Exploring the Impacts of Electricity Generation Composition on the Future Climate

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Abstract

Many studies have talked about natural gas "bridging" as a path to a more sustainable future. Increased interest in the use of natural gas as a "transition" fuel over the last decade or so has spurred many studies into the leak rate of natural gas when used as a source of electricity. This study aims to answer questions about the usefulness of natural gas "bridging" on varying time scales; namely, would a natural gas "bridge" really lead to a lower overall peak temperature? Would it lead to reduced rates of warming? And would it lead to lower long-term temperatures? Societal and economics questions are also discussed such as whether building these natural gas "transition" plants could backfire, slowing down the transition to renewables (e.g. because of business pressures to recoup plant costs)? With the aim of answering these questions, a simplified atmospheric climate model was created using the Absolute Global Temperature Potential metric along with equations for life cycle emissions of coal and natural gas plants. Approximate carbon emissions and global temperature changes were simulated from IGSM future electricity production estimates as well as scenarios based upon projections of fully renewable years with the purpose of better comparing the impacts of short-lived climate pollutants with those that have longer lifetimes. Results show that assessing the use of natural gas bridging is very dependent on the metric chosen to minimize: peak temperature, rate of temperature change or long-term temperature. A transition to natural gas with a moderate-high leak rate ($>6\%$) would likely lead to increased rates of warming in the short-term, no matter the rate of change to renewable energy. The time period considered (rate of changeover to renewables) is critical to the analysis with lower leak rates. While the benefits of natural gas bridging at lower leak rates appear minimal with conversion to renewables in this century, this is not true at longer time periods. At slower rates of changeover to renewables, a conversion rate from coal to natural gas of 4.38% per year would lead to slower rates of warming and a lower peak temperature if the leak rates were below about 6%, but still a comparable peak temperature if leak rates were around 9%.

1 Introduction

It is well documented that anthropogenic greenhouse gas (GHG) emissions are having, and will continue to have, an effect on global temperatures for years to come. While this is known, the complexity of the atmosphere and oceans make it difficult to determine exactly how the global temperatures would respond to various forcings. Over the past few decades, large advancements have been made in creating simple numerical equations to model the interaction of greenhouse gases with the atmosphere and oceans. The aim of these models is to discover how the future atmosphere might look and to investigate how we can limit global temperature changes by altering the makeup of our electricity generation.

Displacing coal with natural gas as the main source for electricity generation has been widely debated, particularly in the last decade. This concept of natural gas as a "transition fuel" has several potential benefits with the most discussed one being the reduction of carbon emissions. While the magnitude of the impact of natural gas bridging on GHG emissions is widely debated, it has been presented as a strategy to reduce temperature changes (Hausfather, 2016; Howarth, 2015; Sanchez and Mays, 2015; Zhang et al., 2014). Comparing natural gas and coal is complicated due to the many steps each fuel source goes through from ground extraction to the interactions with the atmosphere. Some considerations are that natural gas is just over twice as energy dense as coal by mass and methane is 28-36 times more potent a GHG than carbon dioxide on 100-year time scales. (“Understanding Global Warming Potentials.”, 2017).

The first order implications of using a more energy dense fuel are pretty straight forward. Higher energy density means less mass can be used to produce the same amount of electricity and also therefore lower carbon emissions. However, an important characteristic of natural gas is that it is primarily composed of methane (>80%) which presents the important issue of leakage and brings in the consideration of radiative forcings. There is much dispute over leakage rates of natural gas and they are still badly constrained due to the cost of measurement, access to "average" sites, and complicating factors such as natural methane emissions. To complicate things further, emissions vary substantially both regional and temporarily and with the increasing trend of methane from shale deposits, it is likely that future estimations might be higher (Howarth, 2015; Schneising et al., 2014). Over the last decade, estimates of leak rate have varied from 0.4 to 10.1%, but the majority put the rate between 2 and 6% (Sanchez and Mays, 2015). However, more recent satellite derived studies put the estimate of average upstream emissions at 9.5% and Howarth, 2015 adds in average emissions during storage and delivery of 2.5% to get an overal leak rate of 12% (Brandt et al., 2014; Howarth et al., 2011; Howarth, 2015; Schneising et al., 2014). Because of this uncertainty, a range of leakage rates from 0 to 12 % are shown in this study.

To add further complication to comparing natural gas and methane, carbon dioxide and methane impact global temperatures on very different time scales. Methane disappears after about 9-12 years oxidizing to water and carbon dioxide while carbon dioxide hangs around for hundreds if not thousands of years (Joos et al., 1996; Sarmiento et al., 1992). The short lifetime of methane means that under constant emissions its atmospheric concentration remains constant. This doesn’t hold true for carbon dioxide due to the lengthy time it persists in the atmosphere.

As the more developed world begins its slow movement away from coal and towards renewable energies, it is timely that the climate impacts of a natural gas bridge are further explored. Many simplistic studies have been carried out looking only at radiative forcing (Hausfather, 2015), only at natural gas leak rate (Howarth, 2015) and only at carbon dioxide equivalent emissions (Brandt et al., 2014; Sanchez and Mays, 2015). Most of these conclude that natural gas bridging could be a useful tool especially at longer time ranges. The leak rate at which natural gas is not beneficial is around 4-5% at a 20-year time period or 9-10% at a 100-year time period. However, these studies look at the comparison from narrow points of view and because of the many complications explained above, a simple analysis is likely to leave out significant variables. The approach taken in this study is to combine the models and data from previous studies into a comprehensive yet simple model. The purpose of this paper is to supplement the "natural gas bridging" discussion with the presentation of scenarios with varying time scales for conversion to renewable energy and a range of leak rates.

2 Methods

A model is created in this study to convert electricity production estimates to global temperature changes. It is then combined with modeled data of electricity generation composition scenarios that take into account a variety of socioeconomic, technological and earth system response determinants such as the spatial distribution of energy generation and population predictors. Lastly, various scenarios for electricity generation leading to an all-renewable future are created and run through the model with the goal of elucidating the impact of natural gas bridging on the rate of warming and the peak temperature.

2.1 GHG Emissions to Global Temperature Change

The first portion of the work was to create a model that could convert from GHG emissions to global temperature changes. Shine et al. (2005) introduced a metric which they named Absolute Global Temperature Potential (AGTP) as an alternative for Absolute Global Warming Potential (AGWP) and a simple way to calculate temperature changes from GHG emissions.

The AGTP equations used from Shine et al. are for pulse emissions and are integrated over the time period of interest to get the temperature change from time zero to that time. The pulse emissions (signified by the subscript p) were used because they allow for calculations of temperature changes once emissions are eliminated as well as during the emissions period. The units for AGTP are $\frac{\Delta K}{kg\ of\ gas\ emitted}$.

The AGTP equations below were all derived from a simple model of the global-mean surface temperature change, ΔT (K), due to a global-mean radiative forcing, ΔF (W m^{-2}) (Hartmann, 1996). The model used is:

$$C\frac{d\Delta T(t)}{dt} = \Delta F(t) - \frac{\Delta T(t)}{\lambda},$$

and the general solution is:

$$\Delta T(t) = \frac{1}{C}\int_0^t \Delta F(t')exp(\frac{t'}{\lambda C})dt'.$$

where C is the heat capacity ($4.2 \times 10^8\ J\ K^{-1}\ m^{-2}$), t is time (seconds), and λ is the climate sensitivity parameter ($0.8\ K\ W^{-1}\ m^2$) which is the change in surface temperature per unit forcing.

Using the simple forcing model shown above, the AGTP for methane and carbon dioxide were derived. Methane is presented first, followed by that of carbon dioxide:

> For methane (and the majority of GHGs), the radiative forcing following an emission at $t = 0$ has the form $Aexp(-\frac{t}{\alpha})$ where α is the time constant for removal of the gas from the atmosphere and A is the radiative forcing for a 1-kg change in concentration of that gas. (Shine et al., 2005). The AGTP for natural gas can then be presented as:
>
> $$AGTP_P^{CH_4}(t) = \frac{A_{CH_4}}{C(\tau^{-1} - \alpha_{CH_4}^{-1})}[exp(\frac{-t}{\alpha_{CH_4}}) - exp(\frac{-t}{\tau})],$$
>
> when $\tau \neq \alpha_{CH_4}.When\,\tau = \alpha_{CH_4}$,
>
> $$AGTP_P^{CH_4}(t) = \frac{A_{CH_4}t}{C}exp(\frac{-t}{\alpha_{CH_4}}),$$
>
> where A_{CH_4} is $1.3 \times 10^{-13}\ W\ sec\ kg^{-1}\ year^{-1}$, α_{CH_4} is 12 years, τ is time constant of the climate system (10.7 years).
>
> For carbon dioxide, the concentration response (R) is more complicated and does not follow the simple exponential decay form. Again, Shine et al. gives an equation derived from carbon cycle models.
>
> $$R(t) = b_o + \sum_{i=1,4} b_i exp(\frac{-t}{b_i}),$$
>
> $$b_{0-4} = \{0.1756, 0.1375, 0.1858, 0.2423, 0.2589\}$$
>
> The four term equation derived in the Bern carbon cycle model is used (Joos et al., 1996). In the end, the equation for temperature change from carbon dioxide is
>
> $$AGTP_P^{CO_2}(t) = \frac{A_{CO_2}}{C}\{\tau b_o[1 - exp(\frac{-t}{\tau})] + \sum_{i=1,4}\frac{b_i}{\tau^{-1} - \alpha_i^{-1}}[exp(\frac{-t}{b_i}) - exp(\frac{-t}{\tau})]\},$$
>
> $$\alpha_{1-4} = \{421.093, 70.5965, 21.4216, 3.4154\ (in\ years)\}$$
>
> where A_{CO_2} is the radiative forcing for a 1-kg of carbon dioxide ($1.98 \times 10^{-15} W\ sec\ kg^{-1}\ year^{-1}$)

In terms of interpretation, the AGTP metrics derived by Shine et al. were chosen because they give a better understanding of the climate impacts than AGWP. The chain below from the same paper shows the different steps between emissions and human impacts.

emission changes → concentration changes → radiative forcing → climate impacts
→ societal and ecosystem impacts → economic "damage"

AGWP lies in the area of radiative forcing while AGTP lies in climate impacts. Due to the movement down the chain, AGTP is more relevant and Shine et al. shows that it is "robust" to climate uncertainties. AGTP was chosen over GTP because the absolute version shows temperature changes and is not relative to carbon dioxide as in the regular version (Forster et al., 2007).

