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## Beyond global warming potential: A comparative application of climate impact metrics for the life cycle assessment of coal and natural gas-based electricity

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Life Cycle Assessment; Climate Change; Global Warming Potential; Coal; Natural Gas

### Summary

In the ongoing debate about the climate benefits of fuel switching from coal to natural gas for power generation, the metrics used to model climate impacts may be important. In this article, we evaluate the life cycle greenhouse gas emissions of coal and natural gas used in new, advanced power plants using a broad set of available climate metrics in order to test for the robustness of results. Climate metrics included in the paper are global warming potential, global temperature change potential, technology warming potential, and cumulative radiative forcing. We also used the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) climate change model to validate the results. We find that all climate metrics suggest a natural gas combined cycle plant offers life cycle climate benefits over 100 years compared to a pulverized coal plant, even if the life cycle methane leakage rate for natural gas reaches 5%. Over shorter time frames (i.e. 20 years), plants using natural gas with 4% leakage rate have similar climate impacts as those using coal, but are no worse than coal. If carbon capture and sequestration becomes available for both types of power plants, natural gas still offers climate benefits over coal as long as the life cycle methane leakage rate remains below 2%. These results are consistent across climate metrics and the MAGICC model over a 100-year timeframe. Although it is not clear whether any of these metrics are better than the others, the choice of metric can inform decisions based on different societal values. For example, whereas annual temperature change reported may be a more relevant metric to evaluate the human health effects of increased heat, the cumulative temperature change may be more relevant to evaluate climate impacts, such as sea level rise, that will result from the cumulative warming.

### Introduction

In the ongoing debate about the climate benefits of fuel switching from coal to natural gas for power generation, the metrics used to model climate impacts may be important, as different metrics may lead to different conclusions or provide different information. In this article we evaluate the life cycle greenhouse gas (GHG) emissions of coal and natural gas-based electricity in advanced power plants in the United States using a broad set of available climate metrics.

The growth in natural gas production in the United States over the past decade has led to a shift in thinking about domestic electricity generation. The sheer volume of economically recoverable natural gas may signal the end of coal's reign as the primary source of fuel for electricity

generation in the U.S. (US EIA 2014). Although lower commodity prices and resource abundance certainly generate financial incentives for natural gas use in power plants, society must also consider the potential climate impacts when deciding between natural gas and coal. Further, whereas there is a robust literature evaluating the life cycle GHG emissions of coal and natural gas for electricity generation (see, e.g., Spath et al. 1999; Spath and Mann 2000; Jaramillo et al. 2007; Koornneef et al. 2008; Jiang et al. 2011; Howarth et al. 2011; Venkatesh, Jaramillo, Griffin, and Matthews 2012a; Weber and Clavin 2012; T. M. L. Wigley 2011; Alvarez et al. 2012; Littlefield et al. 2014; Burnham et al. 2012; Venkatesh et al. 2011; Hausfather 2015; Zhang et al. 2014; Levi 2013), most of this previous research used an attributional life cycle assessment (ALCA) approach and relied on global warming potential (GWP) to convert all GHGs to CO<sub>2</sub>-equivalent emissions. The use of global warming potential to convert non-CO<sub>2</sub> greenhouse gas emissions to a CO<sub>2</sub> equivalent dates to 1990, when the Intergovernmental Panel on Climate Change released their first assessment report (IPCC 2014). The use of GWP is particularly important when evaluating the life cycle GHG emissions for natural gas, as the natural gas production and transmission processes are a large source of methane (CH<sub>4</sub>) emissions (EPA 2014), which have different climate impacts than carbon dioxide (CO<sub>2</sub>) over different time horizons. Using GWP as a measure of climate impacts in a consequential life cycle assessment (CLCA) framework may be problematic. The CLCA framework aims to better account for changes in the real world that result from the deployment of new technologies or policies (Plevin, Delucchi, and Creutzig 2014). Recent work suggests that GWP may have limitations when used to model the consequences of changes in emissions and inform public policy, and proposes other metrics that could replace it in these applications (Kendall 2014; Alvarez et al. 2012; Edwards and Trancik 2014; Peters et al. 2011; Shine et al. 2005; Shine 2009; Tanaka et al. 2010). As the life cycle community moves towards the use of a consequential life cycle assessment (CLCA) framework, alternative metrics may thus be needed.

Whereas new regulations like the new U.S. EPA Standards of Performance for New, Modified, and Reconstructed Stationary Sources, including electric utility generating units (US EPA 2015b), makes it unlikely that the U.S. will build substantial amounts of new pulverized coal (PC) power plant capacity without carbon capture and sequestration (CCS), other countries will continue building conventional PC plants (e.g. (Yang and Cui 2012)). Thus, in this paper we analyze the life cycle CH<sub>4</sub> and CO<sub>2</sub> emissions for coal and natural gas used in six types of new advanced power plants. The power plants evaluated include a 500-MW subcritical PC power plant with and without CCS, a 500-MW ultra-supercritical pulverized coal (USCPC) plant with and without CCS, and a 500-MW natural gas combined cycle (NGCC) plant with and without CCS.

CH<sub>4</sub> emissions can be a critical contributor to the life cycle climate impacts of natural gas, so it is important to evaluate how alternative metrics to GWP affect the relative climate benefits (or costs) of natural gas compared to other sources of energy. CH<sub>4</sub> leakage rates from the life cycle of natural gas have been widely discussed in recent years and can affect the GHG emissions comparison with coal (Gillett and Matthews 2010). Whereas the definition of leakage rate sometimes varies, such rate is generally reported as the volumetric percentage of natural gas lost through venting and unintentional leaks in the system. Estimates of CH<sub>4</sub> leakage rate from natural gas systems vary widely, but most studies suggest they range between 1% and 5% (Brandt et al. 2014; Schwietzke et al. 2014a, 2014b; Jiang et al. 2011; Tong et al. 2015a, 2015b; Petron et al. 2012). These articles derived their estimates through different methods of analysis, including a statistical inversion model that relies on global CH<sub>4</sub> concentrations (Schwietzke

2014a, 2014b), as well as bottom-up life cycle estimates (Tong, 2015a, 2015b) that relied on methane release measurements across the natural gas system (Allen et al. 2013, 2015a, 2015b; Subramanian et al. 2015; Mitchell et al. 2015). Whereas some studies have reported higher methane leakage rates than 5% (see e.g., Caulton et al. 2014; Karion et al. 2013), these studies have relied on airborne measurements that have occurred over limited periods of time and at individual sites. These higher leakage rates are likely the result of superemitter sites, which have been shown to be a concern, but are likely not representative of the average emissions from the entire natural gas system (Brandt et al. 2014). Further, proposed regulation at the state and federal levels aims to reduce lifecycle methane emissions from the natural gas system (see e.g., (US EPA 2015a)). For this paper, we thus perform a parametric analysis with a leakage rate ranging between 1% and 5% across the entire natural gas system (from production to delivery). For the purposes of this analysis, we define the leakage rate as the volumetric percentage of natural gas that is lost as methane through the entire natural gas system.

In addition to parametric analysis of CH<sub>4</sub> leakage rates, we also include an analysis of the break-even CH<sub>4</sub> leakage rate at which the climate impacts of natural gas would equal those of coal when used in advanced power plants like the ones we model. As more information about methane leakage from the natural gas system becomes available, the break-even leakage rates can provide a benchmark for future evaluations. Our analysis includes the following climate metrics: global warming potential (GWP) for the two standard time frames (20 years and 100 years); cumulative radiative forcing (CRF); technology warming potential (TWP); and global temperature change potential (GTP). These metrics have received attention in the literature and are accessible to life cycle assessment (LCA) practitioners. We also include results from a scenario using the MAGICC model, a simplified climate model (Wigley et al. 2014), to provide a further comparison between the previously listed climate metrics and a simple climate model.

## Methods

### Scenarios

This work models the life cycle CO<sub>2</sub> and CH<sub>4</sub> emissions of an NGCC plant, a PC power plant, and an USCPC plant, all with and without CCS. Note that the addition of CCS reduces the efficiency of the power plants, and thus increases the effect of leakage rates in the natural gas systems, as more fuel (and thus more leakage) is needed to generate the same amount of electricity. We assume the plants operate for 30 years and then retire, consistent with the values reported in the literature (see for example (Zhai and Rubin 2013; Rubin and Zhai 2012; Zhai, Rubin, and Versteeg 2011)). The Appendix S4 the Supporting Information includes an extended analysis conducted with 60-year operating lifetimes. We also assume a variety of CH<sub>4</sub> leakage rates associated with the natural gas plant, ranging from 1% to 5% (Brandt et al. 2014; Schwietzke et al. 2014a, 2014b; Jiang et al. 2011; Tong et al. 2015a, 2015b; Petron et al. 2012). This study is a comparison of the life cycle emissions associated with the production of equal amounts of electricity from six types of newly constructed power plants. We do not account for the emissions associated with the construction of the power plants or the construction of a CCS system for each plant. Nor do we account for emission associated with decommissioning the systems at the end of their life. Ignoring the emissions associated with the construction of a fossil fuel power plant does not materially affect our results, as construction accounts for a very small portion of the life cycle GHGs of the power plant. For instance, Spath and Mann (2000) found construction to account for 0.4% of the life cycle of a combined cycle natural gas plant. Similarly, a recent analysis about the life cycle of natural gas power plants with and without

carbon capture and sequestration found that emissions from construction of the systems do not significantly affect their life cycle GHG emissions (Littlefield et al. 2014). In their review of coal power plant life cycle assessments, Whitaker et al. (2012) found that coal power plant construction and decommissioning were among a set of impacts whose overall contributions to life cycle GHGs was less than 1%.

Tong and colleagues (2015a; 2015b) report that CO<sub>2</sub> emissions from natural gas pre-production, production, processing, and transmission to the power plant range between 3.3 and 15 grams (g) CO<sub>2</sub> per megajoule (MJ) of delivered natural gas, with a mean of 7.22 g CO<sub>2</sub>/MJ (all values in higher heating value ([HHV]). Direct combustion of natural gas further releases 50 g CO<sub>2</sub>/MJ, prior to accounting for efficiency losses in electricity conversion at the power plant. Table 1 summarizes the life cycle CO<sub>2</sub> and CH<sub>4</sub> emissions for natural gas at different leakage rates used in this paper. In this table, the leakage rate is the volumetric percentage of delivered natural gas that is lost as methane throughout the natural gas system. This table also summarizes the CO<sub>2</sub> and CH<sub>4</sub> emissions from the life cycle of coal from Venkatesh, Jaramillo, Griffin, H Scott Matthews (2012). Previous work has evaluated the uncertainty associated with the upstream GHG emissions from coal and natural gas systems (Tong et al. 2015a, 2015b; Jiang et al. 2011; Venkatesh et al. 2011; Venkatesh et al. 2012a). For this analysis, however, we are using deterministic values for these emissions estimates (based on the means of the distributions previously reported), as the purpose of this paper is to evaluate the implications of using different climate metrics to compare the potential climate impacts of coal and natural gas for electricity generation. Performing a complete uncertainty analysis of the life cycle emissions inventory would thus confound the comparison across climate metrics.

*Table 1: CO<sub>2</sub> and CH<sub>4</sub> Emissions from the life cycle of coal and natural gas.*

GHG Emission Type and Source	Coal	Natural Gas with Given Methane Leakage Rate				
		1%	2%	3%	4%	5%
CO <sub>2</sub> from upstream (g/MJ of delivered fuel)	1.90 <sup>b</sup>	7.22 <sup>c</sup>				
CO <sub>2</sub> from direct combustion, prior to losses in electricity generation (g/MJ of delivered fuel)	91 <sup>a</sup>	50 <sup>a</sup>				
Life cycle methane (g/MJ of delivered fuel)	0.15 <sup>b</sup>	0.16 <sup>a</sup>	0.33 <sup>a</sup>	0.49 <sup>a</sup>	0.65 <sup>a</sup>	0.81 <sup>a</sup>

Energy units are in higher heating value (HHV).

<sup>a</sup> Calculated value

<sup>b</sup> Value taken from Venkatesh and colleagues (2012a)

<sup>c</sup> Value taken from Tong, and colleagues (2015a, 2015b)

In order to compare the CO<sub>2</sub> and CH<sub>4</sub> emission factors for electricity generated using coal and natural gas, we need to account for the characteristics of the power plants. Table 2 shows the assumptions regarding power plant capacity, efficiency, carbon capture rate (CO<sub>2</sub> captured per

CO<sub>2</sub> emitted), capacity factor, CO<sub>2</sub> and CH<sub>4</sub> emission factors for each power plant, and the estimated annual CO<sub>2</sub> and CH<sub>4</sub> emissions. Whereas most of the values in this table were directly taken from Rubin and Zhai (2012) and Goto and colleagues (2013), the values are consistent with those reported in the broader literature (see e.g., Zhai and Rubin 2013; Zhai et al 2011; Littlefield et al. 2014). Further, because our goal is to compare new advanced coal and natural gas power plants that provide the same level of service, we used the same operating constraints (i.e. capacity, plant lifetimes, capacity factor, and carbon capture rate) for each of the power plants in our analysis. The entire power system, however, consists of more than two power plants and the operations of each individual power plant will depend on the constraints of the power system. These constraints include hourly demand for electricity, transmission and distribution infrastructure, prices, regulations, and the operating limits of all the available power plants in the system (such as minimum generation limit, minimum downtime, maximum ramp rate, etc.). Previous work has relied on simulations of the power system to evaluate the greenhouse gas emissions of electricity generation under different scenarios, including low natural gas prices (Venkatesh et al. 2012c), reduced coal power plant capacity (Venkatesh et al. 2012b), increased wind penetration (Oates and Jaramillo 2013; Johnson and Novacheck 2015), and increased penetration of electric vehicles (Weis et al. 2015). Such analysis of the entire power systems is beyond the scope of this article.

