



The climate and health effects of a USA switch from coal to gas electricity generation



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ABSTRACT

Abundant natural gas at low prices has prompted industry and politicians to welcome gas as a 'bridge fuel' between today's coal-intensive electric power generation and a future low-carbon grid. We used existing national datasets and publicly available models to investigate the upper limit to the emission benefits of natural gas in the USA power sector. As a limiting case, we analyzed a switch of all USA coal plants to natural gas plants, occurring in 2016. The human health benefits of such a switch are substantial: SO₂ emissions are reduced from the baseline (MATS (Mercury and Air Toxics Standard) retrofits by 2016) by more than 90%, and NO_x emissions by more than 60%, reducing total national annual health damages by \$20 – \$50 billion annually. While the effect on global temperatures is small out to 2040, the USA power plant fleet's contribution could be changed by as much as –50% to +5% depending on the rate of fugitive CH₄ emissions and efficiency of replacement gas plants.

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1. Introduction

Over the past decade shale gas development has increased USA domestic gas production by 40% [1]. Abundant gas at low prices has prompted industry and politicians to welcome gas as a 'bridge fuel' between today's electric power generation system, whose largest single fuel is coal, and a future, low-carbon grid. Current US policy includes "actions to promote fuel switching from oil and coal to natural gas" [2].

Recently, a growing body of research has questioned the ability of domestic natural gas to substantially reduce USA GHG (greenhouse gas) emissions. Natural gas power plants typically emit 50%–60% less carbon dioxide (CO₂) than coal plants due to their higher efficiency and lower carbon content of their fuel [3]. However, fugitive emissions from the production and transportation of natural gas (methane, CH₄), itself a potent GHG, may diminish these climate benefits [4–9].

The human health consequences of such a shift have not received as extensive discussion as the GHG effects. Compared to coal plants without emission controls, natural gas plants emit less sulfur dioxide (SO₂) and nitrogen oxides (NO_x), precursors of

particulate matter. Natural gas also has lower primary emissions of particulate matter up to 2.5 μm in size (PM_{2.5}) and particulate matter up to 10 μm in size (PM₁₀) than coal. Exposure to PM_{2.5} has been linked to human mortality and morbidity [10–14]. EPA regulations, including the CAIR (Clean Air Interstate Rule), the CSAPR (Cross-State Air Pollution Rule), and MATS (Mercury and Air Toxics Standard), are designed to reduce these emissions [14–16]. These regulations have been one cause of a switch from coal to natural gas plants [17,1].

We investigated the potential for natural gas to reduce emissions of criteria pollutants and GHGs from the USA electric power sector. To establish an upper bound on the potential benefits, we analyzed a switch of all USA coal plants to natural gas plants, occurring in 2016. We emphasize that we model this instantaneous shift in order to understand the largest potential changes that such a switch from coal to gas could make. We quantified the reductions in total power sector emissions that would occur, as well as the associated climate and health benefits.

Our intent was not to quantify the cost effectiveness of switching to gas nor the optimal generation fleet. Rather, the goal was to identify the limits to achieving U.S. pollution reduction goals through the use of natural gas power generation. This study differs from existing studies of the climate and health implications of U.S. coal plants [4,18,8,19,6], in that we attempted to quantify the maximum achievable benefit of switching the USA fleet of coal

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generators to gas plants. In reality, the switch from coal to gas would take several years, and the pollution reduction benefits would be less than we identify in the thought experiment we present here. We also directly compare the magnitude of the reduction in criteria pollutant emissions to that of GHG emissions.

We used U.S. DOE (Department of Energy) forecasts of emissions and generation as the baseline for our analysis. These forecasts include a significant reduction in SO₂ and NO_x emissions from existing coal plants from 2016 onward due to retrofits to comply with MATS. From this baseline, we replaced all coal plants with natural gas plants, starting in 2016. We then used two publicly available models to compute the health benefits of such a switch: the APEEP (Air Pollution Emission Experiments and Policy) model [20] and the EASIUR (Estimating Air pollution Social Impact Using Regression) model [21,22]. Using the GTP (Global Temperature Potential), we estimated how switching from coal to gas would affect the power plant fleet's contribution to global temperature until 2040, the last year for which EIA (Energy Information Agency) forecasts emissions and generation. We varied the fugitive methane emission rate from 0% to 7%, a range that includes estimates from existing literature [9].

2. Materials and methods

This section describes our research methods. A graphical representation of the model used in this work is given in [Appendix A](#), and a description of metrics is given in [Appendix B](#).

