasei S, and Bluestein J (2011) Comparing greenhouse gas emissions from natural gas and coal. 25 Aug 2011. Worldwatch Institute/Deutsche Bank. http://lockthegate.org.au/documents/doc-305-comparing-life-cycle-greenhouse-gas-db.pdf

GRI-EPA (1997) Methane Emissions from the natural gas industry, Project Summary, Harrison NR, Shires TM, Wessels JK, and Cowgill RM, EPA/600/SR-96/080. http://www.docstoc.com/docs/19963708/Methane-Emissions-from-the-Natural-Gas-Industry .

Harrison M (2012) Revised Attachment 3: Gas well completion emissions data, URS Corporation Report (aka the URS Devon Study), http://anga.us/media/241555/anga-axpc%20nsps%20memo%20revised.pdf

Hayhoe K, Kheshgi HS, Jain AK, Wuebbles DJ (2002) Substitution of natural gas for coal: climatic effects of utility sector emissions. Climatic Change 54:107–139.

Howarth R, Santoro T, and Ingraffea A (2011) Methane and the greenhouse gas footprint of natural gas from shale formations, Climatic Change, DOI 10.1007/s10584-011-0061-5. http://www.springerlink.com/content/e384226wr4160653/

Howarth RW, Santoro R, and Ingraffea A (2011). Methane and the greenhouse gas footprint of natural gas from shale formations. Climatic Change Letters, doi: 10.1007/s10584-011-0061-5. http://www.springerlink.com/content/e384226wr4160653/

Hughes D (2011) Lifecycle greenhouse gas emissions from shale gas compared to coal: an analysis from two conflicting studies, Post Carbon Institute, 21p, http://www.postcarbon.org/report/390308-life-cycle-greenhouse-gas-emissions-from .

Hultman N, Rebois D, Scholten M, and Ramig C (2011). The greenhouse impact of unconventional gas for electricity generation. Environ. Res. Lett. 6: 044008, doi:10.1088/1748-9326/6/4/044008. http://iopscience.iop.org/1748-9326/6/4/044008/

IPCC (1990), Houghton JT, Jenkins GJ, and Ephraums JJ (eds.), Report prepared for Intergovernmental Panel on Climate Change by Working Group I, Cambridge University Press, Cambridge, Great Britain, New York, NY, USA and Melbourne, Australia , 410 p. http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml

IPCC (1996), Houghton JT, Meira Filho LG, Callander BA, Harris N, Kattenberg A, and Maskell K, ed., Climate Change 1995: The Science of Climate Change, Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, ISBN 0-521-56433-6 (pb: 0-521-56436-0) http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml

IPCC (2001), Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, and Johnson CA, ed., Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, ISBN 0-521-80767-0, http://www.grida.no/publications/other/ipcc%5Ftar/?src=/climate/ipcc_tar/wg1/index.htm (pb: 0-521-01495-6). http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, and Miller HL(eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml

Moore B (2011), Re: Oil and natural gas sector consolidated rulemaking, Docket ID No. EPA-HQ-QAR-2010-0505 (with attached data set documenting gas leakage from unconventional gas wells of 7 companies).

NRC (2011) Climate stabilization targets: Emissions, concentrations, and impacts over decades to millennia, National Acadamies Press, Washington, D.C., 285p. http://www.nap.edu/catalog.php?record_id=12877

Petron G, Frost GJ, Miller BR and 27 others (2012) Hydrocarbon emissions characterization in the Colorado Front Range- a pilot study, Jour. Geophys. Res., doi:10.1029/2011JD016360. http://www.agu.org/journals/jd/jd1204/2011JD016360/2011JD016360.pdf

Saghafi A, Williams DJ, and Lama RD (1997) Worldwide Methane Emissions from Underground Coal Mining, Proceedings of the 6th International Mine Ventilation Congress - May 17-22, Chapter 69 Methane Drainage, CSIRO, p 441-445.

Schwartz, SE (2007) Heat capacity, time constant, and sensitivity of the Earth's climate system, Journal of Geophysical Research, 112, D24S05, 12p., doi:10.1029/2007JD008746

Shindell DT, Faluvegi G, Koch DM, Schmidt GA, Unger N, Bauer SE (2009) Improved attribution of climate forcing to emissions. Science 326:716–718.

Skone TJ (2011) "Life Cycle Greenhouse Gas Analysis of Natural Gas Extraction & Delivery in the United States", oral presentation at Cornell University, May 12, 2011, http://cce.cornell.edu/EnergyClimateChange/NaturalGasDev/Documents/PDFs/SKONE_NG_LC_GHG_Profile_Cornell_12MAY11_Final.PDF

Solomon S, Pierrehumbert R, Matthews D and Daniel JS (2011) Atmospheric composition irreversible climate change and mitigation policy, World Climate Research Programme, 39 p., http://conference2011.wcrp-climate.org/positionpapers.html

Venkatesh A, Jaramillo P, Griffin WM, and Matthews HS (2011) Uncertainty in life cycle greenhouse gas emissions from United States natural gas end users and its effects on policy, Environ. Sci. Technol., 45, 8182-8189. http://pubs.acs.org/doi/abs/10.1021/es200930h

Wigley TML (2011) Coal togas: the influence of methane leakage, Climatic Change, DOI 10.1007/s10584-011-0217-3.

Wigley TML (2011) MAGICC/SCIGEN, http://www.cgd.ucar.edu/cas/wigley/magicc/