Table 2: Power Plant Characteristics and Associated Emissions. Data for the power plant characteristics from (Rubin and Zhai 2012; Goto, Yogo, and Higashii 2013) Note that the efficiency reported is in HHV. PC: Pulverized Coal. CCS: Carbon Capture and Sequestration. USCPC: Ultra-Supercritical Pulverized Coal. NGCC: Natural Gas Combined Cycle

	Ultra super critical PC	Ultra super critical PC w/CCS	PC	PC w/ CCS	NGCC with Given Methane Leakage Rate					NGCC w/CCS with Given Methane Leakage Rate				
					1%	2%	3%	4%	5%	1%	2%	3%	4%	5%
Power Plant Capacity (MW) <sup>α</sup>	500	500	500	500	500					500				
Power Plant Efficiency	45% <sup>β</sup>	35% <sup>β</sup>	39% <sup>β</sup>	28% <sup>β</sup>	50% <sup>γ</sup>					43% <sup>γ</sup>				
Carbon Capture Rate <sup>β,γ</sup>	0%	90%	0%	90%	0%					90%				
Capacity Factor <sup>α</sup>	90%	90%	90%	90%	90%					90%				
CO <sub>2</sub> Emissions (kg/MWh) <sup>δ</sup>	743	113	860	141	412					102				
CH <sub>4</sub> Emissions (kg/MWh) <sup>δ</sup>	1.20	1.54	1.39	1.93	1.17	2.34	3.51	4.69	5.86	1.36	2.71	4.07	5.42	6.78
Annual CO <sub>2</sub> Emissions (million metric tons) <sup>δ</sup>	2.93	0.45	3.39	0.56	1.62	1.62	1.62	1.62	1.62	0.40	0.40	0.40	0.40	0.40
Annual CH <sub>4</sub> Emissions (metric tons) <sup>δ</sup>	4,730	6,082	5,472	7,602	4,618	9,235	13,853	18,470	23,088	5,344	10,689	16,033	21,378	26,722

<sup>α</sup> Modeling assumptions

<sup>β</sup> Value from (Goto, Yogo, and Higashii 2013)

<sup>γ</sup> Value from (Rubin and Zhai 2012)

<sup>δ</sup> Calculated value

## Climate Metrics

GWP is the time-integrated radiative forcing of a pulse emission of a greenhouse gas relative to that of a pulse emission of CO<sub>2</sub> (IPCC 2014). The Intergovernmental Panel for Climate Change (IPCC) has used GWP since its first report in 1990 and has provided updated GWP values for all GHGs in all five assessment reports (IPCC 2014). The transparency of the metric allows for ease of use, and the relatively small number of inputs has made it the most widely used climate impact metric among many members in the climate change research community (Skodvin and Fuglestvedt 1997; Fuglestvedt et al. 2000). In addition, GWP may be particularly appropriate for developing inventories of GHG emissions that can be compared across countries and that can also be used in climate negotiations (Tanaka et al. 2010). These benefits notwithstanding, GWP has noted flaws and limitations, especially for analyses that compare sustained emissions of various greenhouse gases over long periods of time. In fact, Shine (2009) postulates that the continued use of GWP by the IPCC indicates an “inadvertent consensus” driven by a lax assessment of alternatives. A characteristic of GWP is that it models all emissions as pulse emissions and ignores the timing of those emissions (i.e. 1 kg of CO<sub>2</sub> emitted today is treated and valued the same as 1 kg of CO<sub>2</sub> emitted 10 years from now) (Wigley 1998; Fuglestvedt et al. 2000; O’Neill 2000; Smith and Wigley 2000a, 2000b). Edwards and Trancik (2014) suggest that this characteristic of the GWP “disvalues” the climate impacts of CH<sub>4</sub> emissions and may thus be inappropriate for climate mitigation analysis. Finally, Tanaka and colleagues (2010) suggest that there is a need for flexibility in the use of climate metrics used to inform public policy. Despite this shortcoming, GWP continues to be the standard metric for GHG comparisons, and we use it as the reference metric in our analysis.

To evaluate GWP, we use the latest values reported in the fifth assessment report of the IPCC (IPCC 2014). In this paper we use the GWP values for fossil methane that include climate-carbon feedbacks. The values with carbon-climate feedbacks account for the flux of CO<sub>2</sub> from the land and ocean to the atmosphere as temperatures increase (IPCC 2014), and add uncertainty to the base GWP values (Arora et al. 2013). In the 5th Assessment Report (AR5), the IPCC included relative uncertainty for the GWP. Since this paper aims to compare state-of-the-knowledge climate metrics, we include such uncertainty in the GWP analysis. We thus used a normal distribution for the 20-year GWP of CH<sub>4</sub> with a mean of 87 and a standard deviation of 15.9. For the 100-year GWP of CH<sub>4</sub>, the normal distribution has a mean of 36 and a standard deviation of 8.5 (Tong et al. 2015a).

TWP is another climate impact metric that has received recent attention. Alvarez and colleagues (2012) first introduced TWP as a metric that compares the climate impacts caused by emissions over time from two different technologies using a ratio of the CRF of one technology to the other. The results are time dependent and allow for an analysis that illustrates when, and if, a competing technology will produce lower CRF than a reference technology. Values less than 1 indicate that the alternate technology results in lower CRF than the reference technology, while values greater than 1 indicate that the reference technology produces less CRF. If the TWP is equal to 1, there is no preference between two technologies on the basis of CRF. The use of a ratio simplifies the comparison of CRF from two different systems; this makes it easier to communicate results, and at the same time removes some of the information that is available in a direct comparison of CRF. Equations 1 through 5 describe the model and variables used to estimate the TWP of the PC, USCPC, and NGCC plants. It is important to note that these equations do include the impacts of methane on ozone and stratospheric water vapor but do not

account for carbon-climate feedbacks or the decay of CH<sub>4</sub> to CO<sub>2</sub>. This omission suggests that the TWP will underestimate the impacts of CH<sub>4</sub> emissions. The GWP and CRF values on the other hand, do account for such feedbacks.

$$TWP(t) = \frac{E_{1,CH_4}TRF_{CH_4}(t)+E_{1,CO_2}TRF_{CO_2}(t)}{E_{2,CH_4}TRF_{CH_4}(t)+E_{2,CO_2}TRF_{CO_2}(t)} \quad \text{Equation 1}$$

Where  $E_{1,CH_4}$ ,  $E_{1,CO_2}$ ,  $E_{2,CH_4}$ , and  $E_{2,CO_2}$  are the emission factors for the different power plants from Table 2; and TRF values vary depending of the timing of emissions compared to the life of the power plant.

If  $t \leq$  plant lifetime (variable “ $A_{MAX}$ ” is the plant lifetime), then

$$TRF_{CH_4} = RE \left\{ \tau_M t - \tau_M^2 \left( 1 - e^{-t/\tau_M} \right) \right\} \quad \text{Equation 2}$$

If  $t > A_{MAX}$ , then

$$TRF_{CH_4} = RE \left\{ \tau_M A_{MAX} - \tau_M^2 e^{-t/\tau_M} \left( e^{A_{MAX}/\tau_M} - 1 \right) \right\} \quad \text{Equation 3}$$

Where RE is the relative radiative efficiency of CH<sub>4</sub>, which we calculated to be equal to 120; and  $\tau_M$  is the atmospheric lifetime of methane, equal to 12.4.

Similarly if  $t \leq A_{MAX}$ , then

$$TRF_{CO_2} = a_0 \frac{t^2}{2} + \sum_{i=1}^3 a_i \left( \tau_i t - \tau_i^2 \left( 1 - e^{-t/\tau_i} \right) \right) \quad \text{Equation 4}$$

If  $t > A_{MAX}$ , then

$$TRF_{CO_2} = a_0 \left[ A_{MAX} t - \frac{A_{MAX}^2}{2} \right] + \sum_{i=1}^3 a_i \left( \tau_i A_{MAX} - \tau_i^2 e^{-t/\tau_i} \left( e^{A_{MAX}/\tau_i} - 1 \right) \right) \quad \text{Equation 5}$$

Where,  $a_0 = 0.2173$ ,  $a_1 = 0.224$ ,  $a_2 = 0.2824$ ,  $a_3 = 0.2763$ , and  $\tau_1 = 394.4$ ,  $\tau_2 = 36.54$ ,  $\tau_3 = 4.304$

CRF is often used in some capacity as part of other climate metrics. For instance, GWP relies on the CRF of a GHG at a certain time (usually 20 and 100 years) relative to the CRF of CO<sub>2</sub> at that same time (IPCC 2014). Similarly, TWP is the ratio of the CRF of two technologies over the same time period (Alvarez et al. 2012). CRF can also be used as a standalone indicator of climate impacts (Peters et al. 2011). CRF allows a comparison of the climate impacts over an infinite time frame, thereby avoiding the need to arbitrarily select a certain time horizon as GWP does. In



this paper we use the IPCC's approach from AR5 (IPCC 2014) to derive radiative forcing, and then integrate the values over time. An impulse response function (IRF) governs the removal of each gas from the atmosphere. The convolution of an emission function with its IRF provides the mass of a gas in the atmosphere over time. Parameter values for  $a_i$  and  $\tau_i$  in the IRF of  $\text{CO}_2$  and  $\text{CH}_4$  are the same as used for TWP analysis.

$$IRF_{\text{CO}_2}(t) = a_0 + \sum_{i=1}^N a_i \exp\left(-\frac{t}{\tau_i}\right) \quad \text{Equation 6}$$

$$IRF_{\text{CH}_4}(t) = \exp\left(-\frac{t}{\tau}\right) \quad \text{Equation 7}$$

Multiplying the atmospheric mass of a greenhouse gas by its radiative efficiency (RE) gives the radiative forcing from that gas in a given year (Equation 8). We include indirect effects of methane on ozone and stratospheric water by increasing the RE of methane by 65%, consistent with AR5. Furthermore, we account for the decay of fossil methane to  $\text{CO}_2$  using methods described in Boucher et al. (2009) and Schivley et al. (2015). Finally, unlike the TWP equations previously described, we include carbon-climate feedbacks using methods described in Collins et al. (2013) and Schivley et al. (2015).

$$RF_i(t) = RE_i \int_0^t g_i(t') IRF_i(t - t') dt' \quad \text{Equation 8}$$

Where

$g_i(t')$  is the emission function for GHG  $i$

$$RE_{\text{CO}_2} = 1.7517 \times 10^{-15} \text{Wm}^{-2} \text{kg}^{-1}$$

$$RE_{\text{CH}_4} = 1.2767 \times 10^{-13} \text{Wm}^{-2} \text{kg}^{-1}$$

Equations 9 and 10 describe the final step for estimating the cumulative radiative forcing.

$$CRF_{\text{CO}_2}(t) = \int_0^t RF_{\text{CO}_2}(t) dt \quad \text{Equation 9}$$

$$CRF_{\text{CH}_4}(t) = \int_0^t RF_{\text{CH}_4}(t) dt \quad \text{Equation 10}$$

Shine and colleagues (2005) introduced Absolute Global Temperature Change Potential (AGTP), which has units of  $\frac{\Delta^\circ\text{K}}{\text{kg (of gas emitted)}}$ . This metric allows for the simple calculation of the temperature change (in  $\Delta^\circ\text{K}$ ) at time (t) associated with  $\text{CO}_2$  and  $\text{CH}_4$  emissions. AGTP equations are available for sustained emissions (AGTP<sub>s</sub>) and pulse emissions (AGTP<sub>p</sub>). AGTP<sub>s</sub> does not allow for the evaluation of a sustained emission of a finite length further into the future than the length of that sustained emission (i.e. we cannot see the impacts of a power plant that was operational for 30 years, 100 years into the future). For this reason, we modeled AGTP<sub>p</sub> for fossil carbon for 30 annual emission pulses using Equations 11 and 12, which came from AR5 (IPCC 2014). Consistent with the procedure in AR5, the value for  $\text{CH}_4$  radiative forcing ( $A_{\text{CH}_4}$ ) includes a 65% increase due to indirect radiative forcing from methane that results via changes in ozone and stratospheric water vapor (IPCC 2014). We multiply the annual emissions (kg) by the

AGTP values to arrive at the temperature change in a given year (annual AGTP) and integrate from year zero to calculate the cumulative AGTP.

$$AGTP_P^{CH_4}(t) = A_{CH_4} \sum_{j=1}^2 \frac{\tau c_j}{\tau - d_j} \left[ e^{-t/\tau} - e^{-t/d_j} \right] \quad \text{Equation 11}$$

Where

$AGTP_P^{CH_4}(t)$  is the Absolute Global Temperature Change Potential for CH<sub>4</sub> at time t (in years);

$A_{CH_4}$  is CH<sub>4</sub> radiative forcing = 2.145 x 10<sup>-13</sup> W/kg-m<sup>2</sup>;

$c_1 = 0.631$ ,  $c_2 = 0.429$ ;

$d_1 = 8.4$ ,  $d_2 = 409.5$ ; and

$\tau$  is 12.4.

$$AGTP_P^{CO_2}(t) = A_{CO_2} \sum_{j=1}^2 \left\{ a_0 c_j \left( 1 - e^{-t/d_j} \right) + \sum_{i=1}^3 \frac{a_i \alpha_i c_j}{\alpha_i - d_j} \left[ e^{-t/\alpha_i} - e^{-t/d_j} \right] \right\} \quad \text{Equation 12}$$

Where

$AGTP_P^{CO_2}(t)$  is the Absolute Global Temperature Change Potential for CO<sub>2</sub> at time t (in years);

$A_{CO_2}$  is CO<sub>2</sub> radiative forcing = 1.7517 x 10<sup>-15</sup> W/kg-m<sup>2</sup>;

$a_0 = 0.2173$ ,  $a_1 = 0.2240$ ,  $a_2 = 0.2824$ ,  $a_3 = 0.2763$ ;

and  $\alpha_1 = 394.4$ ,  $\alpha_2 = 36.54$ ,  $\alpha_3 = 4.304$ .

A limitation of all the metrics previously described is that in addition to CO<sub>2</sub> and CH<sub>4</sub>, coal and natural gas power plants emit other gases that also have climate forcing impacts. Sulfate aerosols and organic carbon, for example, have been shown to provide a negative climate forcing (“cooling”) (IPCC 2014; Bond et al. 2011), while black carbon has been shown to provide a positive climate forcing (“warming”) (Bond et al. 2011; Skodvin and Fuglestedt 1997; Fuglestedt et al. 2000). Coal power plants have traditionally been the largest source of sulfate aerosol emissions (US EPA 2013; IPCC 2014). A reduction of sulfur emissions from PC power plants thus results in an additional positive warming feedback in the short term. T. M. L. Wigley (2011) showed this effect in his analysis of a power plant fleet conversion from coal to natural gas. He found that even if the CH<sub>4</sub> leakage rate of the natural gas system were zero, the transition to natural gas for power generation would result in short term warming as a result of the reduction in sulfate aerosols and in black carbon. The analysis presented in this paper does not include the climate impacts of sulfur or black carbon emissions. This, however, should not represent a significant bias in our comparisons between coal and natural gas. Advanced PC plants with pollution control technologies like the ones we modeled in this paper have very low sulfur and black carbon emissions that are comparable to those of NGCC plants (Rubin et al.