2.1. Calculation of baseline emissions

We developed baseline emission scenarios for 2016–2040 based on the forecasts from the DOE's EIA (Energy Information Agency) [23]. EIA forecasts installed capacity by plant type, electricity generation by fuel type, and total NO_x and SO₂ emissions from the electric power sector. These forecasts include the effects of existing policies, including CSAPR and MATS. We used the EIA's Reference scenario as our analysis baseline; we also consider the EIA's Low Oil and Gas Resource and High Oil and Gas Resource. Descriptions of each scenario are in [Appendix C](#) in the Supplementary material. We assumed that any switching from coal to gas not forecast by the EIA would be due to future policies, not market forces.

2.1.1. Baseline NO_x and SO₂ emissions

EIA forecasts total electric power NO_x and SO₂ emissions to 2040. It does not forecast emissions by fuel type. We therefore separated out the NO_x and SO₂ emissions associated with coal, oil, and gas plants. We first calculated NO_x and SO₂ emissions from oil and gas plants. We used plant-level emission data from the EPA AMPD (Air Market Program Database) to identify 2012 capacity-weighted average emission rates for oil and gas plants in 27 eastern states regulated by the EPA CAIR (Clean Air Interstate Rule) [24].

Next, we multiplied these emission rates by EIA's forecast of electricity production to find total NO_x and SO₂ emissions from oil and gas plants. Finally, we calculated coal NO_x and SO₂ emissions as the difference between EIA's forecast of total NO_x and SO₂ emissions and total oil and gas plant emissions.

2.1.2. Baseline PM_{2.5} and PM₁₀ emissions

EIA does not forecast direct emissions of PM_{2.5} and PM₁₀ from power plants. We assumed that coal and oil plants emit 0.14 kg/MWh of PM_{2.5} and PM₁₀, the limit imposed by the EPA's MATS [15]. Gas plants are not regulated by MATS, and therefore we used data from the 2005 NEI (National Emissions Inventory) [25] and eGRID 2005 [3] to identify gas plant PM_{2.5} and PM₁₀ combustion emissions

rates. We found the capacity-weighted average emission rate of gas plants in the NEI database to be 0.06 kg/MWh for PM_{2.5} and 0.07 kg/MWh for PM₁₀. For coal, oil and gas plants, we multiplied the assumed emission rates by EIA's forecast of annual electricity generation by each fuel.

2.1.3. Baseline greenhouse gas emissions

EIA does not forecast CO₂ or CH₄ emissions. We calculated CO₂ emissions by multiplying EIA's forecast of total electricity production from each fuel by the 2012 capacity-weighted average CO₂ emission rate of plants of that fuel type. We used plant-level emission data from AMPD to identify 2012 CO₂ emission rates for plants in CAIR states. These generators made up 70% of 2012 CO₂ emissions.

We calculated CH₄ emissions as the sum of combustion emissions and fugitive emissions from CH₄ production and transportation. Combustion CH₄ emissions for each fuel type are the capacity-weighted average CH₄ emission rates of plants in the EPA's eGRID (Emissions & Generation Resource Integrated Database), 2009. We parameterized the rate of fugitive CH₄ emissions in a range of 0–7%, covering estimates from existing literature [9]. We multiplied the fugitive rate by forecasts of total gas to calculate total fugitive CH₄ emissions. Total gas consumed was found by multiplying EIA's forecast of natural gas generation [23] by the capacity-weighted heat rate of existing gas plants in 2012 [3]. Other fugitive emissions (greenhouse gases, NO_x, SO₂, PM_{2.5}, PM₁₀) from the production and transportation of coal and natural gas did not qualitatively change our results and were excluded from the analysis. We did not include the coal life cycle emissions because the upstream emissions are only 5% of total GHG emissions of 96 g CO₂e/MJ, four times less than the overall uncertainty of the mean value [6].

2.2. Calculation of replacement plant emission rates

We modeled two scenarios to investigate the benefits of switching from coal to other fuels.

Scenario a) retired all coal plants and built new, high-efficiency NGCC (natural gas combined cycle) plants. New NGCC plants were assumed to have a heat rate of 5700 Btu/MWh achieved by state-of-the-art GE Flex-60 and Siemens Frame-H [26,27]. The CO₂ emission rate was calculated by multiplying the heat rate by the carbon content of natural gas. Other emission rates were assumed to be the load-weighted average emission rates of 450 existing NGCC plants, as identified by the EPA's National Electric Energy Data System [28]. This assumption somewhat overstates emission rates, as emission rates of new, high-efficiency NGCC will likely be lower than the existing NGCC fleet average. NO_x and SO₂ emission rates were based on 2012 emission rates (AMPD); CH₄ emission rates were from eGRID 2009; PM_{2.5} and PM₁₀ emission rates were based on NEI 2005.

