Anthropogenic Climate Change

Introduction and Overview
Humans induce climate change mainly by introducing carbon dioxide and methane into the atmosphere through fossil fuel combustion, changes in land use, and agriculture.

On average since 1750 AD, ~1/3rd of global anthropogenic CO$_2$ emissions have been from changes in land use and 2/3rd from fossil fuel combustion. Presently the contribution from fossil fuel combustion is ~90% of the total, and the dominance of the fossil fuel sources will increase in the future. Over the next 100 years about 55% of all anthropogenic CO$_2$ emissions will remain in the atmosphere. (Discussion is provided here.)

In contrast, methane emissions will continue to derive from a variety of natural and human sources, and the fossil fuel contribution will remain relatively small. In 1750 farming practices were the only anthropogenic source and they contributed ~10% of the total emissions, with the rest coming from natural (wetlands, termites, etc) and geologic sources. In 2011 fossil fuels contributed ~17%, farming and animal husbandry 38%, and natural sources 45% of total methane emissions. Over the next 50 years fossil fuel contribution will rise to ~28% of the total under a “business as usual” fuel use scenario. Human agriculture emission contributions will remain at ~39%, and natural sources will fall from 45% to 33% of total methane emissions. Fossil fuels will never be a dominate source of atmospheric methane.

Methane also contrasts with CO$_2$ in being removed quickly and completely from the atmosphere by oxidation at a rate that is proportional to its concentration. Since natural emissions will probably not change (although they may fluctuate), changes in the rate of anthropogenic methane emission will determine the atmospheric methane concentration. Full discussion is offered here.

Greenhouse warming is related solely to changes atmospheric greenhouse gas (GHG) concentrations. Thus to calculate greenhouse warming only changes in the GHG content of the atmosphere need be determined.

1. The first step in predicting future anthropogenic climate change is to calculate future atmospheric greenhouse gas concentrations (Figure 2) from future fuel use (Figure 1) and agricultural activity.

The proper way to do this is to introduce yearly aliquots of CO$_2$ and CH$_4$ into the atmosphere according to an agricultural and fuel use scenario, and remove these aliquots at rates summarized by the IPCC (2013). The IPCC(2013) removal protocols are summarized here, and the various fuel use and agricultural scenarios we will use below are discussed here. This approach is described fully in Cathles (2012) and the references cited there.
2. With the atmospheric greenhouse gas concentrations known, the second step is to convert the changes in GHG concentration to radiative forcings in watts per m$^2$ (Figure 3a) by methods described here.

3. The forcings can be converted to the eventual average global temperature change they would produce if the forcings were maintained for a long period of time (Figure 4) by multiplying by the equilibrium climate sensitivity. (See discussion of this parameter here).

4. The temperature change will be reduced and delayed by heat exchange with the ocean (Figure 4), which can be calculated as discussed in Cathles (2012) and in references cited therein. Inclusion of ocean heat exchange allows realistic warming prediction.

What about uncertainties? The changes in atmospheric CO$_2$ and CH$_4$ concentrations depend on future fuel and agricultural use and are uncertain only to the extent these consumption projections are uncertain. The forcings associated with changes in atmospheric greenhouse gas concentrations can be calculated with confidence and little error. The delay in warming caused by heat exchange with the ocean is more complicated and therefore less certain, but its impact can be bounded with simple mixing models. There is also uncertainty regarding the impact of the non-anthropogenic factors which produced significant global temperature changes in the past.

To keep the discussion as solidly grounded as possible we will first analyze greenhouse warming in terms of greenhouse forcing and equilibrium temperature change, and then turn to the substantial modulating influences of heat exchange with the ocean.

Anthropogenic global warming will be significant, so it is important to consider how it might be reduced. Here we ask whether substituting natural gas for other fossil fuels could significantly reduce global warming. Is natural gas a bridge to nowhere, as some have suggested (Howarth, 2014), or a bridge that could be a significant, natural, and economically attractive part of a risk-reduction strategy?