2007; Tong et al. 2015a). Thus, the power plants we modeled would incur the same “warming penalty” that may be associated with reducing sulfate aerosols from conventional power plants.

In addition to the climate metrics described above, we also performed an analysis using MAGICC6, a simplified climate model that couples atmosphere-ocean interactions and the carbon cycle (Wigley et al. 2014). We include MAGICC6 in this analysis in order to validate that the results from the different climate metrics provides results that are consistent with those of a climate model. MAGICC6 takes as input a user-defined emissions pathway and determines the resulting concentration of GHGs and global mean surface air temperature. We examined the IPCC’s representative concentration pathways (RCPs) for scenarios across a range of future possibilities, stabilizing in 2100 at either 4.5 or 8.5 W/m<sup>2</sup> (Van Vuuren et al. 2011a, 2011b; Meinshausen et al. 2011). The RCPs are commonly used and well defined plausible climate futures that could occur as a function of different global energy use pathways. They replicate global emissions, including sectors such as energy and transportation, at increments of a year or more. They are consistent with certain socio-economic assumptions, but should not be directly compared to each other. Unfortunately, since MAGICC6 is a global climate model, the model is unable to capture small changes in emissions associated with the construction of a single power plant. For this reason, we model three large-scale technology deployment scenarios. First we run MAGICC6 using 30 years of emissions from operating 300 gigawatts (GW) of coal capacity (in the form of PC plants with and without CCS, as well as USCPC plants with and without CSS). We then run a scenario that deploys 300 GW of natural gas capacity (in the form of NGCC plants with and without CCS) and compare the results. A limitation of this method is that we are calculating small differences between two global scenarios, and the model output is beginning to near the precision error of the model. Nonetheless, the comparison of the outputs of MAGICC6 to the climate metrics provides validation.

## Results

Here we present the results of these methods assuming a 30-year plant lifetime; Appendix S4 in the Supporting Information summarizes the results of an analysis assuming 60-year plant lifetime. Figure 1 shows the life cycle GHG of coal and natural gas-based electricity using GWP. This figure shows the cumulative distribution functions of the emissions factors for each power plant scenario summarized in Table 2. These cumulative distribution functions result from the normal distribution for the GWP of CH<sub>4</sub>, which was derived from AR5 (IPCC 2014; Tong et al. 2015a, 2015b). Figure 1 shows that using the 100-year GWP value for CH<sub>4</sub>, natural gas-based electricity always has lower GHG emissions than coal-based electricity, within the leakage rates we evaluated in this study. With a 20-year GWP, however, there is a probability that natural gas becomes worse than coal when leakage rates reach 4%. This figure also shows that beyond a 2% leakage rate, NGCC with CCS has higher life cycle GHG emissions than a PC (or a USCPC) plant with CCS.

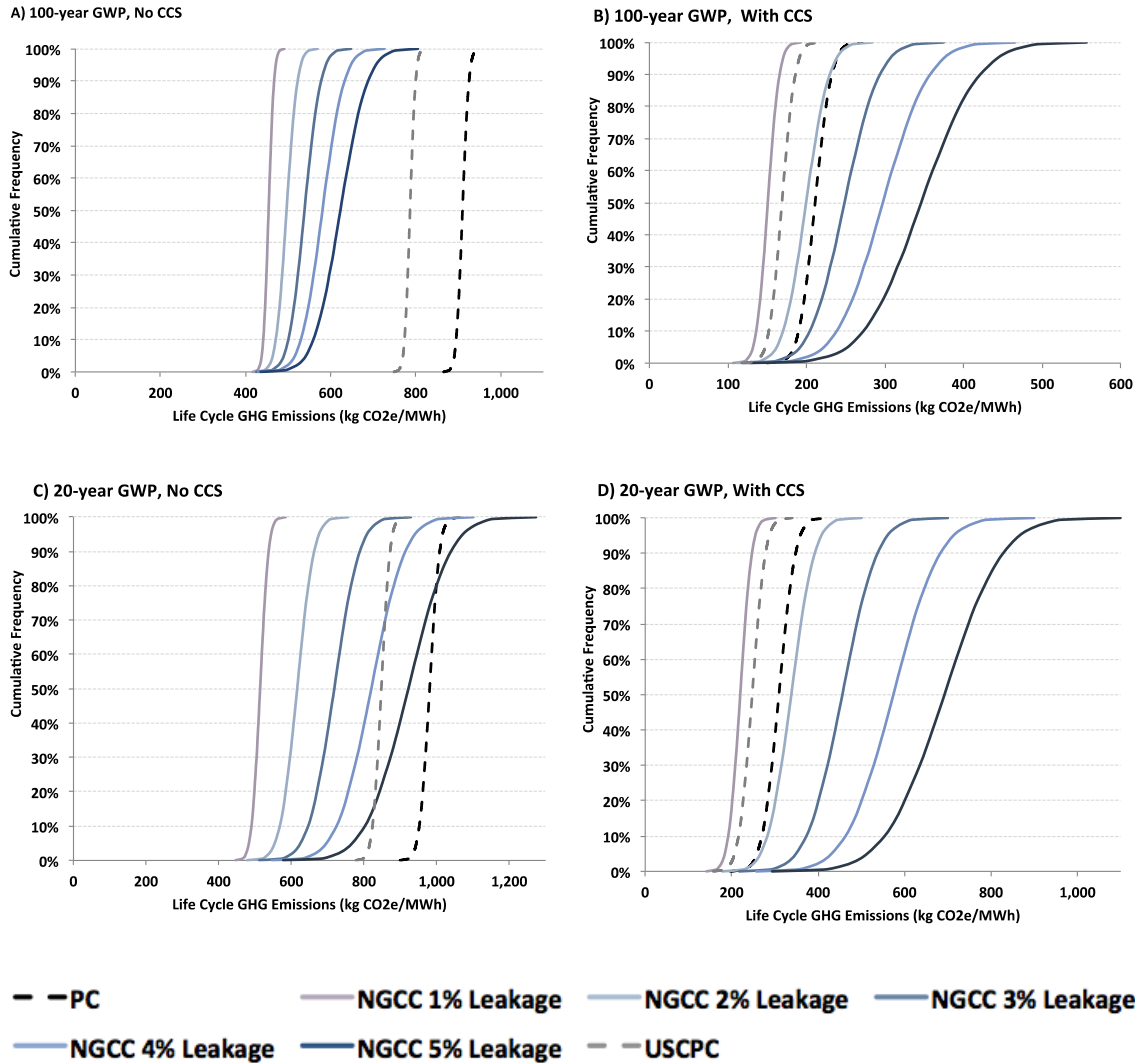


Figure 1: Life cycle GHG emissions comparison between coal and natural gas for power generation using GWP. A. 100-year GWP for methane in plants without CCS. B. 100-year GWP for methane in plant with CCS. C. 20-year GWP for methane in plants without CCS. D. 20-year GWP for methane in plant with CCS. All values include climate-carbon feedbacks. All CCS cases assume 90% capture.

Figure 2 shows the TWP results. Figure 2a shows the results for plants without CCS. If methane leakage rates remain below 5%, using natural gas to generate electricity results in lower CRF than coal at all time frames. At 5%, it would take 15 years for natural gas to produce lesser CRF relative to coal. At all points in time, the USCPC plant produces less forcing than a PC plant (a result that is consistent throughout all metrics) and greater forcing than NGCC plant at 3% leakage or less. It takes about 20 and 40 years for the USCPC plant's CRF to surpass that of NGCC with 4% and 5% leakage, respectively.

Figure 2b shows the TWP results when both plants are equipped with CCS; the time axis is extended to 500 years in this panel in order to show the magnitude to which CCS affects the analysis. In this case, natural gas is always better than coal at a leakage rate of 1%. At leakage rates of 2%, 3%, and 4%, coal is better until after years 45, 150, and 275, respectively. For a methane leakage rate of 5%, CRF for natural gas is still higher than that of the PC plant after 400 years. The USCPC plant with CCS produces lower CRF than all plants except NGCC at 1% leakage over the full 500-year time frame. As stated, all of the power plants in our scenarios stop operating, and thus stop emitting CO<sub>2</sub> and CH<sub>4</sub>, after 30 years. In both panels we see NGCC plants begin to converge at the end of our observed timeframe. This is due to the relatively shorter atmospheric lifetime of CH<sub>4</sub>; after emissions stop in year 30, the long-lived CO<sub>2</sub> (which is constant across all leakage rates) becomes the dominant contributor to CRF.

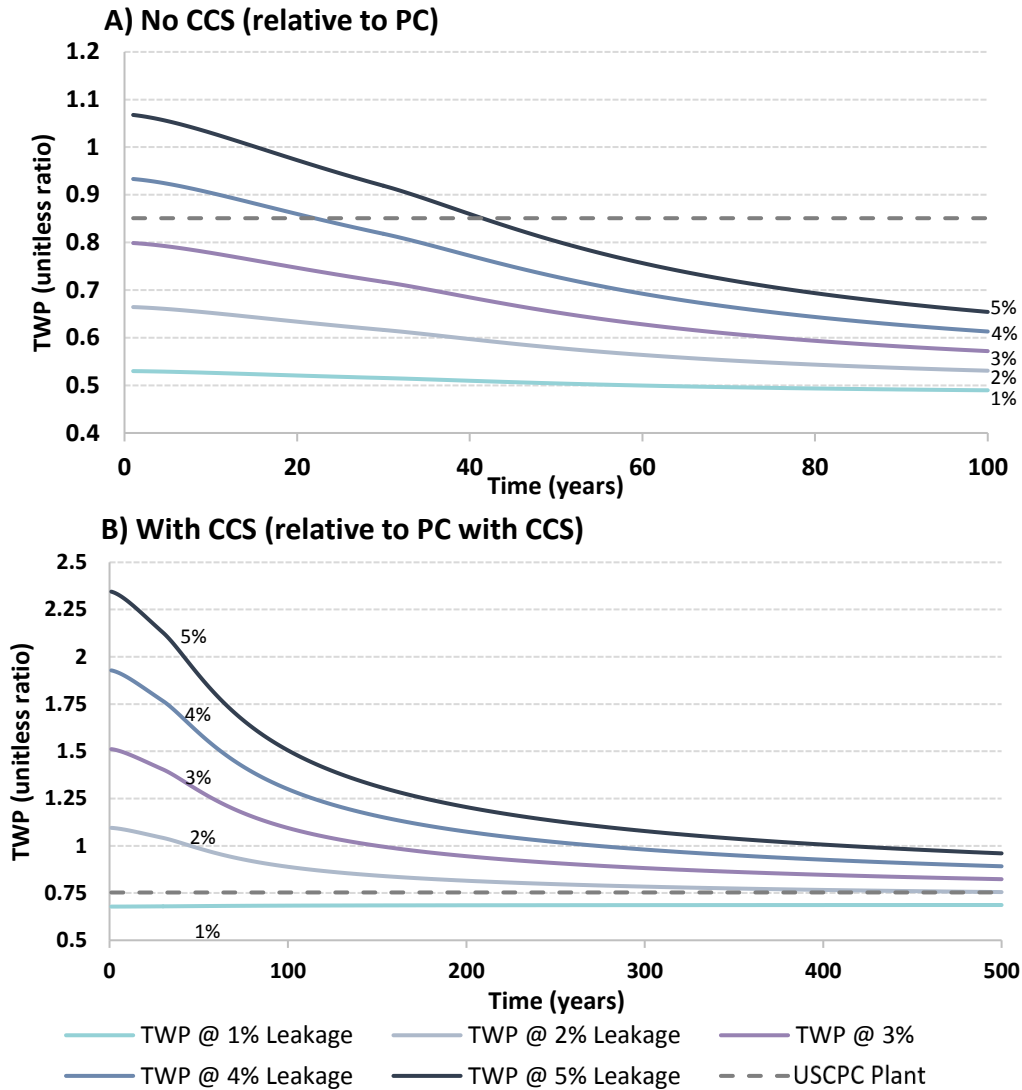
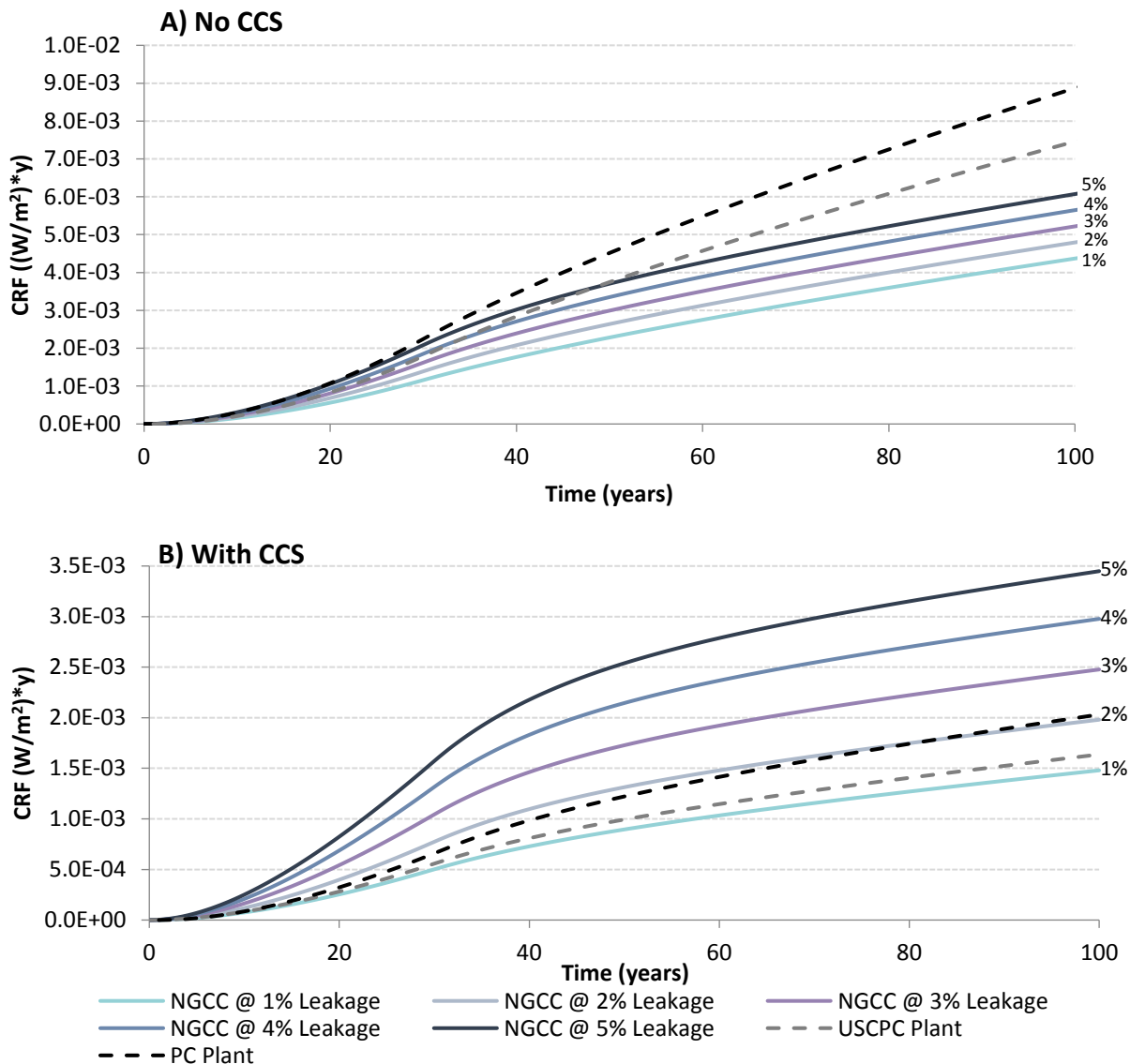


Figure 2: Technology Warming Potential Analysis. A TWP value of one corresponds to the CRF of the relative plant. **A.** Comparison of a NGCC plant and USCPC plant relative to a PC plant without any CCS. **B.** NGCC plant and USCPC plant, with CCS vs. a PC plant, with CCS.