Scenario b) retired all coal plants and built new natural gas plants with same heat rate and emission rates as the existing gas fleet's load-weighted average, considering both NGCC and combustion turbine plants. Heat rates, CO₂, NO_x and SO₂ emission rates were based on 2012 data (AMPD); CH₄ emission rates were from eGRID 2009; PM_{2.5} and PM₁₀ emission rates were based on NEI 2005. This scenario isolates the benefits of fuel switching from the benefits of switching to high-efficiency plants (scenario a). Load-weighted emission rates and load weighted heat rates were calculated as described in the Supplemental material.

In addition to these two scenarios, we also modeled a scenario in which coal plants were replaced by new plants that have zero emissions of all pollutants, either renewable or nuclear plants. Associated results can be found in the Supplemental material,

Appendix C, Figures C.1 – C.4. We assumed the replacement plants could provide firm baseload power; in reality, variable renewables such as wind would need storage to serve as baseload.

We assumed replacement plants are built at the same location and have the same capacity as the coal plants they replace. We believe that this assumption is reasonable, as the sites will have much of the infrastructure needed for new plants, such as access to transmission. Our analysis ignored changes in the dispatch order that may occur due to fuel switching, or changes in load due to consumer price response.

2.3. Calculation of health effects

Many health models exist [29,18] and have been used by the EPA as technical support for major pollution regulations [14]. In this study, we used two publicly available models: the APEEP (Air Pollution Emission Experiments and Policy) model [20] and the EASIUR (Estimating Air pollution Social Impact Using Regression) model [22]. We used these models to monetize the benefit to human health and the environment caused by changes in emissions of SO₂, NO_x, PM_{2.5}, and PM₁₀. We excluded damages due to VOCs (volatile organic compounds) and ammonia (NH₃) from our analysis due to uncertainty in the atmospheric science surrounding these pollutants, and the relatively small damages they cause compared to SO₂, NO_x, and PM [30,31].

APEEP uses a reduced form air transport model and linear dose–response function to monetize the damages to human health and the environment caused by a marginal ton of emissions of NO_x, SO₂, PM_{2.5}, PM₁₀, VOCs, and NH₃ from each county in the USA. Health effects, if valued at \$6 million per statistical life, constitute 94% of the total APEEP damages, dominating environment damages (visibility loss, damages to forestry and agriculture, damage to manmade structures) [20]. Compared to US EPA, APEEP underestimates damages [20].

EASIUR [21,22] was derived using regression on a large dataset created by CAMx, a state-of-the-art chemical transport model [32]. EASIUR closely reproduces the social costs of emissions predicted by full CAMx simulations but without the high computational costs. The EASIUR's social costs are derived only on the basis of the effect of ambient PM_{2.5} on mortality, which usually accounts for more than 90% of social costs. It estimates the monetized effects of PM_{2.5} from emissions of EC (elemental carbon), SO₂, NO_x, and NH₃ affecting over a large area downwind (up to about two thousand kilometers).

Because both models calculate emissions' damages as a function of location, we estimated individual coal plant emissions in the continental United States of SO₂, NO_x, PM_{2.5}, and PM₁₀. Although EIA forecasts total NO_x and SO₂ emissions, plant-level emissions out to 2040 are highly uncertain. We assumed the fraction of total coal SO₂ and NO_x emissions from each plant remains constant from 2012 levels through 2040 [3]. We assumed each coal plant emits 0.14 kg/MWh of PM_{2.5} and PM₁₀ [15].

Switching all coal plants to gas would have a significant effect on criteria pollutants, and it might be argued that both models' baseline emissions are affected enough so that the human health effects are no longer good estimates. However, there is good evidence that the formation of PM_{2.5} caused by SO₂ and NO_x is linear with reduced emissions, with no threshold [33]. Major cohort studies have found PM_{2.5} concentration–response functions and mortality are linear with no threshold [34–36]. Since we find NO_x accounted for only 8% of total health damages from the electricity sector in 2012, we ignore the known second-order nonlinearities in PM_{2.5} formation associated with NO_x emissions due to decreasing SO₂ emissions.