2.2 Electricity Production to GHG Emissions

In order to understand the temperature impact of different electricity generation makeups and amounts, the life cycle emissions from electricity generation have to be calculated. This was done using equations from Zhang et al. (2014). The equations used are as follows:

For natural gas power plants:

annual CO2 emission is -

$$E_{ng.CO2} = [\frac{molpct_{C/ng} - R_{leak} \times molpct_{CH4/Ng}}{1 - R_{leak}}] \times [\frac{Molmass_{CO2}}{Molmass_{Ng}}] \times [\frac{Electr_{ng}}{HV_{ng} \times \eta_{ng}}]$$

annual CH4 emission is –

$$E_{ng.CH4} = [\frac{R_{leak} \times molpct_{CH4/Ng}}{1 - R_{leak}}] \times [\frac{Molmass_{CH4}}{Molmass_{Ng}}] \times [\frac{Electr_{ng}}{HV_{ng} \times \eta_{ng}}]$$

For coal power plants:

annual CO2 emission is –

$$E_{coal.CO2} = masspct_{C/coal} \times [\frac{Molmass_{CO2}}{Molmass_{C}}] \times [\frac{Electr_{coal}}{HV_{coal} \times \eta_{coal}}]$$

annual CH4 emission is -

$$E_{coal.CH4} = rate_{CH4/CO2 \cdot Coal} \times E_{coal.CO2}$$

where $molpct_{C/ng}$ is molar carbon per molar natural gas (1.044), $masspct_{C/coal}$ is the mass percent of carbon in coal (.514), $molpct_{CH4/Ng}$ is the molar fraction of methane in natural gas (0.944), $Molmass_{CO2}$ is the molar mass of CO2, $Molmass_{CH4}$ is the molar mass of CH4,

$Molmass_C$ is the molar mass of carbon, $Molmass_{Ng}$ is the molar mass of natural gas, $Electr_{coal}$ and $Electr_{ng}$ are the electricity productions from coal and natural gas, HV_{coal} (2.3e-11 EJ/kg) and $HV_{ng}(4.8222e - 11EJ/kg)$ are the heating values of coal and natural gas, η_{coal} and η_{ng} are the the efficiencies of coal and natural gas power plants, R_{leak} is the natural gas leak rate, and $rate_{CH4/CO2 \cdot Coal}$ is the ratio of CH4 emissions to CO2 emissions from coal mining.

The equations from Zhang et al. were used because they include the emissions from natural gas and coal power plants from extraction to combustion for electricity generation. In terms of natural gas use this includes: upstream leakage (CH_4), venting (CO_2), leaking during transportation and distribution (CH_4 and CO_2) and combustion (CO_2). It is also assumed that all non-CH_4 components of natural gas are instantly oxidized to CO_2 upon release. In terms of coal use emissions included are: leakage from mining (CH_4), minor emissions from storage (CH_4) and combustion (CO_2). Finally, the typical power plant efficiencies (coal: 34.3%, Natural gas: 40.3%) were assumed.

2.3 Future Electricity Production data and Reference ("Do Nothing") Scenario

Once the model was created, electricity generation composition data was obtained to run through the model and act as a reference scenario. The data from the reference scenario of Integrated Global Systems Model (IGSM) of the Massachusetts Institute of Technology's Joint Program on the Science and Policy of Global Change was chosen to be used in this study. These estimates were created using integrated assessment models based upon socioeconomic and technological determinants and are projections of future electricity use through 2100 broken down by the electricity source. The actual data was taken from the "Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations" report produced by the U.S. Climate Change Science Program (CCSP) in 2007 (Clarke et al., 2007).

The IGSM model is organized into two components: an Earth system and a human system. The Earth system is made up of a coupled atmosphere, ocean, and land model along with urban air pollution processes. The human model contains national and regional economic development projections, emissions projections (based upon population growth and organization), and land use projections. The fluxes of many common gases are exchanged between the models as well as trace gases and policy constraints (Sokolov et al., 2005).

The reference scenario was used because it represented the "business as usual" production. It was generated under the assumptions that no other climate policy was implemented beyond the commitments at the time the report was written. The two agreements at that time were the first period of the Kyoto Protocol (2008-2012) and the United States' goal to reduce emissions per unit of its gross domestic product by 18% by 2012 (Clarke et al., 2007).

The ISGM reference data gives a breakdown of sources for electricity generation but to simplify the analysis, sources are grouped into three fuel types: coal, natural gas (Ng) and non-biomass renewable energy (RE). Oil is not independently analyzed but instead electricity produced from oil was proportioned out to coal and natural gas in the ratio that these two sources were present in each year.

The main focus of the study is observing the climate impact trade offs of natural gas and coal at varying time periods. Consequentially, certain details of electricity production were not included. First, commercial biomass is ignored in this analysis as it was used to generate less than 1.2% of electricity in the world in 2016 ("Biomass to Power:, 2016; "Key World Energy Statistics", 2015). Second, renewable energy is taken as producing no emissions. While a lifecycle analysis shows that renewable energy sources do produce GHGs, the contribution is much lower (by at least an order of magnitude) than that of fossil fuels (Amponsah, Nana Yaw, et al., 2014; Heath, 2013; Lenzen, 2008).

Once the IGSM reference data was run through the created model, total carbon (carbon from both methane and carbon dioxide emissions) and temperatures changes were simulated. In order to look at the upper and lower bounds, two extreme scenarios were also run through the model. These were created by assuming that the electricity (other than the renewable portion) was from either all coal or all natural gas.

2.4 Reduction Scenario Creation (All-renewable Scenarios)

One of the main purposes for the creation of this simplified model was to compare possible GHG reduction scenarios, particularly to assess the usefulness of methane bridging compared to other pathways to a renewable future. In order to carry out this analysis, specific fossil fuel reduction scenarios needed to be formulated and run through the model explained above.

The electricity demand projections from the IGSM reference scenario in Clarke et al. (discussed above) were used as a starting point for the creation of these all-renewable scenarios. Using the reference scenarios as a base allows the reduction in fossil fuels to be built upon what is projected to occur based upon model detailed assumptions.

2.4.1 Electricity Composition Scenarios

Once the source of "business as usual" electricity demand had been established, reduction scenarios are specified. It was decided to use four reduction scenarios summarized in table 1. These cover a range of possibilities and the purpose of these scenarios is to compare the impact of reducing certain electricity sources and the order in which they are reduced.

Table 1: Summary of Electricity Composition Scenarios

Label	Title	Visual
Coal-and-Ng	Coal to RE and Ng to RE	1. Coal ————————> RE Ng ————————> RE
Coal-first	Coal to RE then Ng to RE	2. Coal ———> RE Ng ———> RE
Ng-first	Ng to RE then Coal to RE	3. Ng ———> RE Coal ———> RE
Ng-bridge	Coal to Ng and Coal to RE then Ng to RE	4. Coal ———> Ng Coal ———> RE Ng ———> RE

The electricity composition scenarios were created in order to produce a range of time scales for which coal and natural gas are eliminated from electricity generation. The Ng-bridge electricity composition scenario is the same as the Coal-first scenario except for the inclusion of the natural gas bridge and therefore these two scenarios are directly comparable to assess the usefulness of the bridge.

For the Ng-bridge scenario, the conversion rate from coal to natural gas that is used is 4.38% per year which is the past 10 year average reduction in coal in the United States. The past 10 year average increase in natural gas is 5.71% per year, leading to the conclusion that coal reduction is the limiting factor for the natural gas bridge ("Electric Power Annual", 2018). This scenario assumes that it would be possible for the world to convert coal to natural gas at that same rate.

The conversion of coal to natural gas in the Ng-bridge scenario is in addition to the coal to renewable energy and does not replace any conversion to renewables. This approach was chosen because the infrastructure costs of renewable energy and its intermittent nature are considered the limiting factors in the conversion to renewable energy, not the decrease in coal (Hausfather, 2016; Kariuki, 2018; Luthra et al., 2015). Additionally, technology exists to convert the source of energy in power plants from coal to natural gas and often it is cheaper to convert a coal plant to natural gas than to continue to operate the coal plant.

2.4.2 Fossil Fuel Reduction Timelines

The all-renewable scenarios were run with four different all-renewable goal years. These all-renewable goal years are the years in which global electricity generation would be from only renewable sources. It was chosen to run the scenarios in 40 year increments, meaning that the goal years were 2060, 2100, 2040 and 2018 (shown in Table 2). These produced two quick reduction scenarios (within the century) and two extended scenarios. The reason for this distinction is that the modeled reference electricity production ends in 2100; therefore, the longer scenarios assume electricity production is constant after 2100. This is a reasonable assumption because the latest estimates put the carrying capacity of the Earth around 9-11 billion and as the population reaches that threshold electricity demand should level out with population (Taagepera, 2014).

Table 2: Summary of Fossil Fuel Reduction Timelines

Goal Year	Visual
2060	2020 ⟼ 2060
2100	2020 ⟼ 2100
2140	2020 ⟼ 2140
2180	2020 ⟼ 2180

2.4.3 Electricity Conversion

In this study for a given reduction timeline (discussed in Fossil Fuel Reduction Timelines), each electricity composition scenario has the same rate of change over to renewable energy ($\Delta RE/year$). A constant change over to renewable energy was used so that the different source scenarios could be compared and the only difference at each year was the composition of electricity generation from non-renewables.

Additionally, the rates of change over to renewable energy are set by the goal years for all-renewables. This approach was used rather than attempting to guess the potential rates for switching between energy sources (eg. coal to RE). These potential rates are not well constrained due to the complex and every changing technological and economic factors involved in determining them (Kariuki, 2018). As discussed above in the "Electricity Composition Scenarios" section, the rate of conversion from coal to natural gas in the Ng-bridge scenario is 4.38% per year.

All of the electricity composition scenarios except for the Coal-and-Ng scenario are sequential and not simultaneous to begin (see Table 1). This means that the reduction of the second source begins once the first source is depleted to the point where there is left over electricity to be converted to renewable energy. Looking at the electricity breakdown for 2060, Figure 9a shows the simultaneous Coal-and-Ng scenario (coal and natural gas are reduced at the same time) and Figure 9b/9c show sequential scenarios where one fossil fuel is reduced first.

While not visible on the electricity breakdown figures, there is an added complication due to electricity production increasing through 2100. Sticking with Figure 9b (Coal-first), in order to keep electricity from coal at 0 EJ, increases in electricity production that would normally be taken over by coal need to be reduced.