**Analysis of the Gas Bridge**

**Fuel Use Scenarios**

Greenhouse gas concentrations can be reduced by substituting natural gas for coal and some oil, or by replacing all fossil fuels by zero carbon energy sources. The value of substituting gas can be usefully expressed as the fraction of the greenhouse reduction the “substitute gas” scenario achieves compared to the reduction that could be achieved by abandoning fossil fuels as quickly as possible in a “low carbon fast” scenario. The scenarios are specified in terms of the energy content of the fuels consumed in future times as shown in Figure 1.

- The scenarios all make a transition to zero carbon energy sources over a 100-year period.
- Oil and gas resources (but not coal resources) are largely depleted over the 100 year transition in all scenarios.
- Resource exhaustion will force a transition of roughly the kind depicted in Figure 1 for oil and gas (but not coal). Reduction in coal use will be a matter of political choice.
- Energy consumption in all the scenarios increases at ~1.6% per year, and
- after 100 years every person in a human population of 10.5 billion is provided with the energy enjoyed today by the average Frenchman.

In other words, in addition to transitioning to low carbon energy sources, all the scenarios bring the world up to a European standard of living in 100 years.

- CO₂ emissions are computed from the amounts of fossil fuel burned in each scenario.
- Methane leakage is specified by the m³ of methane released per ton of coal mined, and the percent of gas consumption that is leaked from drilling through delivery.
- The leakage of natural gas is the most uncertain parameter, and it is varied parametrically in our analysis.
- Because coal is replaced in exactly the same fashion in the “substitute Gas” and “Low Carbon Fast” scenarios, short term impacts from SO₂ and carbon black emission changes are the same and cancel out in the analysis. Potential complications are thus removed.

Discussion of the broadest implication of the scenarios is given here. More details and discussion can be found in Cathles (2012).

![Figure 1. Fuel consumption scenarios, starting with world consumption in 2011. Energy consumption increases at ~1.6% per year in the “Business as Usual” scenario as in the recent past and then declines. Gas replaces coal and new oil over the first 50 years and is then reduced in the “Substitute Gas” scenario. Fossil fuels are retired starting immediately in the “Low Carbon Fast” scenario.](image)

**Results**

Figure 2a and b show the rise in CO₂ and CH₄ from 1750 to 2211 AD for the three fuel scenarios in Figure 1, to which agricultural emission increases attending growth of the human population and conversion of methane to CO₂ have been added. These calculations assume a conversion efficiency for electrical gas plants of 60%, and a conversion efficiency for electrical coal plants of 32% (about their present average). Methane leakage from coal is 5m³ per ton of coal mined. IPCC (2013) parameter values for forcing and gas lifetimes in the atmosphere are used. Fossil fuel consumption is terminated at the end of the transition in 2111.

Figure 2a shows that, depending on the natural gas leakage rate, atmospheric methane concentrations could rise substantially under the “substitute gas” scenario. But Figure 2b shows that substituting gas will reduce CO₂ concentrations by ~45% of what could be achieved under the low carbon fast scenario regardless of the leakage rate.
Figure 2. Changes in atmospheric concentration for the fuel consumption scenarios shown in Figure 1 of (a) CH₄ for various leakage rates, and (b) CO₂ for 2% of consumption natural gas methane leakage (except the labeled 1% and 9% leakage curves). Agriculture methane emission increases are added, and the oxidation of emitted methane is one of the (minor) CO₂ emissions. The methane concentration depends on the natural gas leakage from production through distribution (expressed as a percent of consumption on the plot). Substituting gas for the other fuels adds considerable extra methane to the atmosphere but very little extra CO₂ (e.g., the red 9% and 1% methane leakage curves in (b) are almost identical). Gas substitution reduces atmospheric concentration of CO₂ by ~45% of that which could be achieved by the rapid transition to low carbon energy sources.