2.4. Calculation of climate effects

We calculated resulting temperature changes using a metric used by the IPCC, GTP (Global Temperature Potential) [37,38]. GTP is defined as the ratio between the global mean surface temperature change (ΔT) at a given future TH (time horizon) following an emission (pulse or sustained) of a compound x relative to an equivalent mass of CO₂ (36), or:

$$GTP_x^{TH} = \frac{\Delta T_x^{TH}}{\Delta T_{CO_2}^{TH}} \quad (1)$$

Since power plant emissions are typically given at annual intervals, the total change in temperature (ΔT) due to emissions of all pollutant types (x) [38] over the entire TH (time horizon) years can be approximated as:

$$\Delta T = \sum_{x=1}^X \sum_{t=1}^{TH} GTP_x(t) * \Delta T_{CO_2}(t) * M_x(t) \quad (2)$$

where M is the mass of the pollutant x emitted in year t (kg) and ΔT_{CO_2} is the temperature response in year n due to a 1 kg pulse emission of pollutant emitted in year 0 (K/kg). Common time horizons chosen include $n = 20$ (the total temperature change 20 years in the future) and $n = 100$ (the total temperature change 100 years in the future).

For the results shown in this paper, we calculate the temperature forcing due to carbon dioxide and methane. GTP_{CO₂} is defined to be 1, and ΔT_{CO_2} can be represented through empirical analysis [39]. Fossil methane, including climate change feedbacks, is estimated to have a GTP at 20 years (GTP20) of 68, and a GTP100 of 15, although estimates are highly uncertain (roughly $\pm 75\%$); the most recent IPCC report fully characterizes GTP_{CH₄}TH over a century [39]. A discussion of the global warming potential of CO₂ and CH₄ emissions can be found in Appendix B in the Supplementary material.

While this simple model can allow the user to intuitively understand the changes in CO₂ and CH₄, it does not take into account the effects of NO_x, SO_x, BC (black carbon), and OC (organic carbon). Previous literature has shown that a shift from coal to gas would significantly reduce SO₂, offsetting both the climate forcing from the reduction in black carbon and some of the GHGs [7]. However, this literature also assumes the base coal fleet emits a large amount of SO₂, whereas in our analysis, the baseline forecasts of SO₂ emissions account for mandated SO₂ emissions due to the MATS standard, and therefore already have low SO₂ emissions. Thus, we do not expect to see large temperature changes from NO_x, SO_x, or BC.

To confirm this, we modeled climate change effects from NO_x, SO_x, and BC using a chemistry model within the publicly available MAGICC6 model [40] a simple/reduced complexity climate model including an ocean, an atmosphere, a carbon cycle, and indirect aerosol effects; Appendix D in the Supplementary material contains a full model description and validation tests.

Table 1

2016 load-weighted average emission rates for USA coal plants in EIA Reference Case, and replacement plants for scenarios a) and b).

Plant type	Combustion emission rates (kg/MWh)					
	CO ₂	NO _x	SO ₂	CH ₄	PM _{2.5}	PM ₁₀
Coal – 2016	910	0.69	0.72	0.01	0.14	0.14
Scenario a): High-efficiency gas	300	0.09	0.02	0.008	0.06	0.07
Scenario b): Average gas	450	0.17	0.02	0.009	0.06	0.07

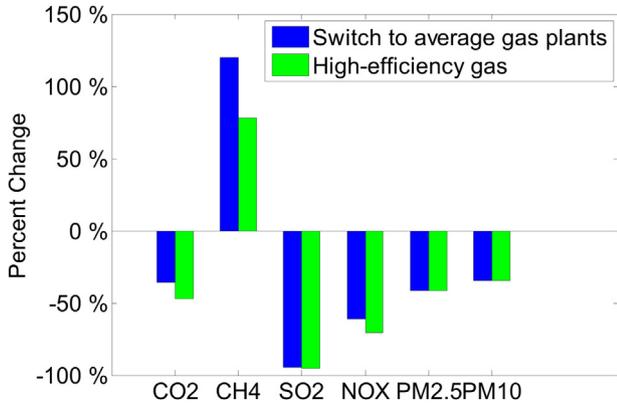


Fig. 1. Effect of coal-to-gas switching as a percent change in total USA electric power GHG emissions (CO₂ and CH₄, the latter using a 3% fugitive CH₄ rate), and criteria pollutants from the EIA Reference Case in 2025. Reductions are constant across years 2016–2040.

3. Results

Table 1 shows the load-weighted average emission rates and heat rates of coal plants in 2012, as well as the emission rates and heat rates for the coal replacement plants in scenarios a) and b). Switching to average gas reduces CO₂ emissions by half; switching to high-efficiency gas reduces CO₂ emissions by 2/3. Both average and high-efficiency gas plants emit an order of magnitude less SO₂ and NO_x than coal plants.