Figure 3 shows the results of the CRF comparisons. The y-axis in this figures represent the CRF with units of  $\frac{W \times yr}{m^2}$ . Figure 3a displays the results without CCS. This panel shows that the CRF from a PC plant without CCS is greater than that of a NGCC plant at leakage rates of 4%. At a 5% leakage rate, NGCC carries greater cumulative forcing through the first 20 years, then the PC plant has the greatest forcing. The USCPC plant produces lower CRF than all NGCC plants at 3% leakage or less, while surpassing the CRF of natural gas plants with 4% and 5% leakage after about 25 and 45 years, respectively.

Figure 3b displays a PC plant, USCPC plant, and an NGCC plant with CCS at varying leakage rates. A NGCC plant with methane leakage rates of 1% produces the least cumulative forcing

among CCS plants throughout the 100 year time frame. Conversely, at leakage rates of 3% and above, the NGCC plant with CCS always produces greater cumulative forcing through the observed time frame. At a 2% leakage rate we observe cumulative forcing from the NGCC plant without CCS greater than that of a PC plant with CCS through the first 80 years. The USCPC plant with CCS produces greater CRF than that of a CCS NGCC plant with 1% leakage although the rates are similar throughout the observed time frame. Unlike the GWP, the comparison of the CRF provides a clearer idea of the magnitude of the difference in climate impacts of the different plant types. The difference in the CRF of natural gas and coal plants over 100 years are much higher than the difference over 20 years across all leakage rates in the natural gas system. If CCS is available in all plants, however, the difference in the CRF of coal and natural gas is practically the same across the two time periods if the life cycle CH<sub>4</sub> leakage rate of natural gas is 2%. Beyond a 2% leakage rate, the difference between the natural gas and coal plants with CCS is larger after 100 years than after 20 years, with the natural gas having a larger CRF than the coal plants.



*Figure 3: Cumulative Radiative Forcing Analysis including indirect RF from CH<sub>4</sub>. A. CRF of PC plant, USCPC plant, and NGCC plants at different leakage rates without CCS B. CRF of a PC plant, a USCPC plant, and NGCC plants at different leakage rates with CCS. These figures include climate-carbon feedbacks.*

We use annual AGTP to illustrate the direct temperature effects due to a single plant's emissions over time. Figure 4 shows the temperature change that results from the various plants and methane leakage rates modeled. Again, the temperature change results from multiplying the annual emissions by the AGTP values for a given time horizon and account for the indirect radiative forcing of CH<sub>4</sub> emissions due to changes in stratospheric ozone and water vapor, consistent with AR5 (IPCC 2014). In the non-CCS cases (figure 4a), after 15 years, annual temperature changes from the PC plant are always greater than those of the natural gas plant, regardless of the leakage rate. Prior to year 15, only the NGCC plant with 5% leakage produces greater annual temperature change. The USCPC plant produces greater temperature change than NGCC with 3% leakage or lower. After years 20 and 35, the USCPC plant produces greater temperature change than NGCC with 4% and 5% leakage, respectively. The temperature change peaks about 5 years after emissions end in year 30, but the long lifetime of CO<sub>2</sub> results in temperature increasing many years beyond this point. The delay in peak temperature change beyond the final year of power plant operation is due to inertia in the climate system (Ricke and Caldeira 2014). Furthermore, this figure makes it clear that the emissions from the coal plants result in higher temperatures for a longer period of time than the emissions from the natural gas plant. This is true even for the USCPC, which has the same peak temperature increase as the NGCC plant with 5% leakage, but leads to higher temperatures between years 40 and 100 than the NGCC emissions over that same period.

With CCS (figure 4b), a NGCC plant with a 1% leakage rate produces the least annual temperature change throughout the 100-year time frame we examined. At a 2% leakage rate, the NGCC plant emissions produces slightly greater temperature change for the first 35 years than the emissions of a PC plant. After year 35, the rates diverge and the warming from the PC plant exceeds that of the NGCC plant. Annual temperature increases from NGCC at 3%, 4%, and 5% leakage rates are higher than those from PC until approximately 60, 70, and 75, years later, respectively. A CCS USCPC plant produces lesser annual temperature changes than all other CCS equipped plants except NGCC with 1% leakage.



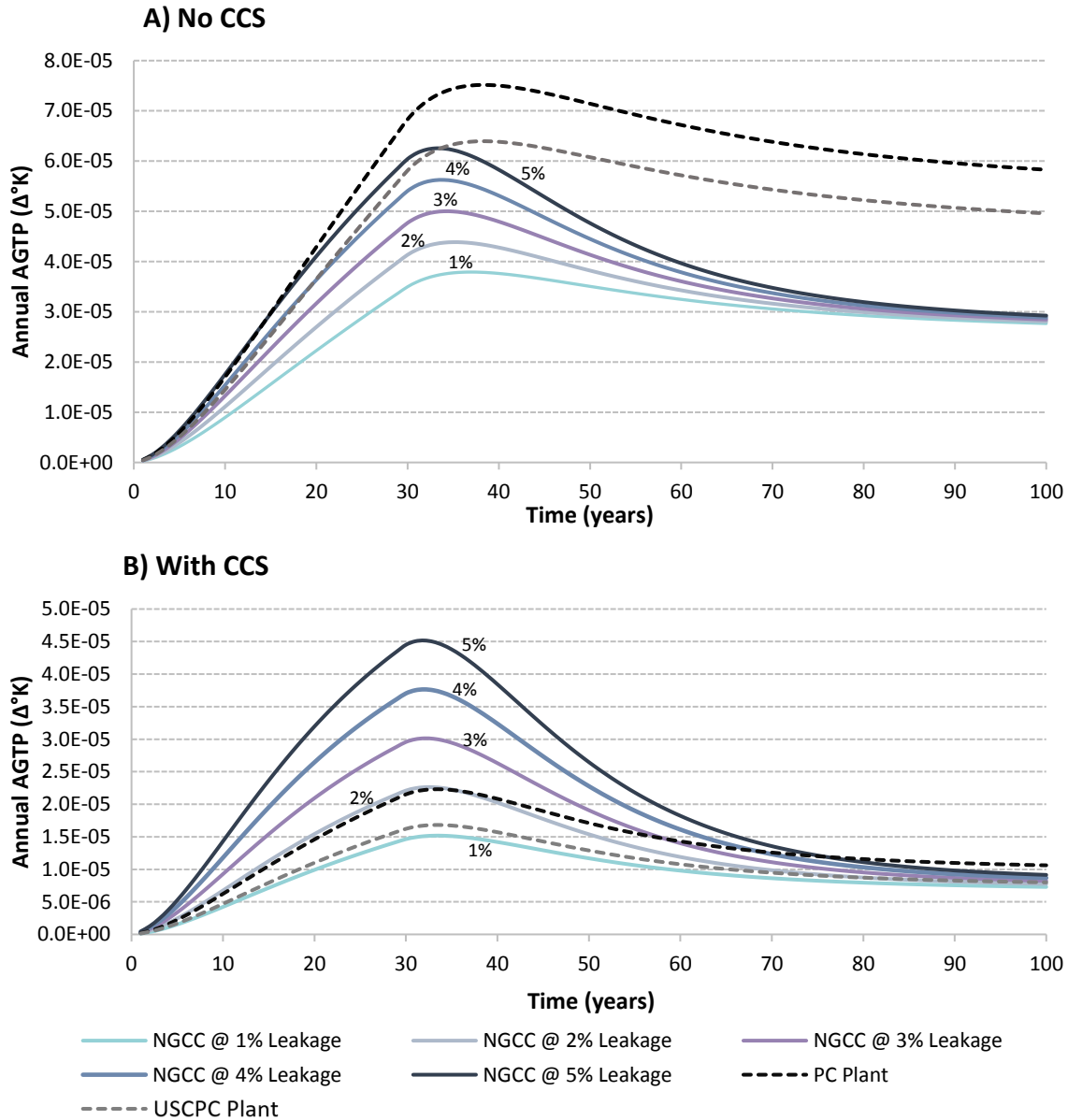


Figure 4: Annual Temperature Change by Plant Type and Methane Leakage Rate including indirect RF from  $\text{CH}_4$  via changes in stratospheric ozone and water vapor. **A.** Non-CCS plants. **B.** CCS Plants.

Figure 5 illustrates the cumulative temperature effects from the plants modeled (including the indirect radiative forcing of  $\text{CH}_4$  emissions due to changes in stratospheric ozone and water vapor). These figures represent the summation of the year on year changes (i.e. the temperature increase from year one and year two are accounted for in the cumulative AGTP in year three). Without CCS (figure 5a), the NGCC plant produces greater cumulative warming than the PC plant with a 5% leakage rate, but only through the first 20 years. After this period, the cumulative temperature increase of the PC plant is higher than that of the NGCC plants, regardless of the methane leakage rate. Again, we see that the USCPC plant produces cumulative temperature change greater than that of NGCC at 3% leakage or less. The cumulative temperature change

from a USCPC plant exceeds that of 4% and 5% leakage after about 30 and 50 years, respectively. If CCS is available on both the PC and NGCC plants (B), the cumulative temperature change from coal emissions is less than that of natural gas with a 2% leakage rate until approximately year 50. Within our 100-year analysis, emissions from the PC with CCS plant never increase temperatures past that of the NGCC with CCS plant at 3% or greater leakage rates. With CCS, USCPC plant produces lesser temperature change than all other CCS plants except NGCC with 1% leakage throughout the 100-year time frame. The non-zero convergence (within 100 years) in the annual AGTP indicate that despite the plants going offline in year 30, their emissions lead to a permanent increase in temperature even with CCS. We can observe this increase in the cumulative AGTP figures, which retain a positive slope.

Note that the graph of cumulative AGTP is similar in shape to that of CRF. This is because AGTP is dependent on the forcing of each gas as shown in equation 11 and 12, although it presents the data in a more intuitive framing (temperature increase versus radiative forcing). The drawback of the AGTP is that it relies on climate sensitivity assumptions, which can be highly uncertain. Thus, while the results in Figure 4 and Figure 5 may be more intuitive than those in Figure 3, they are also subject to increased uncertainty.

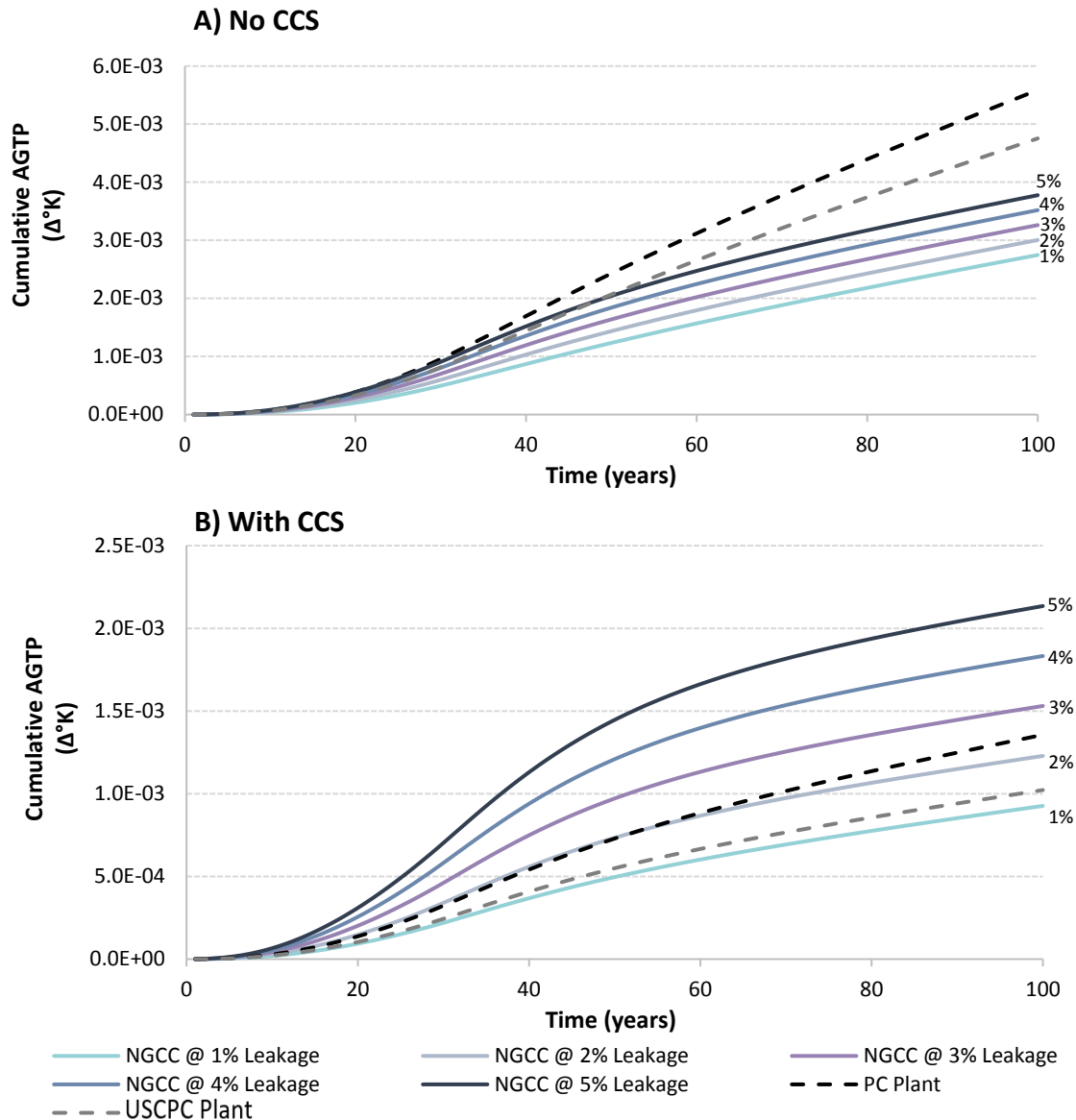


Figure 5: Cumulative Global Temperature Change Analysis including indirect RF from  $CH_4$  via changes in stratospheric  $H_2O$ . **A.** Comparison of a PC plant vs. a NGCC plant at varying methane leakage rates, without any CCS. **B.** PC plant vs. NGCC plant at varying methane leakage rates, with CCS.