The greenhouse gas additions shown in Figure 2 increase the net radiation to the earth’s surface as shown in Figure 3a. With 1% leakage, the greenhouse forcing will increase by ~2.8 W m⁻² under the “substitute gas” scenario. This future increase is about the same as the 2.6 W m⁻² increase that occurred between 1750 and today (black curve). After peaking, the forcing declines significantly.

Figure 3b calculates the increase or decrease of warming achieved by substituting gas at each instant of time, expressed as a percent of the change produced by the low carbon fast fuel usage scenario. The instantaneous view is that taken by GWP (global warming potential) analyses that we will discuss below. Figure 3b shows that substituting gas will reduce greenhouse forcing at all times in the transition if natural gas leakage is less than ~4% of consumption. After the transition substituting gas will reduce greenhouse warming by ~45% of what could be achieved in a low carbon fast scenario, no matter how large the leakage.

Figure 4 expands the top portion of Figure 3a and converts the forcing to temperature by multiplying by an equilibrium climate sensitivity factors of 0.8 K m² W⁻¹, the mid-range value of IPCC(2013). Figure 4 shows that the main benefit of substituting gas is the reduction in the peak warming. At low leakages, substituting gas slightly delays warming (e.g., slight shift of the red compared to the blue curve in Fig. 4a). For a leakage of 5% of production (Figure 4b), substituting gas produces no delay in warming but peak warming is still reduced. At 9% leakage, substituting gas produces a slightly earlier warming than in the “business as usual scenario” (difference between blue and red lines between 2011 and 2080 in Figure 4c), and the peak warming is the same. After the transition, the warming is still much less because much less CO₂ has been emitted in the substitute gas fuel use scenario.
Figure 3. (a) Past and future greenhouse forcing by methane and carbon dioxide combined. (b) High methane leakage increases forcing during the transition period and the same warming is attained slightly earlier (negative forcing reductions), but the >40% benefit of gas substitution returns thereafter.

Figure 4. Equilibrium global temperature change obtained by multiplying the post-2011 parts of the radiation forcing in Figure 3a by an equilibrium climate sensitivity factor of 0.8 K m² W⁻¹. (a) At 2% leakage, substituting gas delays warming slightly and reduces peak warming. (b) At 5% leakage the slight delay in warming disappears, but peak warming is still reduced. (c) At 9% leakage warming comes slightly earlier when gas is substituted and the same peak temperatures are reached as in the Business as Usual scenario. However, warming is substantially reduced in later years. Heat exchange with the ocean substantially reduces warming as discussed next.

Figure 4 is not a complete prediction of future climate change. A complete prediction requires models that account for heat exchange with the oceans (which can significantly reduce warming), replicate the temperature changes that have happened in the past due to natural forcings, project these natural forcings into the future, and then add to them the greenhouse impacts of anthropogenic gas emissions. I have devised methods to do all these things, and Figure 5 shows the results. Figure 5 assumes that the natural forcings in 2011 were similar to what they were at the height of the Medieval Warm Period, and then uses global average measured temperatures compiled by NASA from 1880 to 2011 to calibrate the equilibrium climate sensitivity factor. The equilibrium climate sensitivity factor determined in this
fashion is $0.65 \, \text{K m}^2 \, \text{W}^{-1}$, a value slightly less than the IPCC (2013) mid-range value of 0.8 but well within the band of uncertainty (see figure [here](#)). The natural forcing is extrapolated into the future assuming it remains constant or decreases symmetrically with respect to its recent increases. Agricultural emissions of methane and oxidation of all anthropogenic methane emissions to CO$_2$ are included.

Figure 5 shows that over the next 100 years temperatures will rise at about the same rate as over the past 100 years. The rate of temperature increase will then decline. It will decline more if the natural forcing is declining (Fig 8b). The total temperature increase over the next 200 years will be about the same as the temperature increase from 1700 to present. Substituting gas for coal and some oil will be decrease warming by ~42% of that which could be achieved by moving to low carbon fuels immediately. Particularly if the substitute gas scenario is followed the warming will be well be low the 2°C increase considered the threshold of concern. Substituting gas does no short term harm yet achieves very significant long term benefit at leakages rates up to 14% of consumption. I am currently writing up the methods used and will add links to this discussion when it is accepted for publication.