3.1. Change in emissions

Fig. 1 shows emission reductions due to switching from coal to gas. The switch reduces SO₂ emissions by more than 90%, NO_x emissions by more than 60%, and PM emissions by 40% from the

EIA's reference case (Appendix C, Figures C.8 – C.11 in the Supplementary material). Annual electric power CO₂ emissions are reduced by 35%–47%; CH₄ emissions would increase by 80%–120%, assuming a 3% fugitive CH₄ emission rate. Because coal plants are the primary source of criteria pollutant emissions, switching from coal has a larger effect on criteria pollutant emissions than GHG emissions. Table 2 shows that CH₄ reductions are highly sensitive to the assumed fugitive CH₄ emission rate. Emission reductions are similar for the EIA Reference Case, High Gas Resource Case, and Low Gas Resource Case (see Appendix C in the Supplementary material).

3.2. Effect on human health

Switching from coal to gas would significantly reduce SO₂, NO_x, and PM emissions (Fig. 1). The monetized annual health and environmental damages of emissions, via the APEEP and EASIUR models, are shown in Fig. 2. We find that when considering a switch to either high-efficiency gas or average gas plants, publicly available models provide a large range in damage reductions estimates; damage reductions are \$20 billion - \$24 billion per year (via APEEP) and \$40–50 billion per year (via EASIUR). Both models show damage reductions increase from 2016 to 2025, as the EIA forecasts increasing coal generation over that time period. More than 75% of damage reductions are due to reductions in SO₂; reductions in NO_x and PM_{2.5} each make up 10% of damage reductions. Health and environmental damages vary regionally (Fig. 3). Most damages occur in the Ohio River Valley and Southeast due to the high concentration of coal plants and significant downwind population.

3.3. Effect on atmospheric concentrations of GHG emissions

In agreement with published literature, using the simple GTP model we find that climate benefits for a USA policy of switching from coal to natural gas are limited unless this action results in

Table 2
Sensitivity of CH₄ emissions in 2025 to fugitive CH₄ emission rate, EIA Reference Case.

Scenario	Percent change in CH ₄ emissions			
	0% fugitive CH ₄	3% fugitive CH ₄	5% fugitive CH ₄	7% fugitive CH ₄
Baseline	0	8	13	18
A) Switch to high-efficiency gas	0	14	23	33
B) Switch to average gas	0	17	29	40

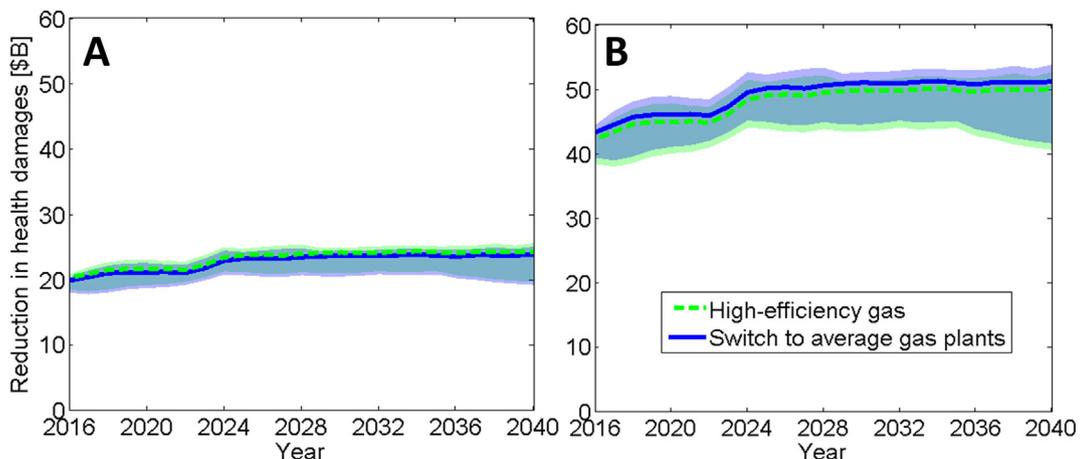


Fig. 2. Reduction in annual health damages due to switching from coal, using a \$6 million value of statistical life. Solid line is EIA reference case; shaded area is the range across EIA reference case, high gas resource case, and low gas resource case. A: APEEP results; B: EASIUR results.