As described in the *Methods* section, to run the MAGICC6 model we first ran a simulation using 30 years of emissions (starting in 2016) from operating 300 GW of coal capacity (in the form of PC plants with and without CCS). We then run simulations that deploy 300 GW of natural gas capacity (in the form of NGCC plants with and without CCS) or 300 GW of coal capacity in the form of USCPC plants, and compare the results. Note that the MAGICC6 model provides results up to 2100, so the model only covers the climate impacts over 85 years. Figure 6 shows the change in temperature from the business as usual (BAU) MAGICC6 cases that result from the emissions from 300 GW of PC, USCPC, and NGCC plants. Without CCS, the emissions from

300 GW PC and USCPC plants lead to significantly higher temperature changes compared to the BAU than the emissions from 300 GW of NGCC plants, regardless of the CH<sub>4</sub> leakage rate or the RCP scenario. Note, however, that the temperature change from the BAU scenario is lower under RCP 8.5. This may occur because the RCP 8.5 assumes the highest emissions trajectories in the BAU, where some of the climate-carbon feedbacks may be less effective. If CCS is available, the emissions in the scenarios with CH<sub>4</sub> leakage rates below 2% results in NGCC plants with lower temperature increase than the PC plants. At a 3% leakage rate, the cumulative warming from the NGCC plants starts being lower than for the PC plants in 2065. Compared to the USCPC plants with CCS, the NGCC plants only offer benefits if leakage rates remain below ~1%. At 4% and 5% leakage rates, NGCC plants lead to significantly higher temperatures until 2080.

Whereas CCS can be available in NGCC plants, most of the research and discussion of CCS has focused on PC and USCPC plants, and the cost per GHG ton avoided for CCS is lower for coal than NGCC plants (Fout et al. 2015). It is thus possible that deployment of CCS will occur in these coal plants before it occurs in NGCC plants. Figure S13 and S14 in the supporting information include the results of the comparison of NGCC plants without CCS and coal plants with CCS for cumulative AGTP and TWP. The results of this comparison suggest that if CCS is deployed in coal-based plants but not on NGCC plants, the climate impacts of the coal-based plants could be lower, even at low CH<sub>4</sub> leakage rates. Thus, the potential benefits of new natural gas plants over new coal plants could disappear if CCS is available only in coal power plants.

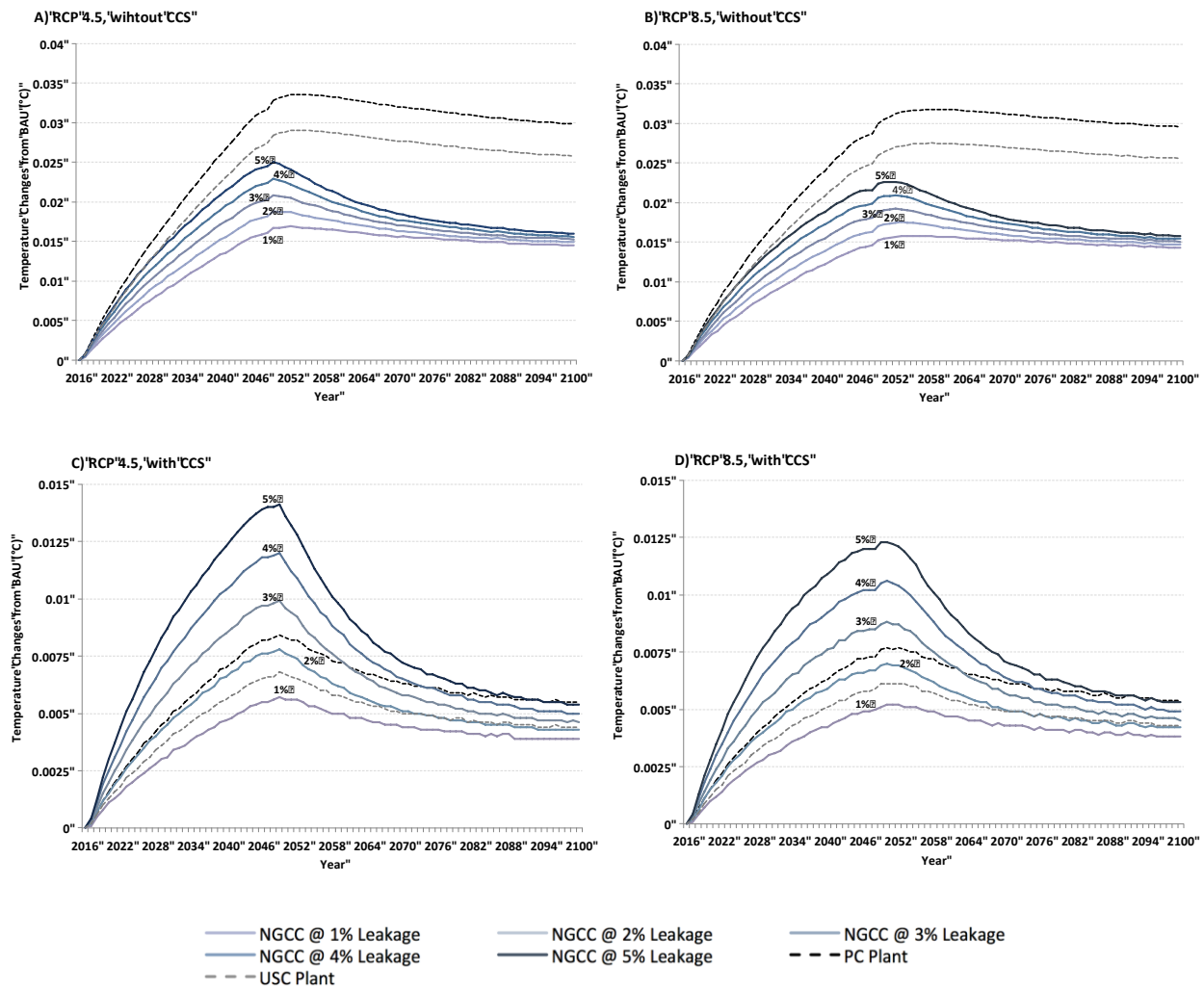


Figure 6: MAGICC results for A. RCP 4.5 without CCS, B. RCP 8 without CCS, C. RCP 4.5 with CCS, D. RCP 8 with CCS.

A different method of comparing metrics is by calculating the break-even leakage rate. Here we define the break-even leakage rate as the life cycle leakage rate (percentage of delivered natural gas lost as CH<sub>4</sub>) at which the natural gas used in a NGCC plants would have the same climate impacts as coal used in a PC plant (or an USCPC plant) at a given year. In conducting this analysis for GWP, TWP, and both types of AGTP, we take an analytical approach and (1) identify pertinent equations, (2) set the value dependent on leakage rate (i.e. the temperature change in year 50 from an NGCC plant found using annual AGTP) equal to that of another (i.e. the temperature change in year 50 from a PC plant found using annual AGTP), and (3) back solve to calculate the lifecycle methane leakage rate necessary to produce such an outcome. A strength of this approach is that it allows any leakage rate between 0 and 100% to be identified as the break-even leakage rate. However, a weakness of this approach is that it requires the ability

to obtain an analytical solution. We performed a similar break-even analysis of CRF using an iterative numerical method to test leakage rates at intervals of less than 0.1%. A break-even calculation of the MAGICC6 temperature change values is not included in this analysis.

Table 3 summarizes the break-even methane leakage rate for the different climate metrics. It is noteworthy that TWP, cumulative AGTP, and CRF provide consistent break-even leakage rates across the years considered. Furthermore, these rates are not substantially different for the GWP values. The results for annual AGTP at 50 and 100 years without CCS, however, differ considerably from the other metrics. The break-even life cycle CH<sub>4</sub> leakage rate in these years is very high. Annual AGTP provides a measure of the change in temperature in a particular year. Since methane has a short half-life, the effect on the temperature change from CH<sub>4</sub> emissions in year 50 (20 years after the plants have stopped operating) is greatly diminished. Thus for the change necessary to match impacts that far into the future, extreme quantities of CH<sub>4</sub> must be emitted during the plant lifetime.

The results in Table 3 highlight that without CCS, natural gas offers opportunities for reducing short-term (30 years) climate impacts compared to coal as long as life cycle CH<sub>4</sub> leakage rates remain below ~5%. If life cycle CH<sub>4</sub> leakage rate remains below 12% (volume of natural gas lost as methane), natural gas could offer long-term (100 years) climate benefits compared to coal used in a pulverized coal plants. If CCS is available at coal and natural gas plants, life cycle methane leakage rates have to remain below 2% in order for natural gas to offer short and long-term climate benefits. Similarly, if USCPC plants become economically viable, the life cycle CH<sub>4</sub> leakage rate has to remain below 4.5% in order for the NGCC plant to offer short-term (30 years) benefits but can be as high as 10% for long term benefits. If CCS is available in both an USCPC plant and an NGCC plant, then the life cycle CH<sub>4</sub> leakage rate for natural gas has to remain below 2%.

Table 3: Break-even methane leakage rate at which a NGCC plant has same climate impacts as a PC plant.

Metric	PC and NGCC Plants without CCS					PC and NGCC Plants with CCS				
	Years after plants start operating					Years after plants start operating				
	10	20	30	50	100	10	20	30	50	100
20-yr GWP*	-	5.7%	-	-	-	-	-	-	-	-
100-yr GWP*	-	-	-	-	12.5%	-	-	-	-	2.6%
TWP	4.8%	5.2%	5.8%	7.7%	12.4%	1.8%	1.8%	1.9%	2.0%	2.5%
Annual AGTP**	4.8%	5.4%	6.2%	12.6%	78.8%	1.8%	1.9%	1.9%	2.5%	8.2%
Cumulative AGTP	4.6%	5.0%	5.5%	6.9%	12.0%	1.8%	1.8%	1.9%	2.0%	2.4%
CRF	4.8%	5.2%	5.7%	7.3%	11.6%	1.8%	1.8%	1.9%	2.0%	2.4%
Metric	Ultra super critical PC and NGCC Plants without CCS					Ultra supercritical PC and NGCC Plants with CCS				
	Years after plants start operating					Years after plants start operating				
	10	20	30	50	100	10	20	30	50	100
20-yr GWP*	-	4.4%	-	-	-	-	1.4%	-	-	-
100-yr GWP*	-	-	-	-	9.4%	-	-	-	-	1.6%
TWP	3.6%	3.9%	4.3%	5.6%	9.8%	1.2%	1.2%	1.2%	1.2%	1.3%
Annual AGTP**	3.6%	4.0%	4.6%	9.2%	56.7%	1.2%	1.2%	1.2%	1.3%	2.5%
Cumulative AGTP	3.5%	3.8%	4.1%	5.1%	8.8%	1.2%	1.2%	1.2%	1.2%	1.3%
CRF	3.6%	3.9%	4.3%	5.4%	8.5%	1.2%	1.2%	1.2%	1.2%	1.3%

\* Reports the mean of the distribution for the breakeven CH<sub>4</sub> leakage rate that relies on the distribution of the GWP from (IPCC 2014). Figures S1 to S8 in the SI show the distribution of these breakeven leakage rates using GWP.

\*\* Annual AGTP is the only instant metric shown in this breakeven analysis, but results would be similar for GTP or temperature results from MAGICC6. Without CCS, the breakeven leakage rate increases dramatically after the end of power plant operations as methane decays.

## Discussion

In this article we compare the climate impacts of electricity generated with coal in a new advanced power plant (PC or USCPC) and a new NGCC plant, both with and without CCS, in the United States. In addition to GWP for 20 and 100 years, we use TWP, CRF, AGTP, and the MAGICC6 model. While each of the different methods yields slightly different curves, this analysis finds that using natural gas instead of coal for power generation will likely have lower climate impacts if the CH<sub>4</sub> leakage rate is below 2%. This is a highly robust finding, and holds across the climate metrics evaluated. This robustness across the climate metrics and the simplified climate model occurs because the approaches rely on similar variables. GWP, TWP and CRF in particular, are closely related as TWP is a ratio of the CRF value of the two technologies. While it is not clear whether any of these metrics are better than the others, the choice of metric can inform decisions based on different societal values. For example, while annual temperature change reported in Figure 4 may be a more relevant metric to evaluate the human health effects of increased heat, the cumulative temperature change in Figure 5 may be more relevant to evaluate climate impacts, like sea level rise, that will result from the cumulative warming.

The robustness of our results suggests that, even in the absence of known value choices guiding analysts toward using a specific metric, decision makers should consider shifting from coal to natural gas if the methane leakage rate is below 2%. Since the actual leakage rate is uncertain, this would suggest that in order to ensure the climate benefits of this shift, a decision maker would need to enact and enforce a leakage rate reduction and verification program. We also note that our results are based on leakage rates defined as the percentage of delivered natural gas lost as CH<sub>4</sub>, yet pipeline natural gas contains a small and varying percentage of several other gases. Hence leakage rate reduction and verification programs should distinguish between components of natural gas with climate forcing potentials and those without. We further suggest that while the scenarios examined focus on in the United States, many of these results should be applicable across the globe.

Another interesting insight from this analysis relates to the effect of CCS deployment in the comparison between a single coal power plant and a single natural gas plant. If CCS is available in both types of plants, natural gas can still offer some climate benefits when it replaces coal. However, the benefits are smaller than when CCS is not available. If CCS became available only at coal power plants, then natural gas power plants without CCS would not offer climate benefits. While there has not been wide scale deployment of CCS, such technology may be critical in meeting climate mitigation targets (IPCC 2014). In addition, countries like China, which rely heavily on coal, are starting to invest on this technology (Hart and Liu 2010). Given the choice of building natural gas plants without CCS or coal plants with CCS, the results of this paper suggest that the coal plant would lead to lower climate impacts, regardless of the CH<sub>4</sub> leakage across the natural gas sector.