Maintaining the elimination of the electricity source that is to be reduced first (in this case coal) is always prioritized, and any remaining reduction then goes to the second source to be reduced (in this case natural gas). Any increases in electricity production from coal are immediately changed to renewable energy and that amount is taken out of the possible conversion of natural gas to renewable energy in that year. This "maintenance" amount is unavoidable because you cannot reduce electricity increases until they occur and it represents the fact that some of the conversion to renewable energy each year goes to covering energy increases.

2.4.4 Summary Table of the All-Renewable Scenarios

Table 3: Summary of all-renewable scenarios along with labels to refer to each scenario

Source Timelines	Electrcity Source Scenarios	Label
2060	Coal to RE and Ng to RE	2060 Coal-and-Ng
	Coal to RE then Ng to RE	2060 Coal-first
	Ng to RE then Coal to RE	2060 Ng-first
	Coal to Ng and Coal to RE then Ng to RE	2060 Ng-bridge
2100	Coal to RE and Ng to RE	2100 Coal-and-Ng
	Coal to RE then Ng to RE	2100 Coal-first
	Ng to RE then Coal to RE	2100 Ng-first
	Coal to Ng and Coal to RE then Ng to RE	2100 Ng-bridge
2140	Coal to RE and Ng to RE	2140 Coal-and-Ng
	Coal to RE then Ng to RE	2140 Coal-first
	Ng to RE then Coal to RE	2140 Ng-first
	Coal to Ng and Coal to RE then Ng to RE	2140 Ng-bridge
2180	Coal to RE and Ng to RE	2180 Coal-and-Ng
	Coal to RE then Ng to RE	2180 Coal-first
	Ng to RE then Coal to RE	2180 Ng-first
	Coal to Ng and Coal to RE then Ng to RE	2180 Ng-bridge

3 Results & Discussion

Through combining an emissions model and a global temperature model, a comprehensive yet simple atmospheric chemical model spanning from electricity production to temperature changes was created. Because a new model was created, it was necessary to begin by making sure it produced reasonable temperatures from electricity production values. The performance was compared to that of a simple model used in Zhang et al., 2014.

3.1 1 GW Case

The global temperature changes from 1 GW of continuous electricity production (8,760 GWh) for 40 years matched well with the ones presented in Zhang et al., 2014 despite the use of different GHG to global temperature models (Figures 1-3). A comparable peak temperature change for the 9% leak rate case was observed. The one significant difference between the models is the thermal inertia. The model used in this study appears to respond on a faster timescale with slightly quicker temperature increases and decreases due to radiative forcings from methane. These differences are probably down to internal model dynamics and how heat capacity is represented.

By looking at the breakdown of temperature changes resulting from carbon dioxide and methane in the 1GW case produced using coal (Figure 1) and natural gas (Figure 2), it can be seen that the temperature changes from carbon dioxide in the natural gas case is less than that from carbon dioxide in the coal case. However, when taking into account the natural gas leak rate, the total temperature change from natural gas can be temporally much larger that that from coal.

Taking a step back and comparing the total temperature change in the two cases (Figure 3), the full impact of the leak rate in the short-term can be seen. This confirms recent results (Hausfather, 2015; Sanchez and Mays, 2015) which show that in the short-term, the benefits of natural gas over coal disappear if the leakage rate is higher than about 4 percent given current coal and natural gas power plants. Furthermore, the importance of time scales is evident with the lifetimes of methane and carbon dioxide shown quite well by the much steeper drop in temperature for the natural gas case once the electricity generation period ends.

3.2 IGSM Reference Scenario

Moving onto the IGSM reference scenario, on which the all-renewable scenarios are based, the electricity composition is shown in Figure 4. The first 100 years is shown, and as mentioned above, electricity production is assumed constant after this. It can be seen that IGSM assumes that coal will continue to be the dominant fuel globally for the foreseeable future with natural gas taking up most of the rest of the electricity production increases. The general trend is correct with natural gas increasingly taking up electricity production from coal. However as this reference scenario was produced in 2007, it under predicted the increase in renewable energy over the last decade.

Looking at the integrated total carbon for the IGSM reference scenario shown in Figure 5 (100 years) and Figure 7 (300 years), the dominance of coal and increased use of natural gas can be seen. The majority of carbon emission would come from carbon dioxide released from coal use; however, there is an increasing proportion of carbon dioxide emissions that are released from natural gas. Additionally, as this is a reference scenario and the proportion of electricity produced from renewable energy remains small, total carbon emissions continue to rise rapidly.

The global temperature changes for 100 years resulting from the electricity production given by the IGSM reference scenario can be seen on Figure 6. The three scenarios explained above are presented here: IGSM mix (blue lines), all coal (black line), all natural gas (orange lines). Figure 6 exemplifies the well known idea that reducing leakage rates always reduces the temperature changes. This is shown in the figure because in each scenario the temperatures from varying leak rates diverge in the beginning and never converge.

Additionally, Figure 6 shows that for the first century converting to natural gas will likely leak to larger temperature changes if the leak rate is medium-high. This is similar to Figure 3 but instead of the "break-even" leak rate being about 4% it is about 6%. This is likely due to the much higher electricity production and the amount of carbon dioxide building up in the atmosphere.

If we look at the all natural gas scenarios on a longer timeline (Figure 8), we can see the higher temperatures at first, but a switch-over that is highly dependent on the leak rate. This is due to the short lifespan of methane. As the leak rate decreases, the methane never reaches as high a concentration in the atmosphere, leading to natural gas being better off earlier on. After 100 years when the electricity production is kept constant, the importance of the short lifetime of methane becomes evident through the lower rate of temperature change compared to that of the all coal scenario.

The all coal (black line) and all natural gas (orange lines) scenarios effectively act as limits in temperature change given no reduction over the next 300 years and constant electricity after 2100.

3.3 All-renewable Scenarios

Taking the analysis one step further and incorporating the fact that the world is trending towards more renewable energy sources, all-renewable scenarios are presented. Electricity composition is shown in Figures 9-12 and integrated total carbon in Figures 13-16. It can been seen that the scenarios cover the whole range from minimizing natural gas (Ng-first) to increasing natural gas to minimize coal (Ng-bridge).

The resulting temperature changes from the all-renewable scenarios are presented on different time scales (Figure 17). Three metrics are used to compared the scenarios: peak temperature, rate of temperature change and 300 year temperature (representing long-term temperature).

Figure 17 shows that as expected the importance of the natural gas leak rate increases as more natural gas is incorporated into the electricity generation mix and for a longer period of time. This can be seen in the much larger range of possible temperature changes (leaks rates 0 to 12 %) in the Ng-bridge scenario versus the Ng-first scenario. Looking at the carbon emissions for the two scenarios (parts c and d for Figures 13-16), the difference in carbon from methane can be seen with the Ng-bridge scenario containing a much larger amount. While the carbon from methane is a small proportion of the total carbon emitted, the disproportionate importance of the leakage rate on temperatures can be explained by the "potency" of methane as a GHG in comparison to carbon dioxide.

The Ng-first and Coal-and-Ng scenarios contain less natural gas than the Coal-first and Ng-bridge scenarios (parts a and c for Figures 9-12). This means that the temperature changes for the former scenarios are less dependent on leakage rate throughout all of the times periods considered. Additionally, the less natural gas present translates to more electricity generated from coal and because natural gas produces about 60% less carbon emissions than coal (Hausfather, 2015), more carbon emissions result when the electricity is produced from coal instead (parts a and c for Figures 13-16).

The lowest possible temperature changes (0% leak rate) for these scenarios are higher than those in all the other two scenarios. Consequentially, the Ng-first and Coal-and-Ng scenario are definitely worse off at low leak rates, but potentially preferable at moderate to higher leak rates. This "cutoff" leak rate at which these two scenarios lead to lower peak temperatures and lower rates of temperature changes increases as the change over to renewables slows. This progression can be seen clearly in Figure 17 as these two scenarios shift up in the temperature envelope of the other two. Finally, the higher electricity from coal in the Ng-first and Coal-and-Ng scenarios produce greater temperature changes in the long-term (Figure 17, Tables 4-7 part d).

It is important to note, one reason that the Coal-and-Ng scenario might not appear as favorable is that is assumes that the two reductions are not independent and reducing one leaves less conversion for the other. This is an artifact of keeping the total conversion to renewable constant.

In relation to natural gas bridging, two general conclusions can be made from Figure 17. Firstly, at a low leak rate, the Ng-bridge scenario is always better. This holds true for peak temperature, rate of temperature change and long-term temperature. Secondly, as the leak rate increases, there is a tradeoff between higher rates of temperature change and the long-term temperatures.

While at leak rates $< 3\%$ the Ng-bridge scenario is always better compared to all three metrics, if the leakage rate is above around 3%, the Ng-bridge scenario reaches a peak temperature at the same time or faster in all of the time periods considered (Tables 4-7 part a). This earlier peak can be explained by the natural gas bridge allowing coal to be reduced faster and therefore the reduction of natural gas in turn beginning earlier (Figures 9-12). Note this faster time to peak temperature alone does not mean a faster rate of temperature change, but can if combined with a certain peak temperature.

Tables 4-7 show that the natural gas bridge produces a lower peak temperature even for higher leaks rates particularly at longer time periods. In the 2180 and 2140 scenarios, a lower or similar peak temperature is found in the Ng-bridge scenarios compared to the others with leak rates up to about 9% (Tables 4b and 5b). The advantage is less robust in the 2100 and 2060 cases, holding true for up to 6% and 3% respectively (Tables 6b and 7b). Comparing the Ng-bridge scenario only to the Coal-first one, the advantages are a bit greater with lower or similar peak temperature for leak rates up to about 12% for 2180 and 2140 and 9% and 6% for 2100 and 2060 respectively (Tables 4-7 part b).

One possible reason that break-even leak rates, in terms of peak temperature, are higher in the longer (2140 and 2180) scenarios is that the peak temperatures don't occur until between 111 to 155 years (Tables 4a and 5a). Combining this longer time period with the increases in electricity production means that there is a much larger carbon dioxide saving from generating the electricity from natural gas instead of coal.

It interesting that at higher leak rates, the Ng-bridge scenario does not always peak at higher temperatures than the Coal-first scenario (Tables 4-7 part b). This might be explained by a competition between using a more energy dense fuel (natural gas) and more methane being released due to leakage. Because natural gas is a more efficient energy source, it would act to bring the change in temperature down; however, the methane leakage would push the peak temperature higher at shorter time scales. Further, the reason for the lower peak temperature on longer time scales is most likely caused by the difference in lifetimes of methane and carbon dioxide. Increased methane has a greater impact on shorter time scales and the reduction in carbon dioxide wins out on longer times scales. This would then lead to the simulated result that higher leak rates in the Ng-bridge scenario would produce a similar peak temperature to the Coal-first scenario at longer time periods but not at shorter ones.