![Figure 5. Predicted future average global temperature increases assuming 2% methane leakage and either (a) constant natural forcing or natural forcing that (b) declines in a symmetric way with its recent increases. The black line indicates the termination of the fossil fuel use. The red dashed line shows warming for the substitute gas scenario with 14% methane leakage. At this extreme leakage rate, the same warming is attained as in the Business as Usual scenario but the warming is attained slightly earlier (slight offset of dashed red and solid blue curves). After 2111 the benefit of substituting gas manifests itself even for the high leakage case (divergence of blue and dashed red curves). The depression of the dashed red curve below the solid red curve results from the methane leakage boundary condition at 2011 (see discussion here).](#)

### Additional Issues

There are other matters that are important that have not received attention in the literature or are just now receiving some attention.

There is the possibility that humans will not completely stop burning fossil fuels in 2111 as assumed in the calculations we have presented so far. Figure 6 shows that if hydrocarbon use continues at the low rate indicated for 2111 in Figure 1, climate forcing by anthropogenic release of carbon dioxide will
produce a slow but steady increase in climate forcing. This “slow bleed” will need to be addressed. If fossil fuel use continues past the transition in Figure 1, carbon dioxide management methods may be needed.

Also, as Schindell et al. (2012) point out, because of methane’s rapid atmospheric response, reducing anthropogenic methane emissions could rapidly reduce greenhouse warming. They suggest anthropogenic reductions of $140 \text{Tg}_\text{CH}_4 \text{yr}^{-1}$ might be possible and that this, together with other measures (ozone and carbon black) could lower equilibrium temperatures by $\sim 0.5^\circ$C. Figure 7 shows that reducing only the rate of anthropogenic methane emission by $110 \text{Tg}_\text{CH}_4 \text{yr}^{-1}$ would decrease atmospheric methane concentrations by $\sim 300$ ppbv and equilibrium global warming by $\sim 0.2^\circ$C. Thus, not only can substituting gas reduce warming by 40% of that possible by immediately replacing fossil with zero carbon fuels, but reducing methane emissions from fossil fuel production and agricultural practices could reduce global warming. Methane represents a double opportunity to reduce greenhouse risk.

Figure 6. Predicted greenhouse gas forcing for 2% methane leakage. Dashed curves indicate forcings of the three scenarios if fossil fuel use is terminated at 2111 (as assumed in the previous calculations presented). Solid curves indicate the forcing if fossil fuel consumption continues at the rate in 2111 AD.
Figure 7. Methane is emitted in fossil fuel production and agriculture. The solid curves show (a) the changes in atmospheric methane for the three scenarios in Figure 1 and (b) the equilibrium greenhouse warming by methane and CO\textsubscript{2}. The dashed curves show the atmospheric methane concentration and warming if there are no agricultural emissions. Since agricultural emission rates increase by 110 Tg CH\textsubscript{4} yr\textsuperscript{-1} from 2011 and 2111 as the population grows to 10.5 billion and are then steady, eliminating this contribution shows the impacts of a gradual reduction in methane emission rate of 110 Tg CH\textsubscript{4} yr\textsuperscript{-1}.

Approximate Excel Spreadsheet Analysis
Confidence in the results presented in Figure 2-4, 6 and 7 is provided by the ability to substantially replicate them with very simple approximate spreadsheet calculations. The simple spreadsheet analysis also provides insight. Changes in atmospheric methane concentration can be estimated by assuming that methane is in equilibrium with anthropogenic fossil fuel and agricultural emission rates as discussed here. Carbon dioxide concentrations can be estimated by assuming 55% of the emitted CO\textsubscript{2} is retained in the atmosphere. Changes in greenhouse gas concentrations based on these approximations predict greenhouse forcings very similar to those computed above, and this simple confirmation promotes confidence and provides insight.