One limitation of this study is that we focus on a comparison of a single coal plant with a single natural gas plant. However, these plants operate within integrated power systems, which have to



operate under significant constraints. Previous work has shown that natural gas offers opportunities to support large-scale deployment of renewable resources like wind. For example, Oates and Jaramillo (2013) found that the availability of natural gas plants increased the emissions benefits that result from meeting a 20% wind energy target. In such a system, wind would displace coal, but would also drive natural gas to displace coal. As a result, a 20% wind penetration resulted in a 30% reduction in CO<sub>2</sub> emissions from power generation (Oates and Jaramillo 2013). On the other hand, there are concerns that cheap natural gas would lead to the retirement of nuclear generators or reduce the growth in renewables deployment, which would then result in a net increase in CO<sub>2</sub> emissions. It is thus important to highlight that while one natural gas power plant can result in lower climate impacts than one coal power plant, the overall benefits of large-scale deployments of natural gas plants will depend on the effects that this deployment may have on the capital and operational decisions across the entire power system. Of course, the use of natural gas for electricity generation still results in GHGs, and we find positive climate forcing (warming) associated with natural gas use with all the climate metrics in this paper. Furthermore, serious action to mitigate the impacts of climate change will require a significant transformation of the energy system, energy efficiency and conservation, as well as climate adaptation. In fact, scenarios to reach a 2°C stabilization target require the deployment of gross negative emissions to compensate for the continued use of gross positive emission sources like natural gas (Raupach et al. 2014; IPCC 2014).

## Conclusion

This paper reviews greenhouse gas metrics commonly used in life cycle assessment and policy analysis in several scenarios comparing electricity generation from coal and natural gas in the US. We find that the qualitative results of all the climate metrics are similar for the scenarios examined, which increases the confidence in the results. However, the different metrics provide different information that may be useful in the decision-making process. In models that aim to capture changes in GHG emissions over time, metrics that calculate results over time are better able to accurately show the evolution of impacts. Direct calculation of forcing, CRF, or AGTP also shows the absolute difference in results between systems, which is masked by the use of relative metrics such as GWP or TWP. Finally, unlike MAGICC6, many of these metrics can be employed in a simplified empirical model or in a breakeven analysis, thus further easing use. An expanded use of these alternative metrics can support the robustness of the analysis and provide additional information about the life cycle climate impacts of methane emissions from the energy system. These metrics may also be particularly suited for consequential life cycle assessments, which aim to capture the system-wide changes that results from interventions in the system.

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**Summary**

This supporting information document includes appendices S1 through S4. Appendix S1 contains more information about power plant characteristics and associated emissions given in table 2 of the main article. Appendix S2 contains a table that lists the indirect climate effects accounted for in each metric analyzed. Appendix S3 contains figures that show histograms of the breakeven leakage rates obtained using 10,000 simulations based on the full distribution of the GWP. Appendix S4 illustrates the extended analysis assuming plant operating lifetimes of 60 years, as opposed to 30 years.



## Appendix S1: Power plant Characteristics and Associated Emissions

This appendix contains more information about power plant characteristics and associated emissions given in Table 2 of the main article, where PC, USPC, and NGCC plants' Life Cycle CO<sub>2</sub> and CH<sub>4</sub> emissions are calculated as:

$$(Upstream\ CO_2 + Combustion\ CO_2) * \frac{3.6MJ/kWh}{Plant\ Efficiency} \quad \text{Equation S1}$$

And PC w/ CCS, USPC w/ CCS, and NGCC w/ CCS plants' Life Cycle CO<sub>2</sub> and CH<sub>4</sub> emissions are calculated as:

$$(Upstream\ CO_2 + Combustion\ CO_2 * (1 - Carbon\ Capture\ Rate)) * \frac{3.6MJ/kWh}{Plant\ Efficiency} \quad \text{Equation S2}$$

Annual CO<sub>2</sub> (all plants) emissions are:

$$\frac{Plant\ Capacity * Life\ Cycle\ CO_2 * 365days * 24hours * Capacity\ Factor}{10^9} \quad \text{Equation S3}$$

Finally, annual CH<sub>4</sub> (all plants) emissions are:

$$\frac{Plant\ Capacity * Life\ Cycle\ CH_4 * 365days * 24hours * Capacity\ Factor}{1000} \quad \text{Equation S4}$$

**Appendix S2: Indirect Climate Effects in Each Metric**

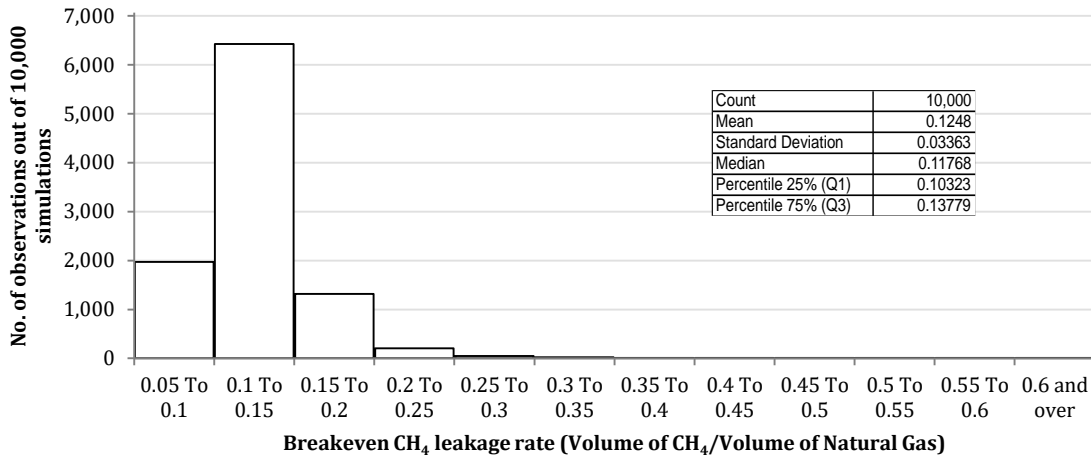
Table S1 lists the indirect climate effects accounted for in each metric analyzed.

*Table S1: List of indirect climate effects incorporated into each metric.*

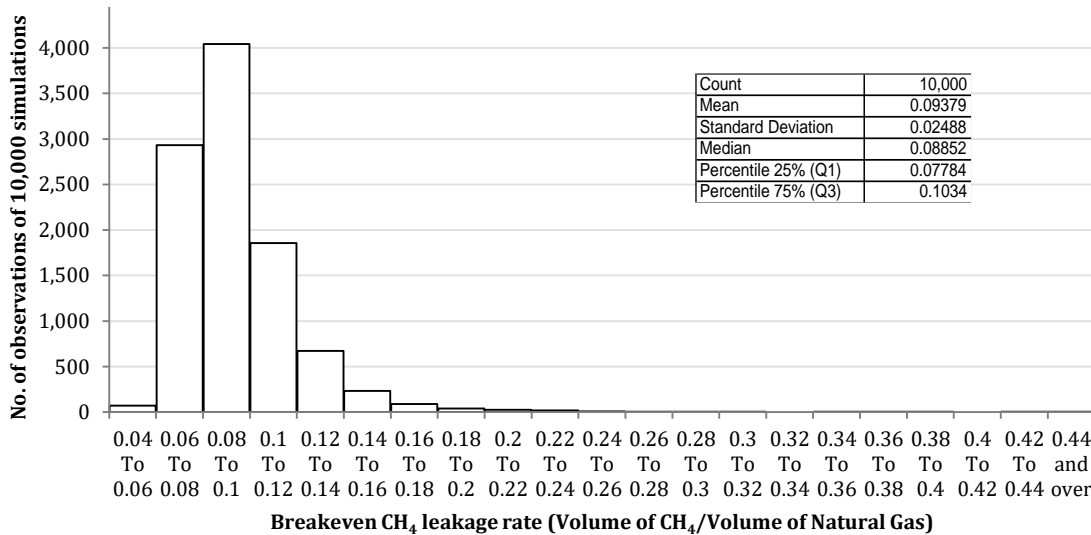
	<b>Tropospheric Ozone (+50%)</b>	<b>Stratospheric Water Vapor (+15%)</b>	<b>Climate- Carbon Feedback</b>	<b>Methane Oxidation</b>
<b>GWP</b>	✓	✓	✓	✓
<b>AGTP</b>	✓	✓		
<b>TWP</b>	✓	✓		
<b>CRF</b>	✓	✓	✓	✓
<b>MAGICC6</b>				

**Appendix S3: Breakeven leakage rate for GWP**

Table 3 in the main article reports the breakeven leakage rate at which the natural gas used in a NGCC plants would have the same climate impacts as coal used in a PC plant (or an USCPC plant) at a given year. The value reported when using GWP relies on the mean of the normal distributions of GWP values included in Figure 1. Figures S1 to S8 show the histograms of the breakeven leakage rates obtained using 10,000 simulations based on the full distribution of the GWP.



*Figure S1: Histogram of Breakeven CH<sub>4</sub> Leakage Rate - NGCC vs. PC w/o CCS and 100-year GWP*



*Figure S2: Histogram of Breakeven CH<sub>4</sub> Leakage Rate - NGCC vs. USCPC w/o CCS and 100-year GWP*

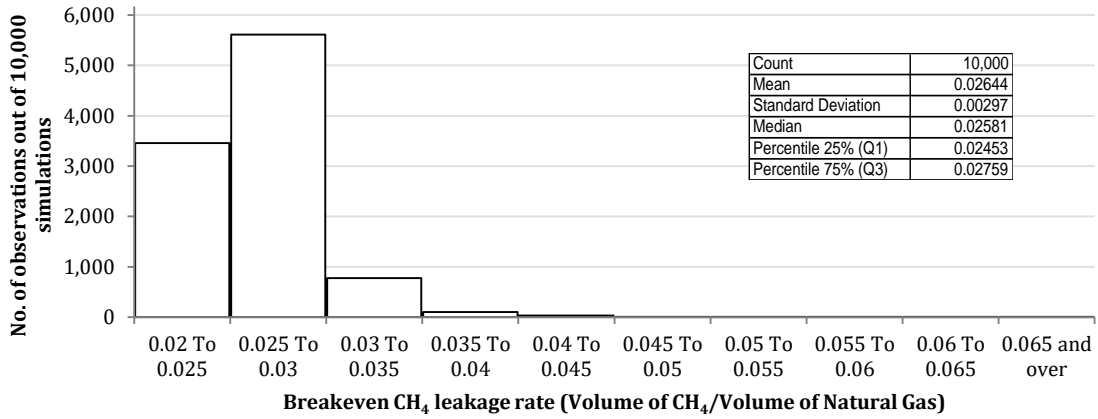


Figure S3: Histogram of Breakeven CH<sub>4</sub> Leakage Rate - NGCC vs. PC w/ CCS and 100-year GWP

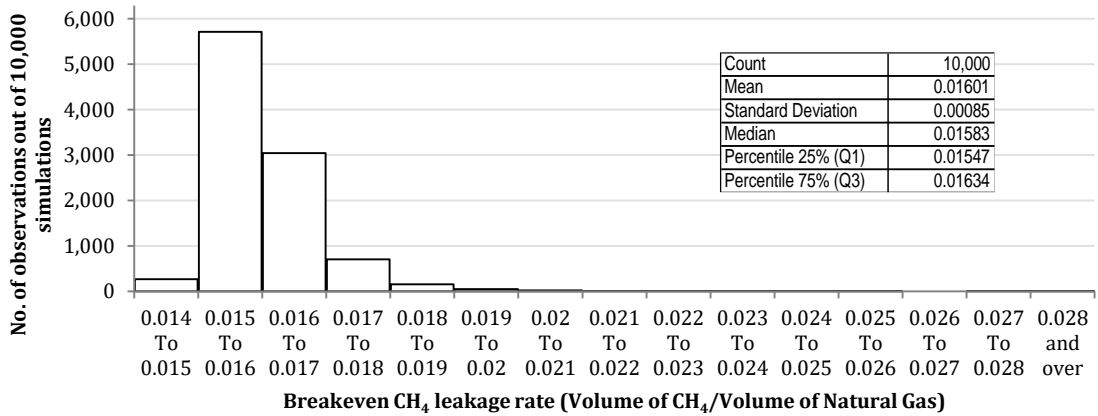


Figure S4: Histogram of Breakeven CH<sub>4</sub> Leakage Rate - NGCC vs. USCPC w/ CCS and 100-year GWP

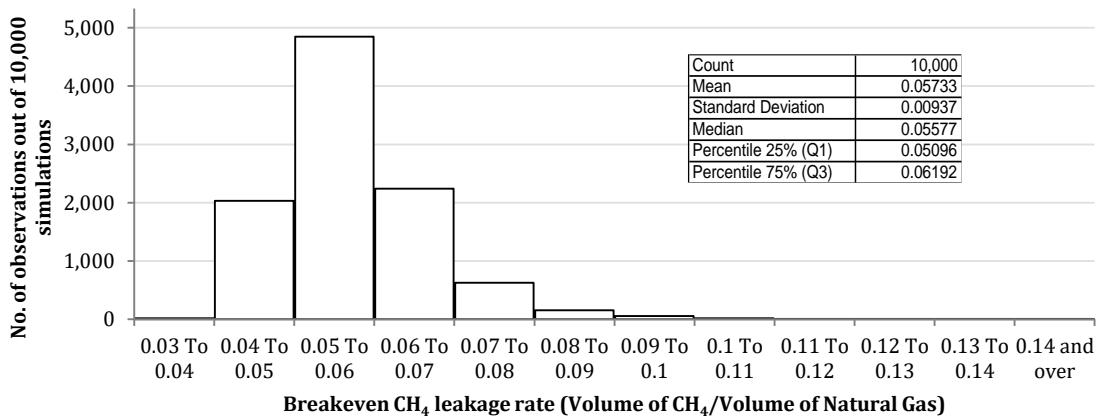


Figure S5: Histogram of Breakeven CH<sub>4</sub> Leakage Rate - NGCC vs. PC w/o CCS and 20-year GWP