The largest difference in the short-term is that the rate of temperature change in the Ng-bridge scenario is highly dependent on leak rate (Figure 17). As discussed above, this is because this scenario has the most natural gas of any of the scenarios and methane impacts the temperature on much shorter time scales. The leak rate where natural gas bridging produces a larger rate of temperature change, compared to the other scenarios, increases as the change to renewables slows (time period considered increases). In the 2060 and 2100 scenarios, this break-even leak rate is between 3-6% and for the 2140 and 2180 scenarios it is between 6-9%.

The dependency of the results on the time horizon demonstrates how important this variable is in analyzing the usefulness of natural gas bridging. There are two conclusions that are not dependent on the time period considered. First, is that at a low leak rates (<3%) the Ng-bridge scenario leads to lower peak temperatures, lower rates of warming and a lower long-term temperature. Second, a transition to natural gas with a moderate-high leak rate (>6%) would likely lead to increased rates of warming. As the leak rate increases, there is a tradeoff between higher rates of temperature change and the long-term temperatures.

4 Concluding Thoughts

While the model created is comprehensive due to the fact that it converts electricity composition estimates to approximate global temperature changes, only carbon based emissions from coal and natural gas are included. It could be beneficial to expand the types of GHGs emitted from electricity production beyond carbon dioxide and methane to possibly include nitrous oxides, black carbon, and sulfur dioxide. Further, to simulate more realistic temperature changes it would be useful to separate oil from coal and natural gas by finding a way to represent its emissions independently and also to explore the lifecyle emissions from renewable energy sources and see if they are significant. Carrying out these additions to the model would give a more complete picture of emissions/temperature changes and analysis of scenarios leading to a renewable future.

Possibly more important than the extra detail in the model are the economic impacts on the usefulness of natural gas bridging. For example, if new natural gas plants are built to utilize the natural gas bridge, companies will not want to retire the plants before their useful life is up. This in turn could act to slow the transition to renewable energies and backfire. This exemplifies that an economics analysis cannot be forgotten and must be part of any decision on natural gas bridging.

Weighing the usefulness of a natural gas bridge is no simple task. Many scenarios such as a slower transition to fully renewable energy, the possibility of retiring natural gas plants early, or the importance of a lower long-term temperature could lead to conclusions that a natural gas bridge would be beneficial. At the same time, consequences of an increased proportion of electricity coming from natural gas could include a faster rate of warming in the short-term and a delay of the transition to renewable energy. Three things are for certain: 1) immediate constraining of the natural gas leak rate would make any analysis more useful 2) unless the leak rate is near the bottom of the possible range, there will be tradeoffs in global temperatures at different times and

3) for a natural gas bridge to be useful the target leak rate must be below the break-even one because the goal is lessening temperature changes through fuel substitution.

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5 Figures

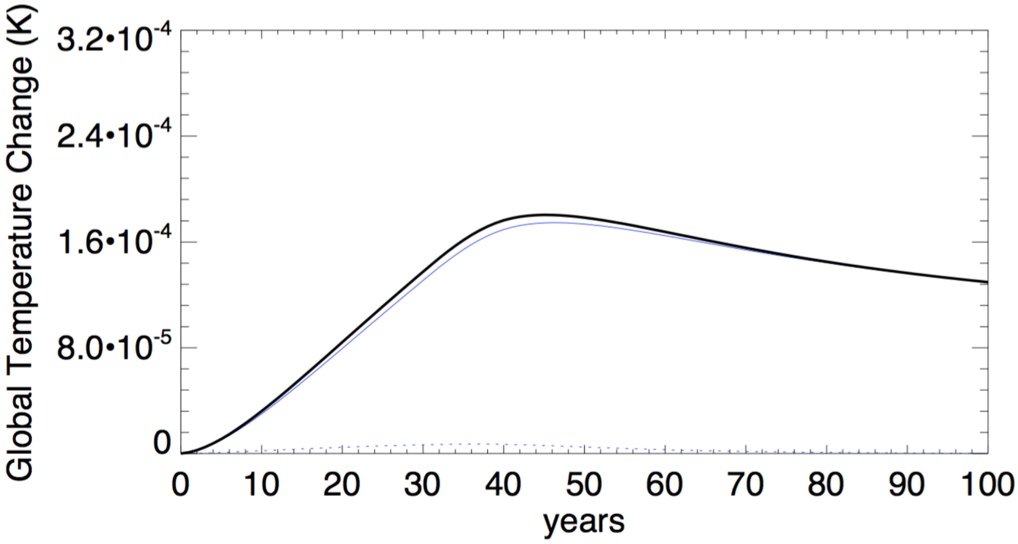

Figure 1: Global temperature change from 1GW (8,760 GWh) electricity production operating for 40 years if all electricity was produced from coal. Note that emissions cease after 40 years but temperature changes persist. The blue lines are the components of temperature change with the dashed representing that from methane emissions and the solid represented that from carbon dioxide emissions. The black line is the total temperature change.

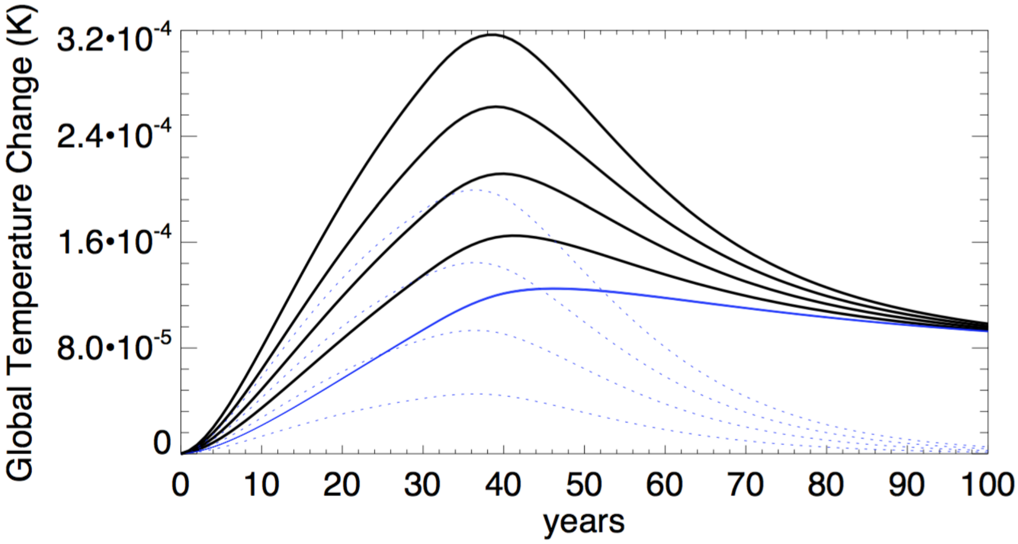

Figure 2: Global temperature change from 1GW (8,760 GWh) electricity production operating for 40 years if all electricity was produced from natural gas. Note that emissions cease after 40 years but temperature changes persist. The blue lines are the components of temperature change with the dashed representing that from methane emissions and the solid representing that from carbon dioxide emissions. The black lines are the total temperature change. Natural gas leakage rates shown are 0 to 12% with each line being an increase of 3%

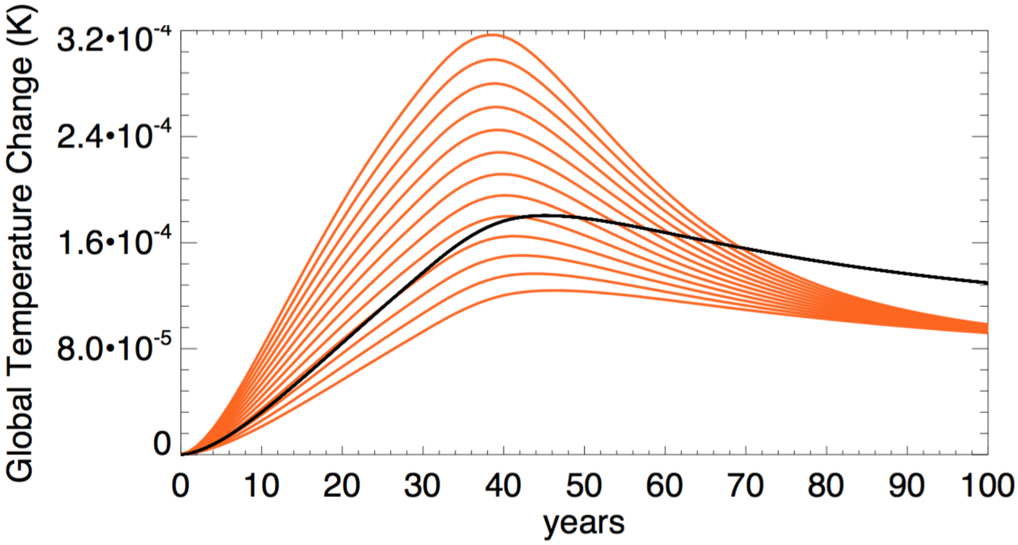

Figure 3: Global temperature change from 1GW (8,760 GWh) electricity production operating for 40 years if all electricity was produced from either coal (black line) or natural gas (orange lines). Note that emissions cease after 40 years but temperature changes persist. In the natural gas case, the given leakage rates from 0 to 12% are shown using the orange lines with each line being a 1% increase in leakage rate.

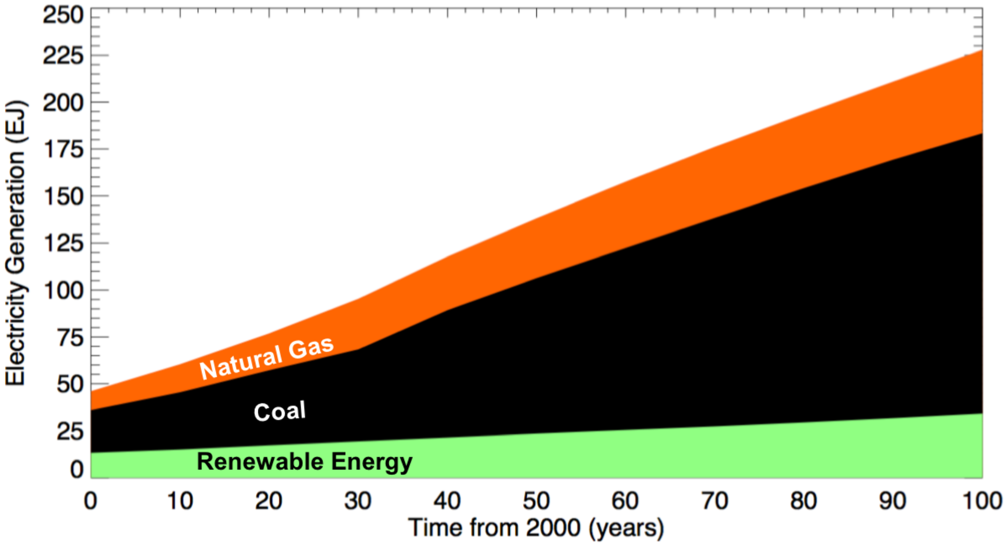

Figure 4: Electricity breakdown by source in IGSM reference scenarios. Electricity generation is kept constant after 2100.