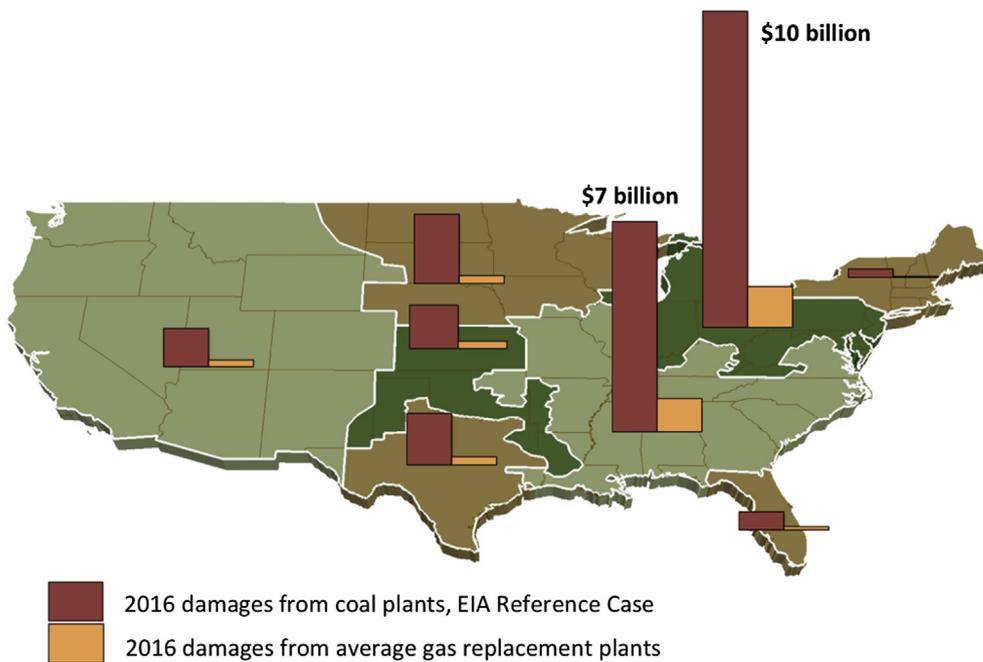


Fig. 3. 2016 annual health and environmental damages due to emissions of criteria pollutants from coal plants, by NERC region, using the APEEP model. Replacing coal plants with average gas plants (scenario b) reduces damages most significantly in the Midwest and Southeast.

other major pollutants reducing their GHG emissions. Figs. 4 and 5 show the change in temperature from business as usual minus the change in temperature for the two scenarios. Switching from coal to natural gas results in a difference of temperature change between $-0.02\text{ }^{\circ}\text{C}$ and $+0.03\text{ }^{\circ}\text{C}$, depending on the assumed fugitive CH_4 rate. Differences in temperature changes are insensitive to the baseline EIA case assumed. As shown in the Appendix D in the Supplementary material, the MAGICC6 model simulates a nearly identical contribution of CO_2 and CH_4 to temperature.

While a small change to global temperatures, these changes are a significant change to the temperature contributions from the US power plant fleet. Table 3 shows the fraction of change in temperature from scenarios a) and b) divided by the change in

temperature from business as usual (EIA Reference Case). The table shows results for a $\text{GTP}_{20\text{CH}_4}$ of 68, as well as the $\text{GTP}_{20\text{CH}_4}$ uncertainty range of $\pm 75\%$. Assuming $\text{GTP}_{20\text{CH}_4}$ is 68, we find that a switch to an average gas plant can change the power plant fleet's contribution to temperatures in 2040 by -40% to $+30\%$, depending on fugitive emissions rate. A switch to clean plants can change the power plant fleet's contribution to temperatures by -50% to $+5\%$. Results are insensitive to the baseline EIA case assumed.

Appendix D in the Supplementary material contains an analysis of the effects of SO_x , NO_x , BC, and OC on warming through 2100 using the publicly available MAGICC6 model. None of these cause large climate change effects; SO_2 due to the greatly lowered

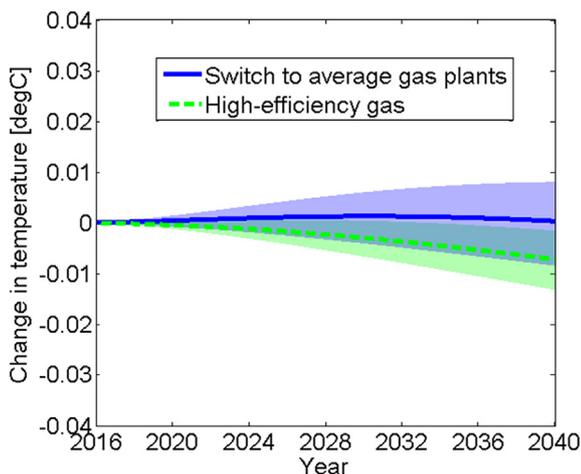


Fig. 4. Change in temperature from scenarios (A) high-efficiency gas and (B) average gas minus change in temperature from business as usual. Temperature changes include contributions from CO_2 and CH_4 only. Solid line is 3% fugitive CH_4 rate for the EIA reference case; shaded area is range across EIA reference case, high gas resource case, and low gas resource case. Assumed $\text{GTP}_{20\text{CH}_4}$ of $68 \pm 75\%$.