Figure 8a compares spreadsheet predictions of future atmospheric methane concentrations to those computed by convolution methods in the previous section. The fuel scenarios in Figure 1 are used. The approximate spreadsheet curves (solid lines) start at the equilibrium concentration of 74.4 ppbv and increase faster and decline slower than the convolution curves (dashed), and of course the spreadsheet curves are much more peaked because they are not smeared out by the gradual removal of methane. Figure 8a includes methane emissions from agriculture (rice cultivation, animal husbandry, etc.), which we assume increases in proportion to the growth of the human population as described here. Figure 8b does not include agricultural emissions.
Figure 8. Prediction of methane concentration based on the rate of anthropogenic CH4 emissions from the three fuel use scenarios illustrated in Figure 1 (blue= “business as usual”, red= “substitute gas”, green= “low carbon fast”). The dashed curves show the accurate convolution predictions, and the solid curves show the approximate spreadsheet predictions. In (a) agricultural emission are included, in (b) agricultural emissions are not included.

Figure 9a compares spreadsheet predictions of atmospheric CO2 concentrations made assuming that 55% of all emitted CO2 remains in the atmosphere to the convolution calculations described in the previous section. Figure 9b compares the forcings from the CO2 and CH4 spreadsheet concentrations to the combined forcing calculated in the previous section. The spreadsheet and convolution forcings are very similar.

Figure 9. (a) Comparison of convolution predictions of future atmospheric methane concentrations (dashed with methane oxidation, dotted without) to spreadsheet estimations (solid) of them made by assuming 55% of anthropogenic CO2 emissions remain in the atmosphere. As in previous figures blue= “business as usual”, red= “substitute gas”, and green= “low carbon fast”. (b) Forcing from combined atmospheric CO2 (Figure 6a) and CH4 (Figure 5b).
Figures 8 and 9 show that future climate forcing can be quite easily estimated using the rate of CH$_4$ emission and assuming that 55% of emitted CO$_2$ is retained in the atmosphere. The spreadsheet is provided and discussed here. More can be learned by changing control variables yourself. The calculations are not difficult to make using this spreadsheet.

Why simplified metrics have confused the discussion

There is considerable confusion on these issues, largely because simplifying metrics have been introduced to help policy makers. Rather than simplify, however, these metrics have unfortunately confused the discussion. The main reason for this is that the metrics are myopic— they do not provide the context of the numbers they calculate. Because of this they have supported a nearly endless discussion of how the leakage of methane, the more powerful greenhouse gas, could increase warming over short periods, although admittedly not over long periods, and allowed attention to be inappropriately focused on cross-over and tipping points.

The global warming potential metric of methane, GWP$_{CH_4}$, is the average greenhouse forcing, over some time interval, of a mass of methane compared to an equal mass of CO$_2$ introduced at the same time into the atmosphere. GWP$_{CH_4}$ takes into account both the intrinsic greenhouse strength of the methane and CO$_2$ and their rate of removal from the atmosphere. For example, at the moment of release, a kilogram of CH$_4$ would have 120 times the greenhouse impact of a kilogram of released CO$_2$, but over 20 years period it will have an impact 84 times that of CO$_2$, and over 100 years an impact 28 times CO$_2$. The drop in impact as the time interval increases is due to methane’s more rapid removal from the atmosphere that CO$_2$ (see discussion here).

GWP methods are useful because they are simple and can quickly screen many factors. The electrical conversion efficiency of coal and gas plants, the rate of methane leakage associated with coal and gas extraction, and the time interval over which emissions have taken place are the parameters which all agree control greenhouse warming. GWP$_{CH_4}$ can be used to convert CH$_4$ emissions to equivalent CO$_2$ emissions so that the impact of alternative fuel uses can be assessed. For example, GWP methods can be used to calculate the gas leakage at which substituting gas for coal will no longer reduce greenhouse warming. At some leakage natural gas will produce more greenhouse warming than coal for the same amount of electricity delivered over some interval of time. Howarth et al. (2011) determined this crossover in their famous paper that asserted that the greenhouse impact of natural gas could be twice as bad as coal if the gas leakage exceeds 7.9% of consumption. We have implemented the methods of Howarth et al. (2011) in the excel spreadsheet provided here, and use the spreadsheet to analyze the benefits for swapping gas for coal in electricity generation (the only major use of coal) below.