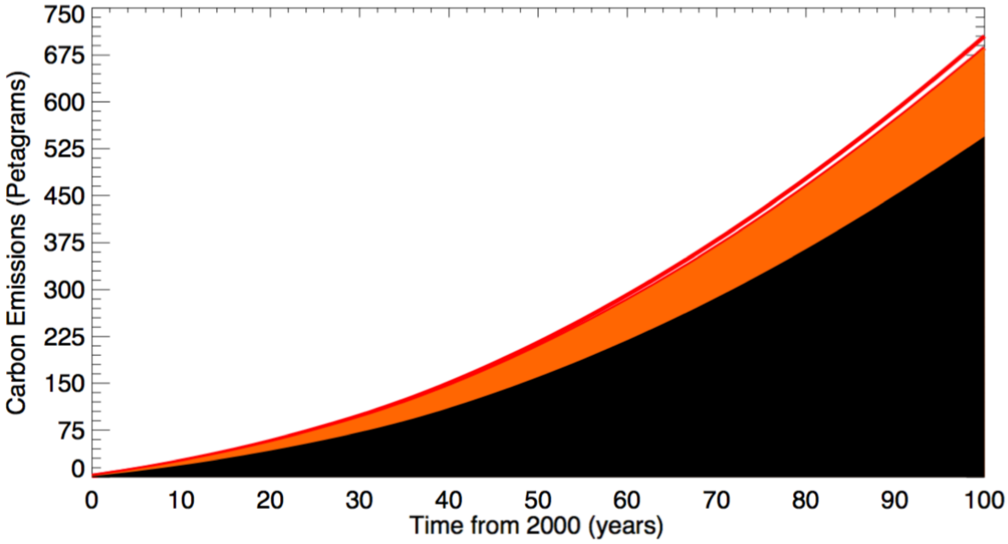

Figure 5: Total carbon emitted during electricity production in IGSM reference scenario for 100 years. The orange and black areas are total carbon in CO2 produced from natural gas and coal respectively. The remaining area below the top red line is the carbon in CH4 leaked mainly from natural gas given a leak rate of 12%. The lower red line (only barely visible just above the top of the orange area) is the carbon in CH4 leaked from natural gas given a leak rate of 0% or in other words, the carbon in CH4 leaked from coal. This is extremely small. The x-axis is years from 2000.

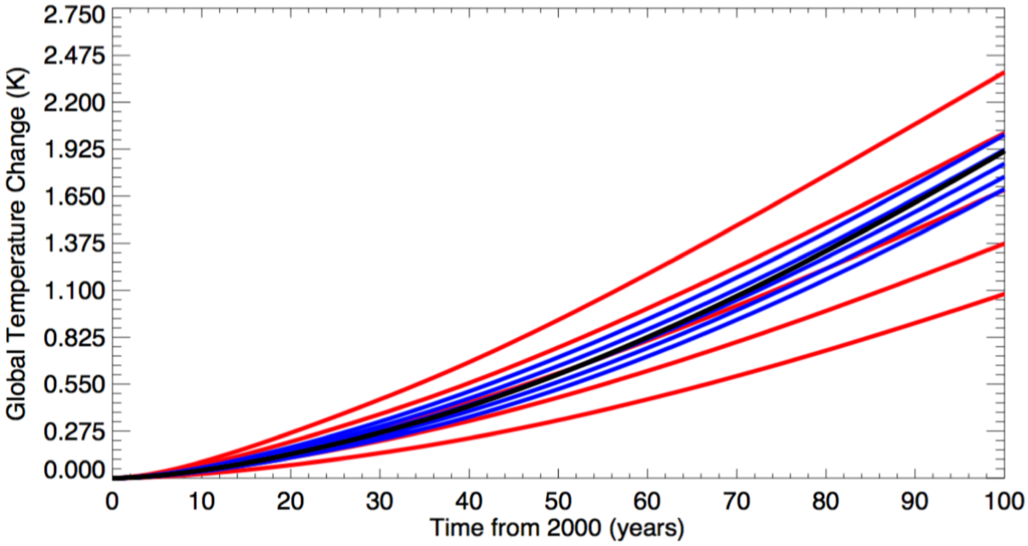

Figure 6: Global temperature changes from carbon emissions during electricity production in IGSM reference scenario for 100 years. The blue lines are the electricity mix predicted by the scenario with the orange and black lines representing all electricity from natural gas and coal respectively. Natural gas leak rates of 0-12% by 3% intervals are shown. The x-axis is years from 2000.

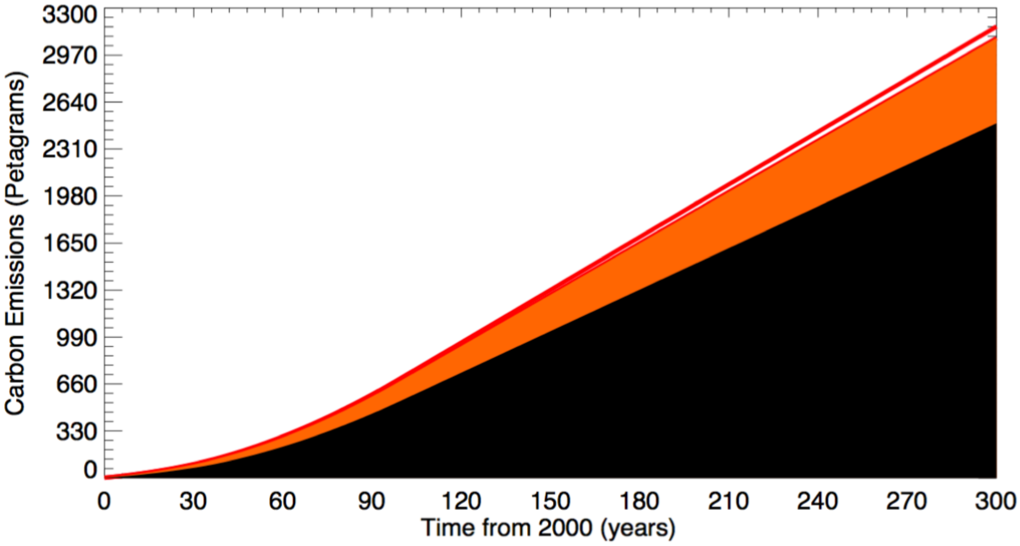

Figure 7: Total carbon emitted during electricity production in IGSM reference scenario extended out for 300 years with the electricity production after 100 years being kept constant. The orange and black areas are total carbon in CO2 produced from natural gas and coal respectively. The remaining area below the top red line is the carbon in CH4 leaked mainly from natural gas given a leak rate of 12%. The lower red line (only barely visible just above the top of the orange area) is the carbon in CH4 leaked from natural gas given a leak rate of 0% or in other words, the carbon in CH4 leaked from coal. This is extremely small.

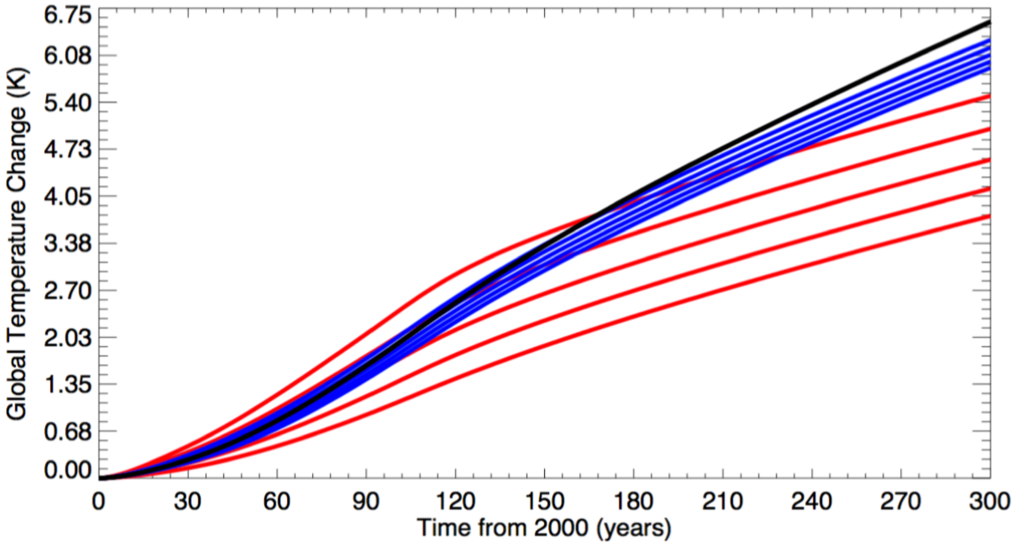

Figure 8: Global temperature changes from carbon emissions during electricity production in IGSM reference scenario extended out for 300 years with the electricity production after 100 years being kept constant. The blue lines are the electricity mix predicted by the scenario with the orange and black lines representing all electricity from natural gas and coal respectively. Natural gas leak rates of 0-12% by 3% intervals are shown.