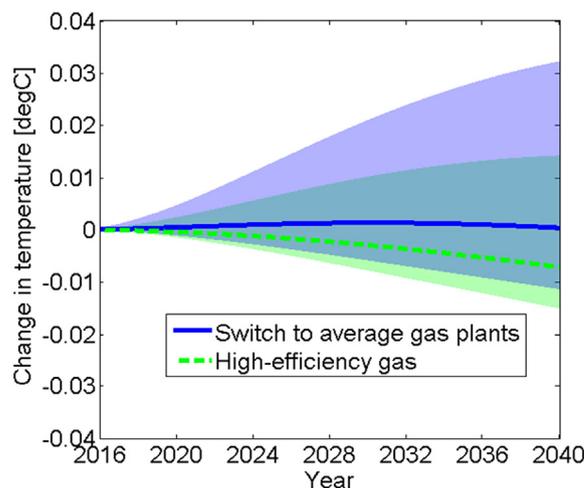


Fig. 5. Effect of fugitive CH_4 rate uncertainty. Change in temperature from scenarios (A) high-efficiency gas and (B) average gas minus change in temperature from business as usual. Temperature changes include contributions from CO_2 and CH_4 only. Solid line is 3% fugitive CH_4 rate for the EIA reference case; shaded area is represents uncertainty across EIA reference case, high gas resource case, and low gas resource case and 0%–7% fugitive CH_4 rate. Assumed $\text{GTP}_{20\text{CH}_4}$ of $68 \pm 75\%$.

Table 3

Fraction of change in temperature in 2040 from scenarios (A) high-efficiency gas and (B) average gas plants divided by the change in temperature from baseline EIA reference case. Temperature changes include contributions from CO₂ and CH₄ only. Reductions are constant across 2016–2040. Assumed GTP20_{CH4} of 68; uncertainty range of ±75% in parenthesis.

Scenario	Change in warming contributed by U.S. electric power sector, 2040			
	0% fugitive CH ₄	3% fugitive CH ₄	5% fugitive CH ₄	7% fugitive CH ₄
A) Switch to high-efficiency gas	−47%	−18% (−38%, −3%)	−5% (−33%, +11%)	+5% (−28%, +21%)
B) Switch to average gas	−35%	+1% (−24%, +18%)	+16% (−18% + 36%)	+28% (−12%, +49%)

emissions in order to meet the MATS standards, NO_x because it is a very weak climate change forcer, and BC because newer literature has shown that the amount of BC from coal power plants is much less than previously expected [41,42].

4. Conclusions

Human health in the United States can greatly benefit from policies that continue the reduction of criteria pollutant emissions from coal plants, by switching to gas, installing emissions controls, or switching to renewables or nuclear. Switching to gas would greatly reduce criteria pollutant emissions; SO₂ emissions would be reduced by more than 90%. Annual health damages could be reduced further by \$20 – \$50 billion if coal plants are either replaced with gas plants or fitted with flue gas desulfurization emission controls.

In the short term, the potential for natural gas to reduce the USA power sector's contribution to global warming is highly sensitive to the CH₄ fugitive rate and efficiency of gas plant installed. Assuming 3% fugitive CH₄ emissions, switching all coal plants to high efficiency NGCC plants would reduce the power sector's contribution to warming by 20% in 2040. Assuming GTP20_{CH4} of 68, a switch to high-efficiency NGCC plants can change the power sector's contribution to warming changes by −50% to +5% for fugitive CH₄ rates of 0%–7%. Switching to average-efficiency plants can change warming contribution by −35% to +30% for fugitive rates of 0%–7%. Considering the uncertainty in GTP20_{CH4} estimates further increases the uncertainty in our results. In all cases, the net effect on global temperatures by 2040 is inconsequential unless US leadership induces pollution control by other large nations.

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Appendix. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.energy.2016.03.078>.

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The climate and health effects of a USA switch from coal to gas electricity generation

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Appendices

Appendix A: Methods overview

Appendix B: Definitions

Appendix C: Detailed emission results

Appendix D: Climate Model to 2100

Appendix A: Methods overview

A graphical representation of the model used in this work is shown in Figure S1. We use existing national datasets of USA power plants, as well as forecasts of future energy production and emissions from the US Department of Energy's Energy Information Agency (EIA, 2013). In particular, we identify total annual combustion emissions of carbon dioxide (CO₂), CH₄, nitric oxide and nitrogen dioxide (NO_x), sulfur dioxide (SO₂), and 2.5 micrometer and 10 micrometer particulate matter (PM_{2.5} & PM₁₀) for the years 2016 - 2040. We then examine the benefits of three replacement scenarios: a) coal is replaced by new, high-efficiency natural gas combined cycle (NGCC) plants; b) coal is replaced by a combination of new NGCC and natural gas combustion turbine (NGCT) generators that matches the current gas fleet; and c) all coal is replaced by plants with zero emissions, either renewables or nuclear plants. We investigate the effect of fugitive methane emissions from the production and transportation of natural gas (ranging from 0-7%).