Table 1 and Figure 10 show that if electricity is generated with equal efficiency by coal and gas (e.g., the fuels are compared on the basis of their heat content as done by Howarth et al., 2011 as they are when both have 60% conversion efficiency in Table 1), the crossover leakage is 2.7% for a 20 year period. Using the spreadsheet one can find that gas is twice as bad as coal if the leakage is 8.3%. Howarth et al.’s “twice as bad” leakage of 7.9% results from the slightly different (than IPCC, 2013) parameter values they use. The electrical generation efficiencies of natural gas and coal are not equal because gas can
drive a turbine, and then a boiler with the left over heat. Coal generation efficiencies can reach ~43.3% with ultra-supercritical pulverized coal technology, but carbon capture would reduce this efficiency to ~34% (MIT, The Future of Coal, 2007). For a coal electricity generation efficiency of 30%, the 20 year crossover is 8.3%.

Table 1. The crossover natural gas leakage at which substituting gas for coal in electricity generation has no greenhouse benefit. Parameters are as specified in IPCC(2013) and discussed here. Table is plotted in Figure 7.

<table>
<thead>
<tr>
<th>Coal Conversion Eff.</th>
<th>Crossover leakage (Lcoal m³/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 yr</td>
</tr>
<tr>
<td>60% 60%</td>
<td>2.1%</td>
</tr>
<tr>
<td>50% 60%</td>
<td>3.0%</td>
</tr>
<tr>
<td>40% 60%</td>
<td>4.3%</td>
</tr>
<tr>
<td>30% 60%</td>
<td>6.3%</td>
</tr>
</tbody>
</table>

Figure 10. Leakage rate (crossover) at which generating electricity with gas rather than oil has no greenhouse benefit. Numbers plotted are shown in Table 1.

The GWP assessment in Figure 10 is compatible with the calculations we have presented above. For the 32% conversion efficiency we considered in the calculations presented in the previous two sections, Figure 10 suggests that substituting gas for coal will have benefit for all time intervals provided the leakage is less than ~5.2%, which is what we found above in Figure 3. Figure 10 also shows that the benefit of substituting gas increases with the time interval considered, in the sense that the crossover leakage increases with time.

GWP-based Figure 10 does not, however, communicate that regardless of leakage substituting gas will reduce warming by 45% reduction in the long term (Figure 3b). The GWP method is impoverished
because it does not include agricultural emissions or the way in gas is substituted over time. But the biggest deficiency in GWP calculations is that they are myopic— they do not communicate the broader context.

The metrics show that over a particular interval of time substituting gas will lead to higher temperatures. This is correct, and is captured in Figure 3b and 5b above. What the simplified metrics miss is what is shown so clearly in Figure 4 and 5b: that the same warming will occur just a few years earlier or later. For leakages below 9% (Figure 4c) or 14% (Figure 5b), substituting gas simply produces warming ~5 years sooner, and this shift is not important. What difference does it make if the same global temperature is reached a few years earlier or later? If methane leakage exceeds 9% of production, a leakage larger than anyone has suggested, the peak warming would be greater (and this could be of importance), but the peak warming is temporary and in the longer term the benefit of emitting less CO₂ because of substituting gas returns (divergence of blue and red curves after ~2111 in Fig. 4c and 5b). Figure 3a, 4 and 5 make it clear that what counts is the reduction in peak warming that can be achieved by substituting gas. When the broader context is considered it is clear that the extensive literature discussion of GWP cross-over and tipping points represent distractions from discussion of the issues that are actually important.

References


MIT (2007), The Future of Coal, an interdisciplinary MIT study, Massachusetts Institute of Technology, Boston, 175p.