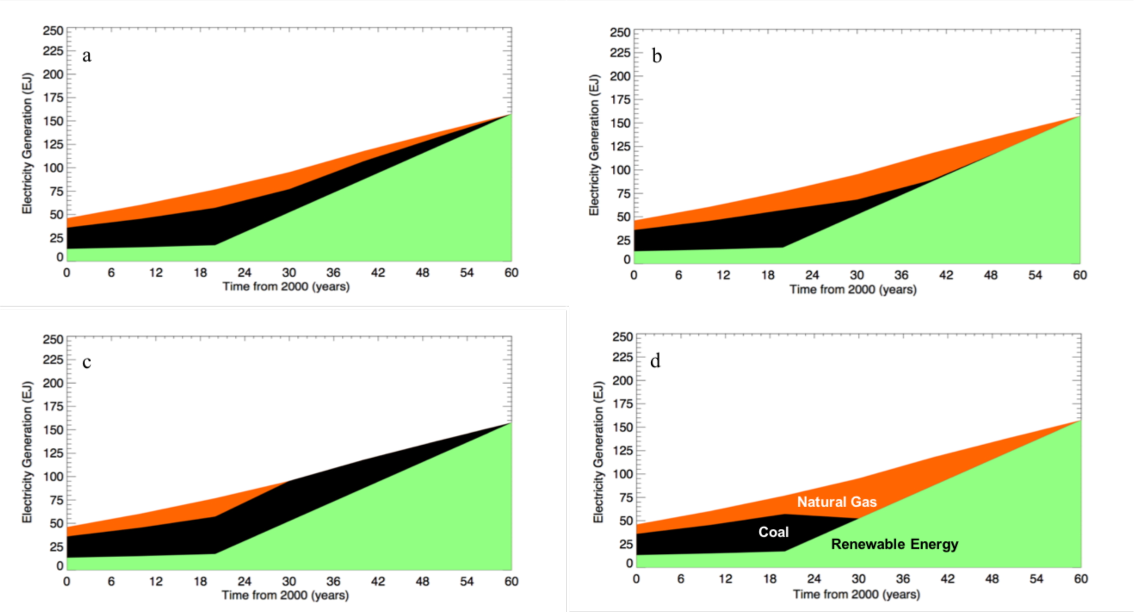

Figure 9: Electricity breakdown by source in all-renewable scenarios with a goal year of 2060: a) 2060 Coal-and-Ng, b) 2060 Coal-first, c) 2060 Ng-first d) 2060 Ng-bridge. The rate of changeover to renewable energy is constant throughout the reduction time period (in this case 2020-2060). All electricity is produced from renewables after 2060. Note that no conversion to renewable energy beyond the reference scenario occurs before 2020.

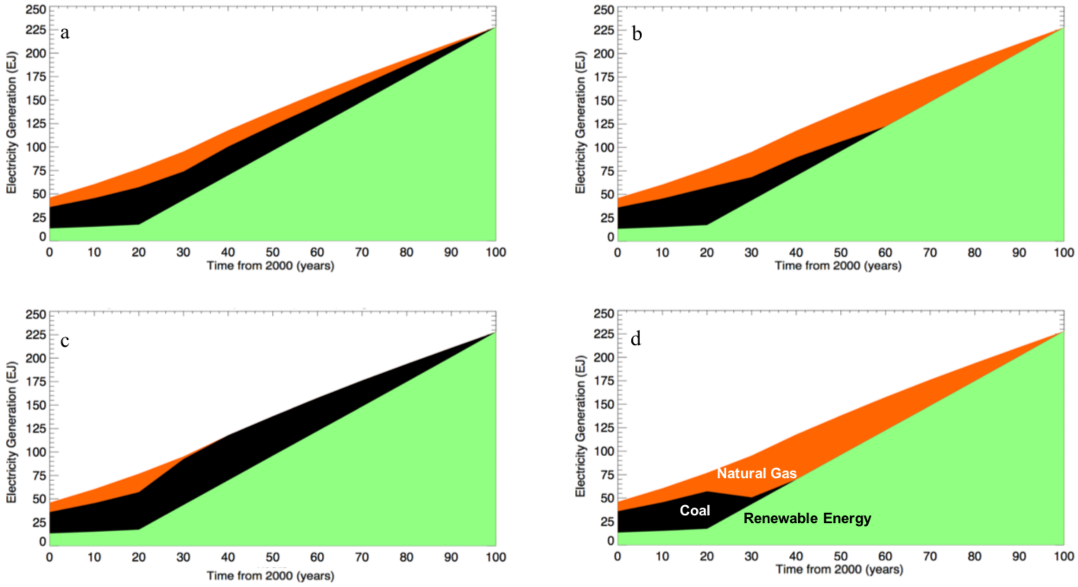

Figure 10: Electricity breakdown by source in all-renewable scenarios with a goal year of 2100: a) 2100 Coal-and-Ng, b) 2100 Coal-first, c) 2100 Ng-first d) 2100 Ng-bridge. The rate of changeover to renewable energy is constant throughout the reduction time period (in this case 2020-2100). All electricity is produced from renewables after 2100. Note that no conversion to renewable energy beyond the reference scenario occurs before 2020.

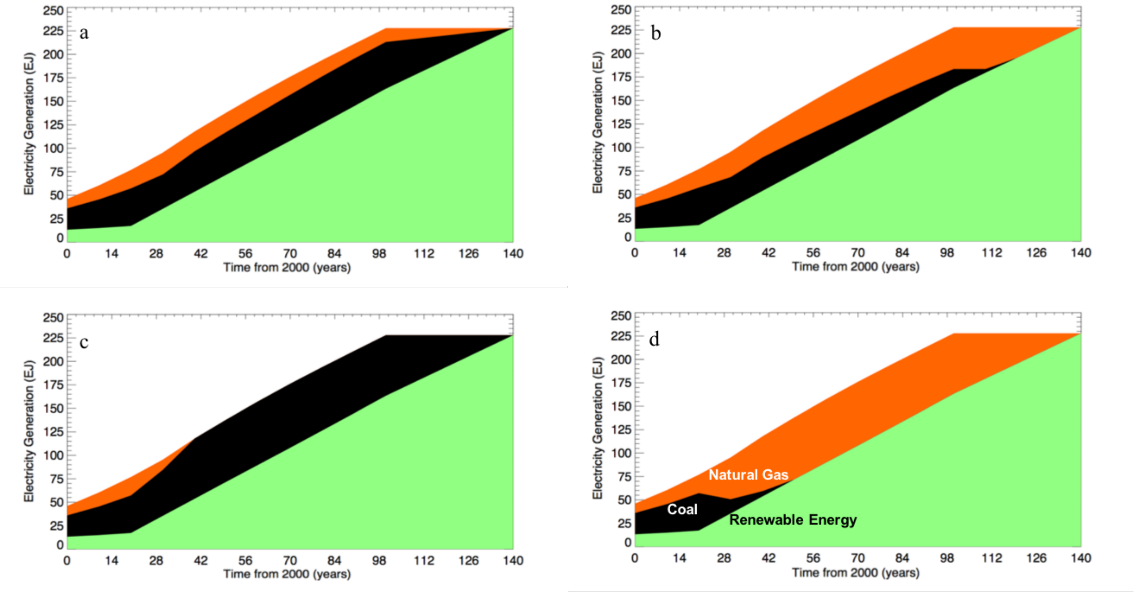

Figure 11: Electricity breakdown by source in all-renewable scenarios with a goal year of 2140: a) 2140 Coal-and-Ng, b) 2140 Coal-first, c) 2140 Ng-first d) 2140 Ng-bridge. The rate of changeover to renewable energy is constant throughout the reduction time period (in this case 2020-2140). All electricity is produced from renewables after 2140. Note that no conversion to renewable energy beyond the reference scenario occurs before 2020.

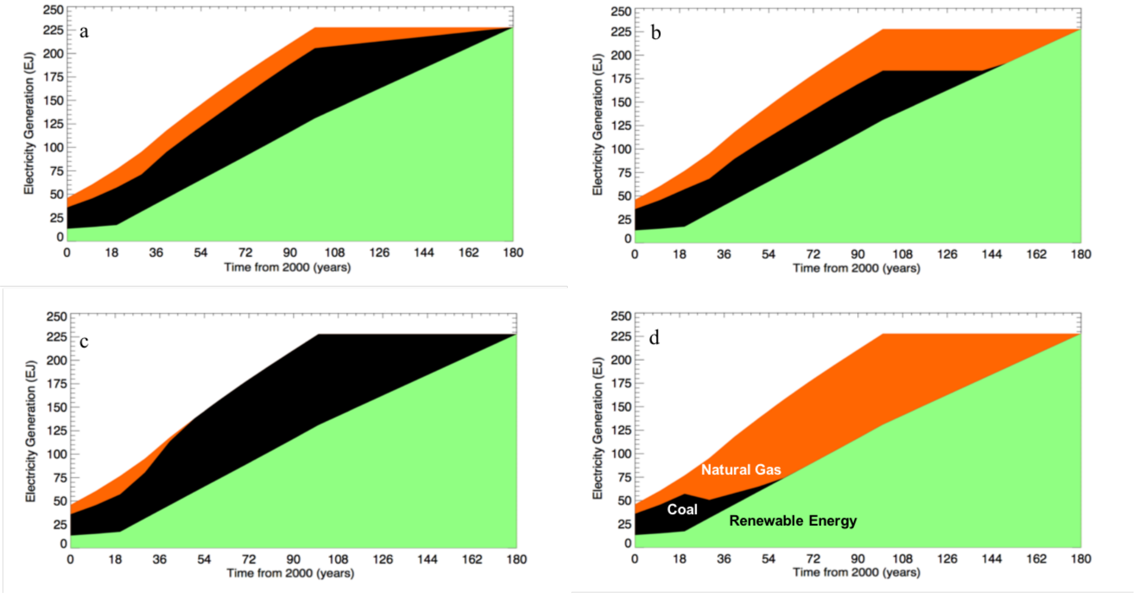

Figure 12: Electricity breakdown by source in all-renewable scenarios with a goal year of 2180: a) 2180 Coal-and-Ng, b) 2180 Coal-first, c) 2180 Ng-first d) 2180 Ng-bridge. The rate of changeover to renewable energy is constant throughout the reduction time period (in this case 2020-2180). All electricity is produced from renewables after 2180. Note that no conversion to renewable energy beyond the reference scenario occurs before 2020.