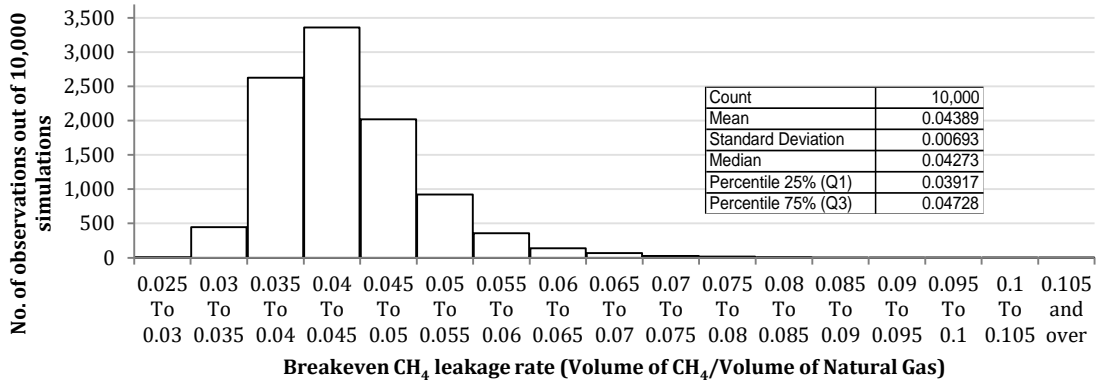


Figure S6: Histogram of Breakeven CH<sub>4</sub> Leakage Rate - NGCC vs. USCPC w/o CCS and 20-year GWP

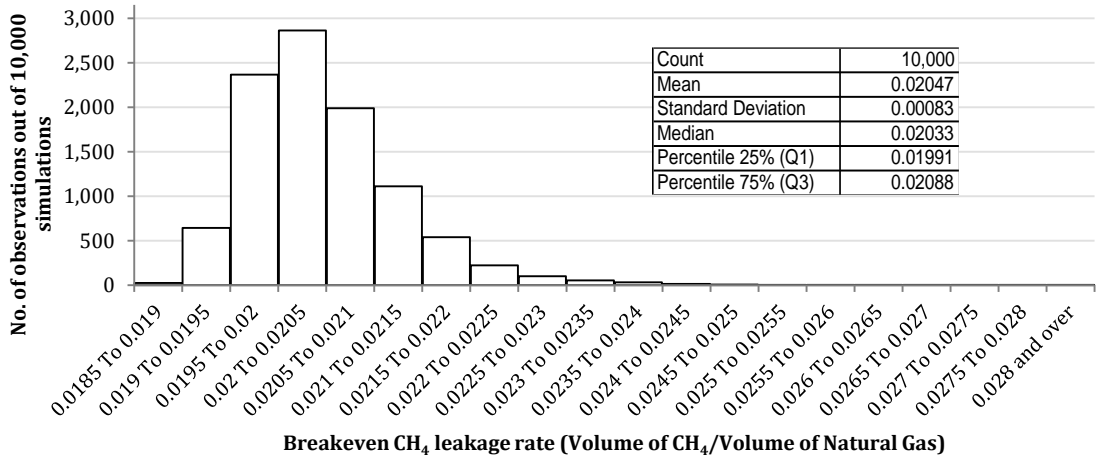


Figure S7: Histogram of Breakeven CH<sub>4</sub> Leakage Rate - NGCC vs. PC w/ CCS and 20-year GWP

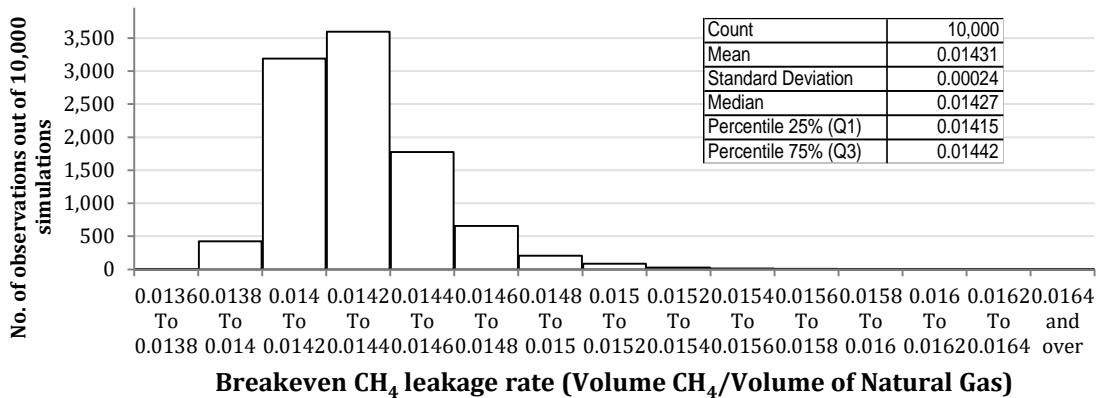


Figure S8: Histogram of Breakeven CH<sub>4</sub> Leakage Rate - NGCC vs. USCPC w/ CCS and 20-year GWP

## Appendix S4: Results of Additional Analysis

### 60 year operating lifetime

This section illustrates the extended analysis assuming plant operating lifetimes of 60 years, as opposed to 30 years. In general, we see that this simply extends the impacts of all effects further into the future, but does not change the qualitative difference between coal and natural gas plants. The results do suggest, however, that if plants operate longer than their stated lifetimes, there would thus be a longer commitment to warming.

Figure S9 shows TWP analysis for non-CCS USCPC and NGCC plants compared to a PC plant with operating lifetimes of 60 years. Recall TWP is the ratio of CRF between a comparison plant (here NGCC and USCPC) and that of a reference plant (here PC with or without CCS); values less than one indicate that the reference plant produces more CRF. Panel A demonstrates that the extended operating lifetimes have no noticeable effect on the non-CCS scenario (the NGCC plant with 5% leakage produces less CRF after about 15 years and all other plants maintain the same ratios throughout the 100-year timeframe). The effects of a 60-year lifetime can be better seen in Panel B, which extends the analysis to 500 years after initial plant operations. The USCPC plant and the NGCC plant at 1% leakage maintain relatively constant values over the 500-year period, and they provide climate benefits over the reference plant (PC without CCS). At leakage rates of 2%, 3%, 4%, and 5%, we see an increase in the time before NGCC produces less CRF than the PC reference plant compared to the 30-year operating lifetime.

Figure S10 shows the results of the CRF comparisons with 60-year plant lifetimes. With CRF, we see an increase in the total forcing at the end of our observed time frame across all plants in both the non-CCS (A) and CCS (B) scenarios. Panel A shows an increase in total CRF throughout the 100-year timeframe of about 70% for PC and USCPC, while NGCC increases by about 75% to 80% from 1% leakage to 5% leakage. In addition, the USCPC plant now produces greater CRF than the NGCC plant with 5% leakage after about 50 years, as opposed to 45 with 30-year plant lifetimes. Similarly, Panel B in Figure S10 (CCS applied to all plants) shows increases in total CRF throughout the timeframe. The CRF of PC and USCPC plants with an operating life of 60-years is 80% higher than the CRF when the plants have a lifetime of 30 years. The CRF of the NGCC plant operating over 60 years is about 75% to 90% higher than when it operates for 30 years.

Figure S11 shows the annual temperature change that results from the various plants and methane leakage rates modeled over 60 years. In this figure, we observe increases in the maximum annual temperature change of about 85% in the PC and USCPC plants, compared to the 30-year operating lifetime analysis. In the NGCC plants, the greatest maximum temperature increases occur at lower leakage levels with an 80% increase at 1% leakage while 5% leakage increases only 60%. This is a result of a similar change in temperature divided over different numbers. That is, a change in peak temperature of 0.00002 is a higher percentage of the lower peak temperature change observed in the 30-year analysis with a leakage rate of 1% than the higher peak temperature change observed in the 30-year analysis with a leakage rate of 5%. With CCS (B), the maximum

temperature increase in PC and USCPC is a little higher than 60%. In the CCS scenario, max annual temperatures from NGCC increase the most at 1% leakage (60%) and the least at 5% leakage (40%).

Finally, Figure S12 illustrates the cumulative temperature effects from the plants modeled with 60-year lifetimes. Without CCS technology (A), the 100-year temperature increase from PC and USCPC plants increases about 65% over the 30-year plant lifetime values. Observed cumulative temperature increase in the NGCC plants, at all leakage levels, is about 70% above 30-year plant lifetime values. With CCS (B), an NGCC plant operating for 60 years with 5% leakage produces nearly double (90% increase) the cumulative temperature change as its 30-year counterpart. At 1% leakage, we see a relatively smaller increase of cumulative temperature near 75%.

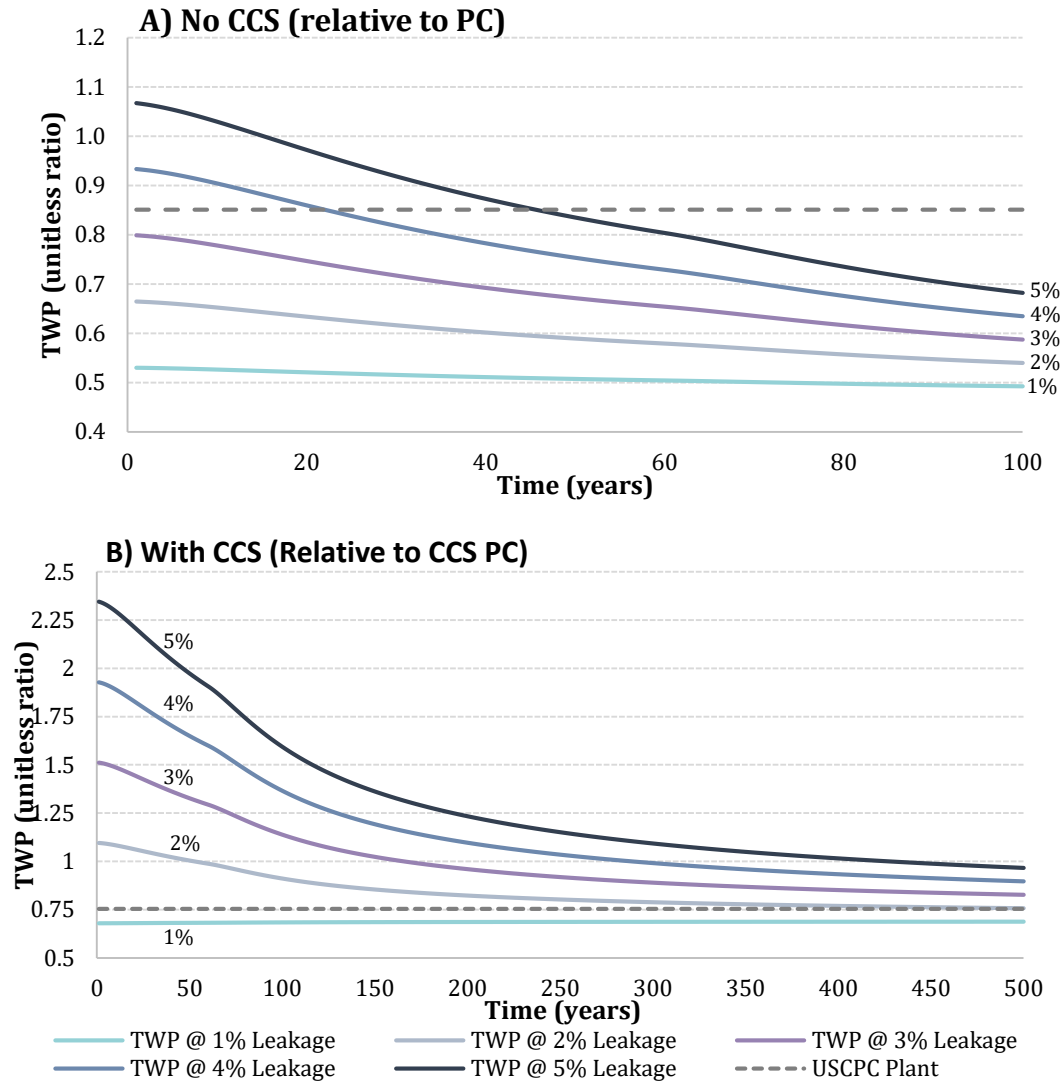


Figure S9: Technology Warming Potential Analysis with 60-year plant lifetime. A TWP value of one corresponds to the CRF of the relative plant. A. TWP of a NGCC plant and USCPC plant relative to a PC plant without any CCS. B. NGCC plant and USCPC plant, each with CCS, vs. a PC plant with CCS



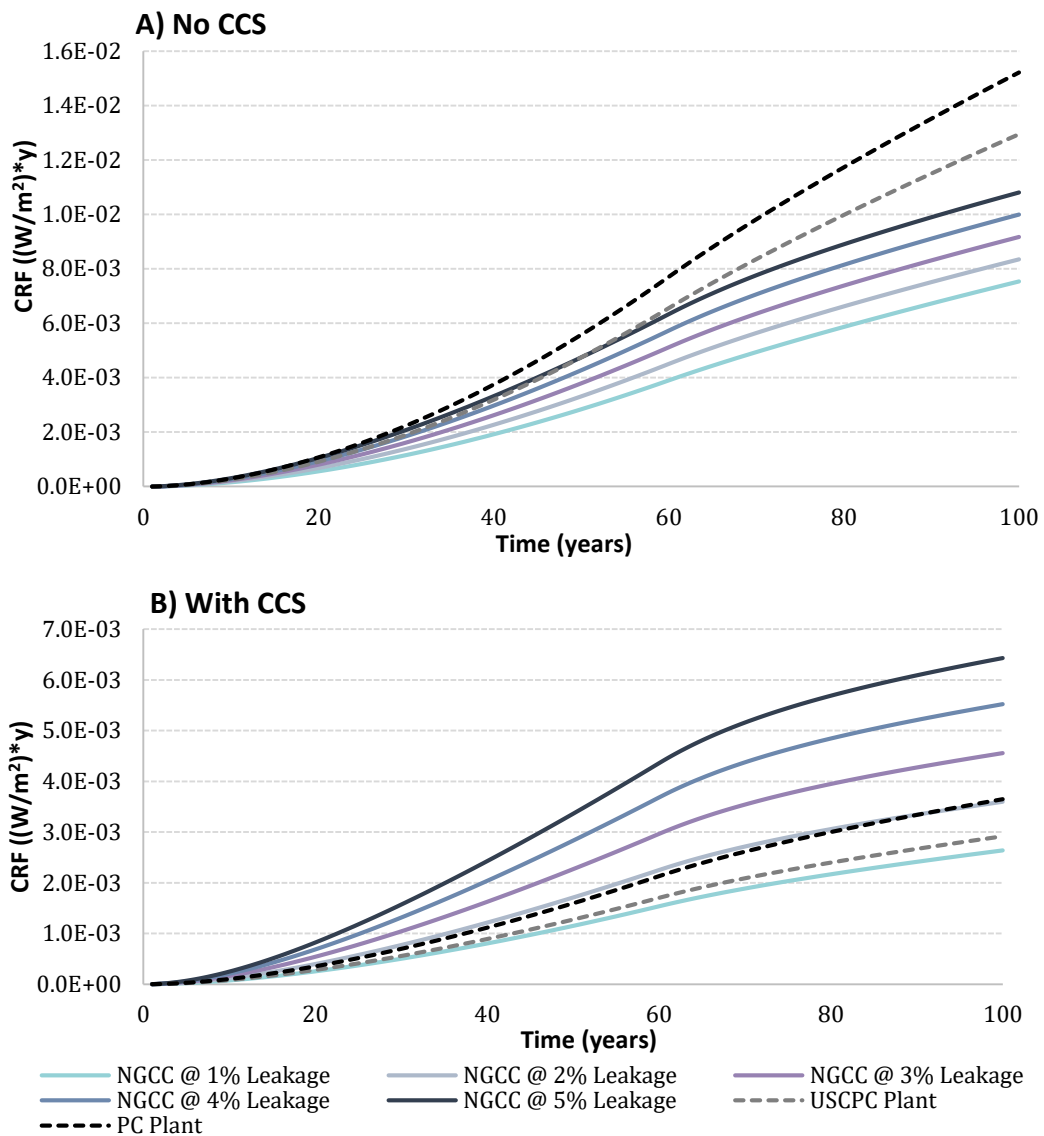


Figure S10: Cumulative Radiative Forcing Analysis with 60-year plant lifetimes. **A.** CRF of PC plant, USCPC plant, and NGCC plants at different leakage rates without CCS **B.** CRF of a PC plant, a USCPC plant, and NGCC plants at different leakage rates with CCS. These figures include climate-carbon feedbacks