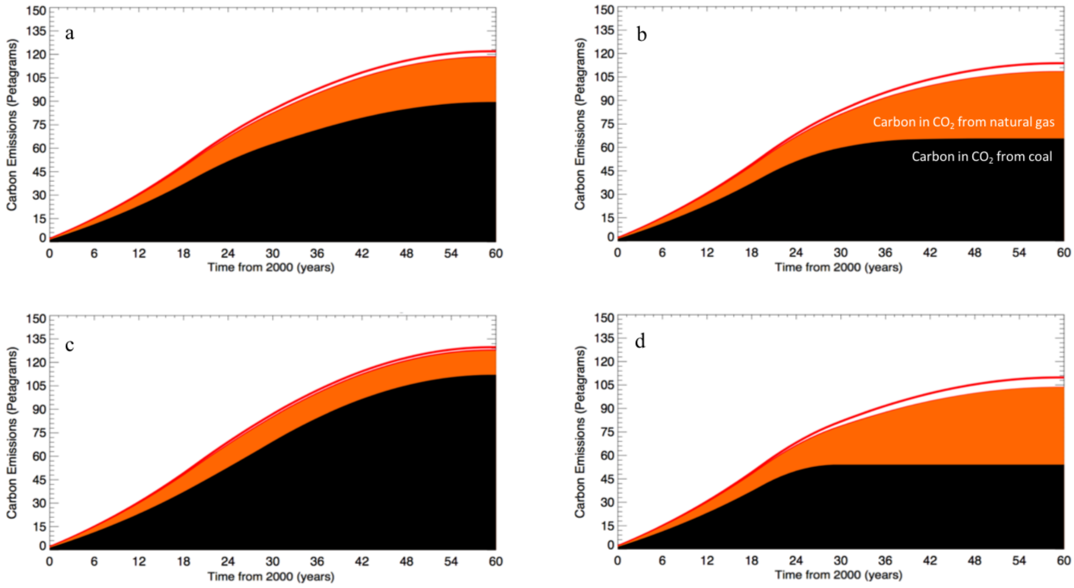

Figure 13: Total carbon emitted during electricity production in all-renewable scenarios with a goal year of 2060: a) 2060 Coal-and-Ng, b) 2060 Coal-first, c) 2060 Ng-first d) 2060 Ng-bridge. All electricity is produced from renewables after 2060 so there are no emissions after that year. The orange and black areas are total carbon in CO2 produced from natural gas and coal respectively. The remaining area below the top red line is the carbon in CH4 leaked mainly from natural gas given a leak rate of 12%. The lower red line (only barely visible just above the top of the orange area) is the carbon in CH4 leaked from natural gas given a leak rate of 0% or in other words, the carbon in CH4 leaked from coal. This is extremely small. Note that no conversion to renewable energy beyond the reference scenario occurs before 2020.

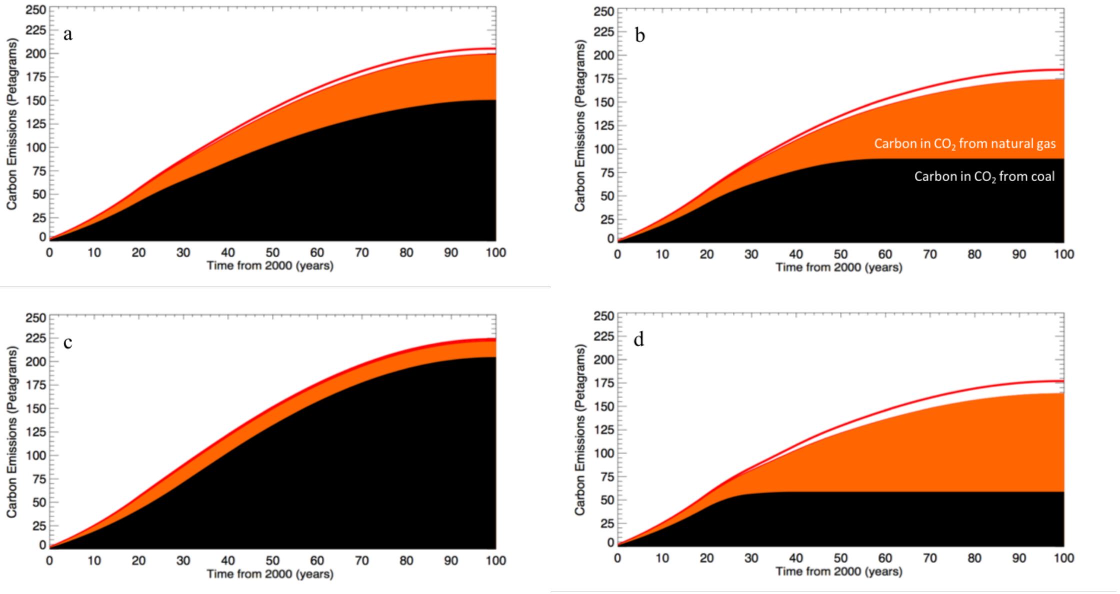

Figure 14: Total carbon emitted during electricity production in all-renewable scenarios with a goal year of 2100: a) 2100 Coal-and-Ng, b) 2100 Coal-first, c) 2100 Ng-first d) 2100 Ng-bridge. All electricity is produced from renewables after 2100 so there are no emissions after that year. The orange and black areas are total carbon in CO2 produced from natural gas and coal respectively. The remaining area below the top red line is the carbon in CH4 leaked mainly from natural gas given a leak rate of 12%. The lower red line (only barely visible just above the top of the orange area) is the carbon in CH4 leaked from natural gas given a leak rate of 0% or in other words, the carbon in CH4 leaked from coal. This is extremely small. Note that no conversion to renewable energy beyond the reference scenario occurs before 2020.

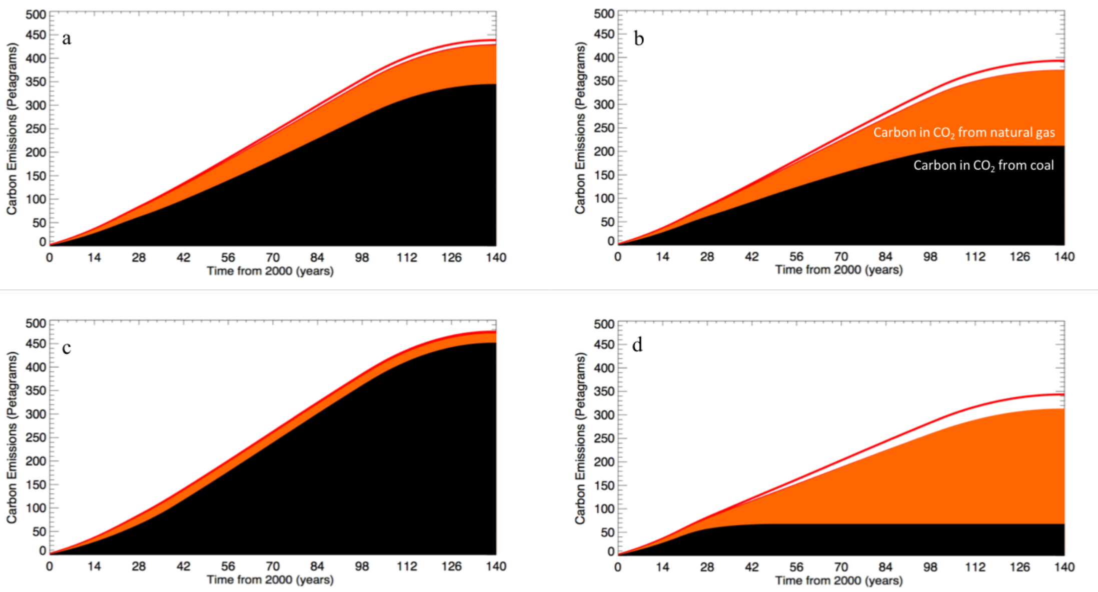

Figure 15: Total carbon emitted during electricity production in all-renewable scenarios with a goal year of 2140: a) 2140 Coal-and-Ng, b) 2140 Coal-first, c) 2140 Ng-first d) 2140 Ng-bridge. All electricity is produced from renewables after 2140 so there are no emissions after that year. The orange and black areas are total carbon in CO2 produced from natural gas and coal respectively. The remaining area below the top red line is the carbon in CH4 leaked mainly from natural gas given a leak rate of 12%. The lower red line (only barely visible just above the top of the orange area) is the carbon in CH4 leaked from natural gas given a leak rate of 0% or in other words, the carbon in CH4 leaked from coal. This is extremely small. Note that no conversion to renewable energy beyond the reference scenario occurs before 2020.

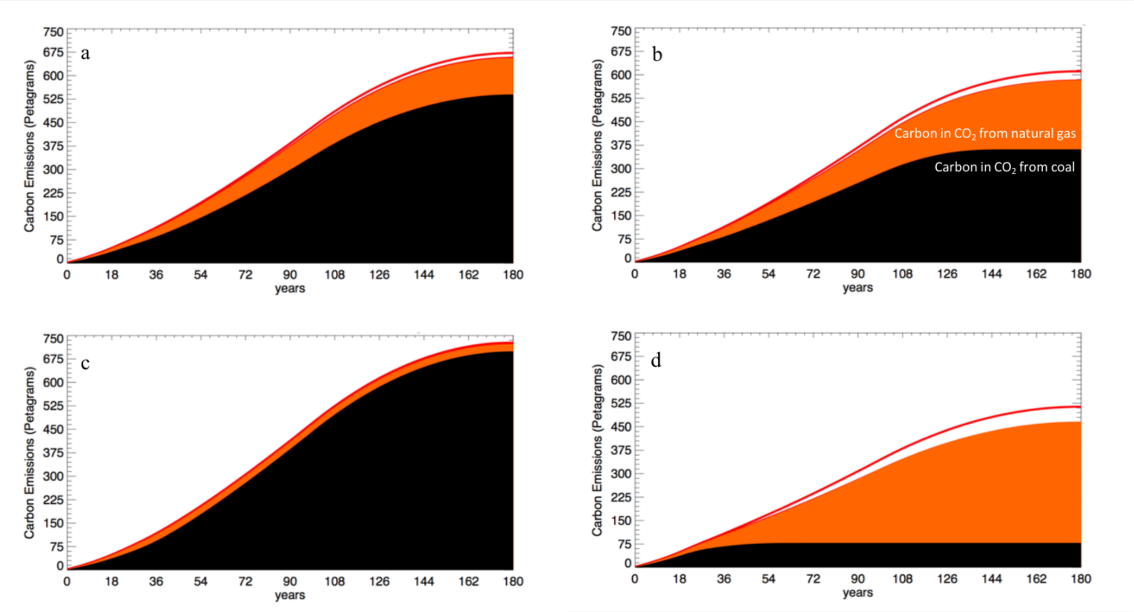

Figure 16: Total carbon emitted during electricity production in all-renewable scenarios with a goal year of 2180: a) 2180 Coal-and-Ng, b) 2180 Coal-first, c) 2180 Ng-first d) 2180 Ng-bridge. All electricity is produced from renewables after 2180 so there are no emissions after that year. The orange and black areas are total carbon in CO2 produced from natural gas and coal respectively. The remaining area below the top red line is the carbon in CH4 leaked mainly from natural gas given a leak rate of 12%. The lower red line (only barely visible just above the top of the orange area) is the carbon in CH4 leaked from natural gas given a leak rate of 0% or in other words, the carbon in CH4 leaked from coal. This is extremely small. Note that no conversion to renewable energy beyond the reference scenario occurs before 2020.