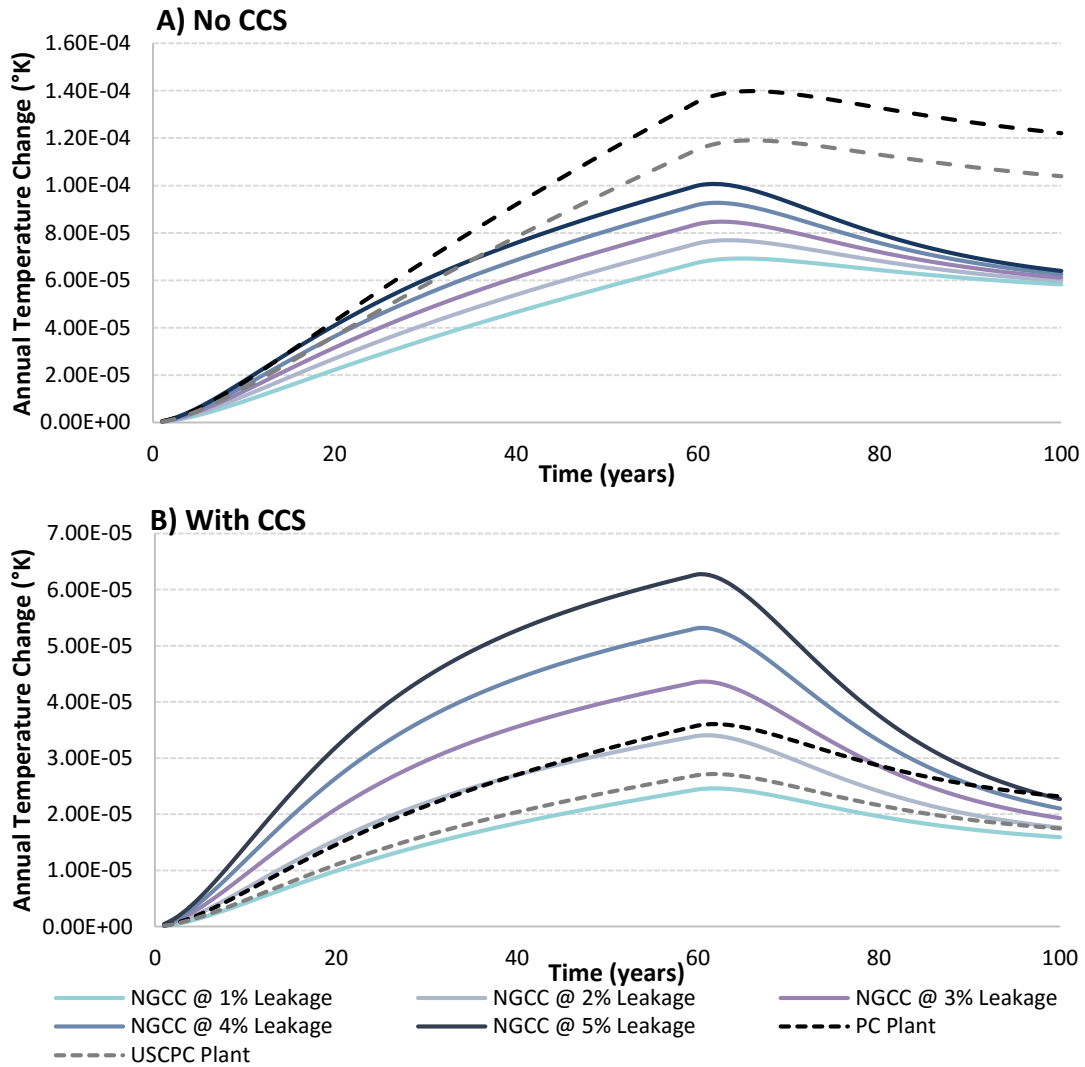
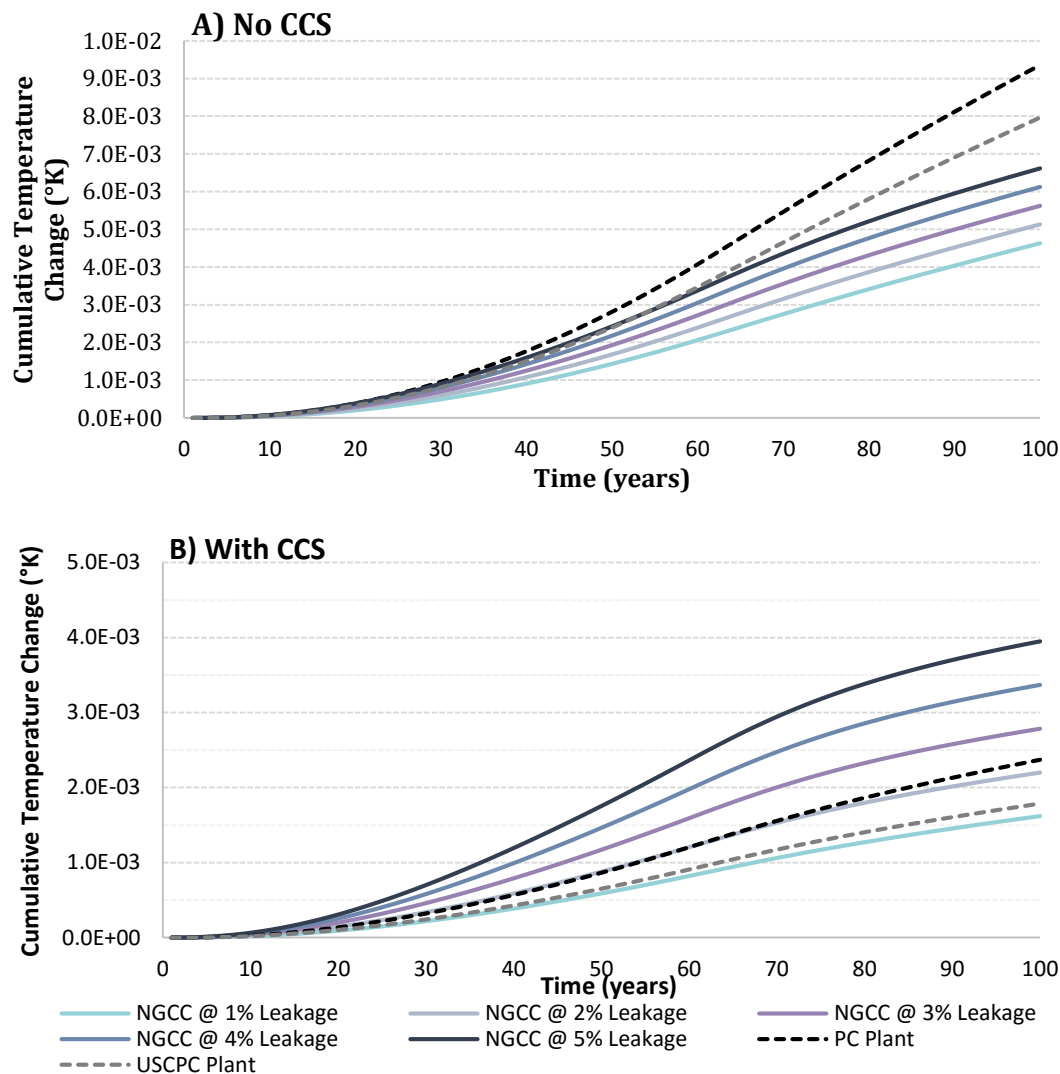


Figure S11: Annual Temperature Change by Plant Type and Methane Leakage Rate with 60-year plant lifetimes. **A.** Non-CCS plants. **B.** CCS Plants



*Figure S12: Cumulative Global Temperature Change Analysis with 60-year plant lifetimes. A. Comparison of a PC plant vs. a NGCC plant at varying methane leakage rates, without any CCS. B. PC plant vs. NGCC plant at varying methane leakage rates, with CCS*

### Availability of CCS technology in natural gas plants.

In addition to the 60-year plant lifetime analysis, we conducted an analysis assuming CCS is applied only to the two types of coal plants examined, leaving NGCC without the technology using TWP (NGCC and CCS USCPC relative to CCS PC) and cumulative AGTP. Although the emission rates reported in Table 2 of the main article indicate intuitively that the non-CCS emission rates are dominant, Figure S13 (TWP) and Figure S14 (cumulative AGTP) highlight this fact.

Figure S13 shows that if CCS is applied to the coal plants, NGCC without CCS performs worse throughout the 100-year period. After 100 years, even an NGCC plant at 1%

leakage produces about twice as much forcing as the PC plant. Again we see that USCPC will always produce less forcing than a PC plant as modeled.

In Figure S14 we see that emissions of a PC plant with CCS result in lower cumulative temperature change than the emissions of a NGCC plant without CCS, even at low CH<sub>4</sub> leakage rates from the natural gas system. As expected, the more efficient CCS USCPC plant produces lower cumulative temperature than the CCS PC plant.

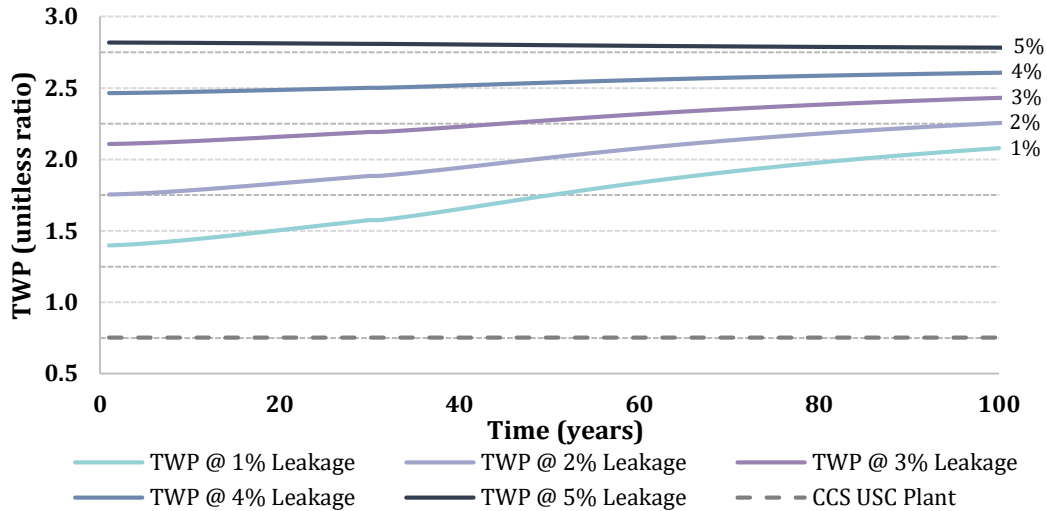


Figure S13: Technology Warming Potential Analysis. Comparison of a NGCC Plant without CCS and an USCPC with CCS relative to a PC plant with CCS.

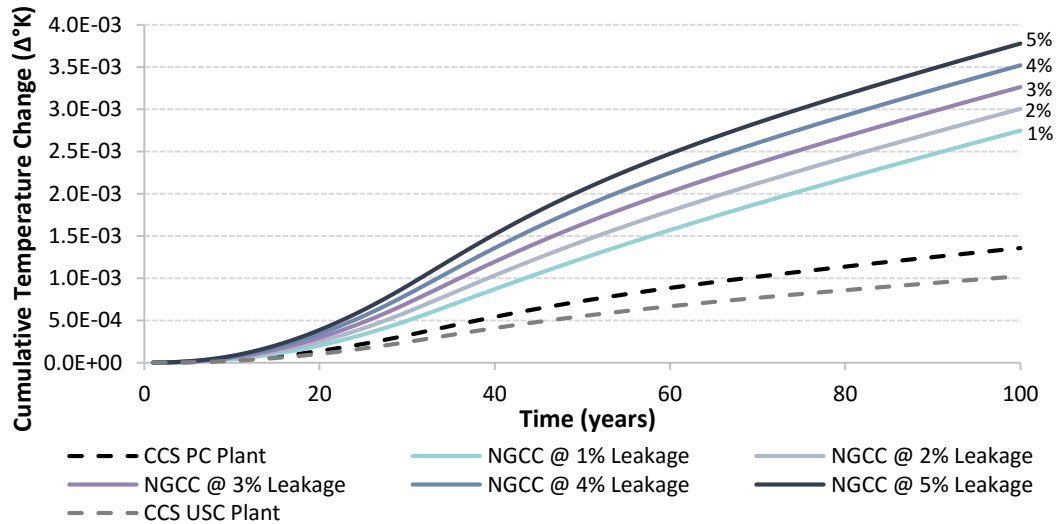


Figure S14: Cumulative Global Temperature Change Analysis. Comparison of CCS PC plant, CCS USCPC Plant, and non CCS NGCC plants at varying methane leakage rates.