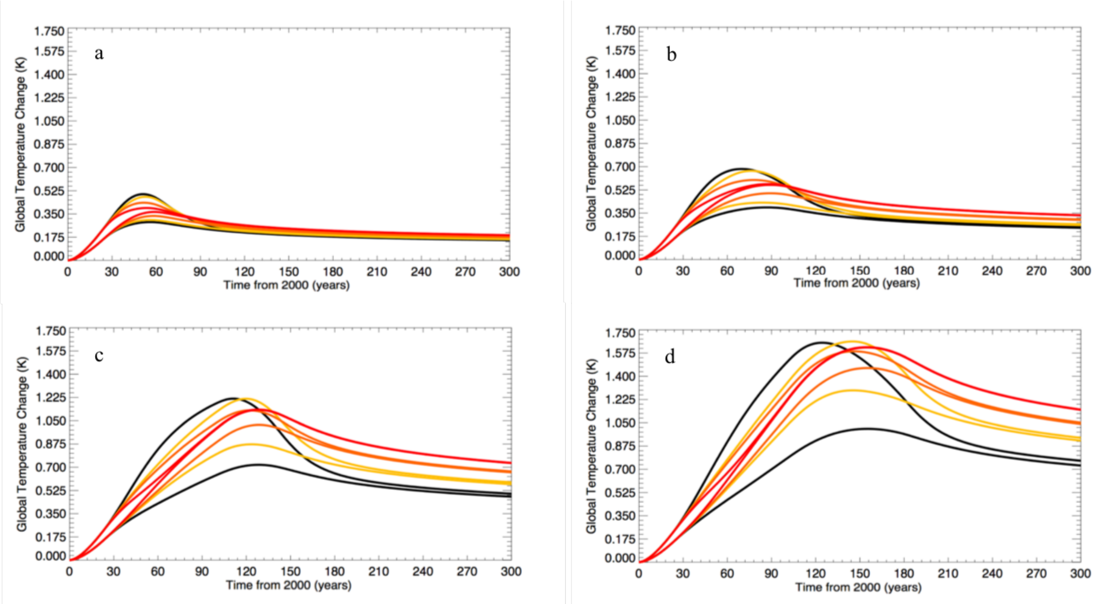

Figure 17: Global temperature changes from carbon emissions during electricity production in all-renewable scenarios (orange - Coal-and-Ng; yellow - Coal-first; red - Ng-first; black - Ng-bridge) based upon IGSM reference output with varying goals a) 2060, b) 2100, c) 2140, d) 2180. In each scenario the min natural gas leak rate (0%) and the max leak rate (12%) are shown. Note that no conversion to renewable energy beyond the reference scenario occurs before 2020.

Table 4: Summary of resulting peak temperatures, rates of temperature changes, and long-term temperatures for the different all-renewable scenarios with a goal year of 2180 split by temperature variable.

a)

Time to Peak Temp (yr) 2180				
Leak Rate	Ng-bridge	Coal-first	Coal-and-Ng	Ng-first
0%	**155**	145	**155**	**155**
3%	142	145	153	**155**
6%	134	145	151	**155**
9%	128	145	148	**155**
12%	124	145	146	**155**

b)

Peak Δ Temps (k) 2180				
Leak Rate	Ng-bridge	Coal-first	Coal-and-Ng	Ng-first
0%	**1.00468**	1.29374	1.46206	1.61700
3%	**1.12939**	1.37731	1.48898	1.61756
6%	**1.28261**	1.46621	1.51870	1.61816
9%	**1.45827**	1.56097	1.55153	1.61880
12%	1.65281	1.66220	**1.58790**	1.61948

c)

Rate Δ Temps (k/yr) 2180				
Leak Rate	Ng-bridge	Coal-first	Coal-and-Ng	Ng-first
0%	**6.48E-03**	8.92E-03	9.43E-03	1.04E-02
3%	**7.95E-03**	9.50E-03	9.73E-03	1.04E-02
6%	**9.57E-03**	1.01E-02	1.01E-02	1.04E-02
9%	1.14E-02	1.08E-02	1.05E-02	**1.04E-02**
12%	1.33E-02	1.15E-02	1.09E-02	**1.04E-02**

d)

Long-term Δ Temps (k) 2180				
Leak Rate	Ng-bridge	Coal-first	Coal-and-Ng	Ng-first
0%	**0.72839**	0.916149	1.04016	1.14715
3%	**0.736559**	0.920861	1.04258	1.14759
6%	**0.74525**	0.925875	1.04515	1.14806
9%	**0.754515**	0.931219	1.04788	1.14856
12%	**0.764411**	0.936927	1.05081	1.14909

Table 5: Summary of resulting peak temperatures, rates of temperature changes, and long-term temperatures for the different all-renewable scenarios with a goal year of 2140 split by temperature variable.

a)

Time to Peak Temp (yr) 2140				
Leak Rate	Ng-bridge	Coal-first	Coal-and-Ng	Ng-first
0%	128	123	**129**	128
3%	120	122	127	**128**
6%	116	121	125	**128**
9%	113	120	124	**128**
12%	111	120	122	**128**

b)

Peak Δ Temps (k) 2140				
Leak Rate	Ng-bridge	Coal-first	Coal-and-Ng	Ng-first
0%	**0.718174**	0.872362	1.01871	1.13132
3%	**0.820747**	0.949588	1.04215	1.1319
6%	**0.940176**	1.03225	1.0679	1.13251
9%	**1.07237**	1.12063	1.09631	1.13316
12%	1.21621	**1.21518**	1.12754	1.13385

c)

Rate Δ Temps (k/yr) 2140				
Leak Rate	Ng-bridge	Coal-first	Coal-and-Ng	Ng-first
0%	**5.61E-03**	7.09E-03	7.90E-03	8.84E-03
3%	**6.84E-03**	7.78E-03	8.21E-03	8.84E-03
6%	**8.10E-03**	8.53E-03	8.54E-03	8.85E-03
9%	9.49E-03	9.34E-03	**8.84E-03**	8.85E-03
12%	1.10E-02	1.01E-02	9.24E-03	**8.86E-03**

d)

Long-term Δ Temps (k) 2140				
Leak Rate	Ng-bridge	Coal-first	Coal-and-Ng	Ng-first
0%	**0.478275**	0.571972	0.661228	0.731261
3%	**0.483309**	0.575282	0.662894	0.731638
6%	**0.488664**	0.578804	0.664666	0.73204
9%	**0.494372**	0.582559	0.666555	0.732468
12%	**0.500469**	0.58657	0.668573	0.732925

Table 6: Summary of resulting peak temperatures, rates of temperature changes, and long term temperatures for the different all-renewable scenarios with a goal year of 2100 split by temperature variable.

a)

Time to Peak Temp (yr) 2100				
Leak Rate	Ng-bridge	Coal-first	Coal-and-Ng	Ng-first
0%	87	84	**89**	**89**
3%	79	80	86	**89**
6%	74	78	83	**89**
9%	72	77	80	**88**
12%	70	76	78	**88**

b)

Peak Δ Temps (k) 2100				
Leak Rate	Ng-bridge	Coal-first	Coal-and-Ng	Ng-first
0%	**0.392738**	0.42875	0.49929	0.562786
3%	**0.452866**	0.481931	0.519831	0.564072
6%	**0.522461**	0.539743	0.543256	0.56544
9%	0.599157	0.601817	0.569709	**0.566949**
12%	0.68244	0.66834	0.599411	**0.568581**

c)

Rate Δ Temps (k/yr) 2100				
Leak Rate	Ng-bridge	Coal-first	Coal-and-Ng	Ng-first
0%	**4.51E-03**	5.10E-03	5.61E-03	6.32E-03
3%	**5.73E-03**	6.02E-03	6.04E-03	6.34E-03
6%	7.06E-03	6.92E-03	6.55E-03	**6.35E-03**
9%	8.32E-03	7.82E-03	7.12E-03	**6.44E-03**
12%	9.75E-03	8.79E-03	7.68E-03	**6.46E-03**

d)

Long-term Δ Temps (k) 2100				
Leak Rate	Ng-bridge	Coal-first	Coal-and-Ng	Ng-first
0%	**0.239388**	0.258923	0.298119	0.332753
3%	**0.24142**	0.260597	0.299072	0.33307
6%	**0.243582**	0.262377	0.300087	0.333408
9%	**0.245886**	0.264275	0.301167	0.333767
12%	**0.248348**	0.266302	0.302322	0.334151

Table 7: Summary of resulting peak temperatures, rates of temperature changes, and long term temperatures for the different all-renewable scenarios with a goal year of 2060 split by temperature variable.

a)

Time to Peak Temp (yr) 2060				
Leak Rate	Ng-bridge	Coal-first	Coal-and-Ng	Ng-first
0%	56	56	58	**59**
3%	53	54	56	**58**
6%	52	53	54	**57**
9%	52	53	53	**55**
12%	51	53	52	**54**

b)

Peak Δ Temps (k) 2060				
Leak Rate	Ng-bridge	Coal-first	Coal-and-Ng	Ng-first
0%	**0.288471**	0.304572	0.334919	0.364925
3%	**0.335138**	0.343741	0.355953	0.370946
6%	0.38589	0.385765	0.379484	**0.377725**
9%	0.440317	0.43081	0.405672	**0.385516**
12%	0.498781	0.478928	0.434453	**0.394537**

c)

Rate Δ Temps (k/yr) 2060				
Leak Rate	Ng-bridge	Coal-first	Coal-and-Ng	Ng-first
0%	**5.15E-03**	5.44E-03	5.77E-03	6.19E-03
3%	**6.32E-03**	6.37E-03	6.36E-03	6.40E-03
6%	7.42E-03	7.28E-03	7.03E-03	**6.63E-03**
9%	8.47E-03	8.13E-03	7.65E-03	**7.01E-03**
12%	9.78E-03	9.04E-03	8.35E-03	**7.31E-03**

d)

Long-term Δ Temps (k) 2060				
Leak Rate	Ng-bridge	Coal-first	Coal-and-Ng	Ng-first
0%	**0.152118**	0.15938	0.174412	0.188558
3%	**0.153082**	0.160212	0.174967	0.188854
6%	**0.154109**	0.161097	0.175559	0.189169
9%	**0.155203**	0.16204	0.176189	0.189505
12%	**0.156372**	0.163047	0.176862	0.189864