We use the publicly available APEEP model (Muller and Mendelsohn, 2007) and the EASIUR model (EASIUR, 2015; Heo, 2015) with their respective empirical health damages as a function of particulate type and location to value the reductions in damages to human health and the environment associated with NO_x, SO₂, PM_{2.5}, and PM₁₀. We calculate the change in temperatures in two ways: using a global temperature potential model under different EIA scenarios as described in the Main text Section 2, and the publicly available MAGICC6 climate model (Meinshausen et al., 2011b) under different representative concentration pathways (RCPs) as described in Appendix D.

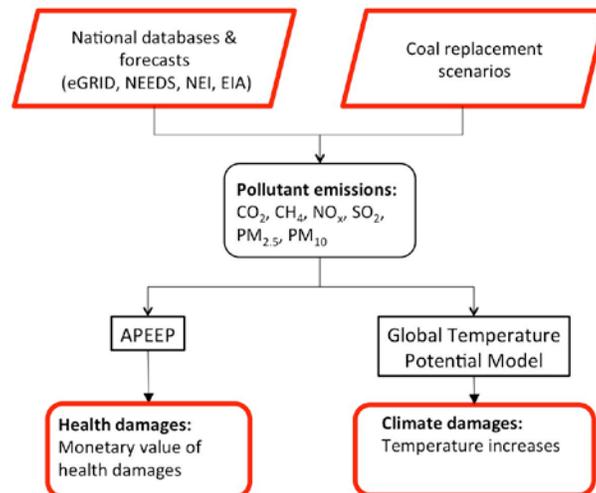


Figure A.1. Graphical representation of the model used in this work. Thick red parallelograms denote inputs we varied. Thick red ovals indicate outputs.

Appendix B: Definitions

As many different metrics have been applied to this problem, we briefly describe 1) what we mean by carbon dioxide equivalent, and 2) climate metrics.

B.1 What we mean by carbon dioxide equivalent

Combining different types of emissions and obtaining a value that is equivalent to carbon dioxide can be done in the following ways.

Carbon dioxide equivalent, or CDE, is a forward-looking measurement. This value is the **mass** of carbon dioxide that would have the same global warming potential as the **mass** in question when measured over a specified timescale. This value is calculated as:

$$CDE = \sum_n GWP_n m_n \quad \text{Equation B.1}$$

where n is number of types of molecules or particles, m_n is the total mass of n , and GWP_n is the global warming potential of a unit of particle n .

Equivalent CO₂, or carbon dioxide equivalent concentrations (CO₂eq), is a snapshot in time. This value is the **concentration** of carbon dioxide that would have the same radiative forcing as the **concentration** in question when measured over a specified timescale. Usually it includes historical emissions. This value is calculated as:

$$CO_2eq = C_o e^{\frac{RF}{\alpha}} \quad \text{Equation B.2}$$

where C_o is the concentration of the pre-industrial concentration of carbon dioxide (278 ppm), RF is the radiative forcing of the concentration in question, and α is a constant (5.35 W/m²).

CDE and CO₂eq depend on only the components of mass or concentration that are of interest. Most often, these values are calculated as a function of greenhouse gases only. Sometimes, these values include both greenhouse gases and land use changes. For instance, MAGICC's "KYOTO CO2EQ" is a function of CO₂, CH₄, N₂O, and halogenated gases regulated under the Kyoto protocol. MAGICC's "CO2EQ" is a function of CO₂, CH₄, N₂O, and halogenated gases regulated under both the Montreal and the Kyoto protocol. Another choice is to use CO₂eq as a function of CO₂ and CH₄ only. In other possible choices, these values also include aerosols.

B.2 Climate metrics

Radiative forcing, CO₂eq, and temperature have quite different uncertainties. A climate model such as MAGICC6 requires as input specifications the emissions of different constituents (e.g., CO₂, CH₄, SO_x, NO_x, and BC). Due to different scenarios, fugitive methane emissions assumptions, and representative concentration pathways, there is significant uncertainty present in the model inputs. At each time step, the model calculates (with some uncertainty) the atmospheric concentrations of individual constituents, and from that (with additional uncertainty) the individual radiative forcings. Since individual radiative forcings can be added linearly, the first system-level output metric is total radiative forcing. While small, an additional layer of uncertainty is added

when using the radiative forcing to calculate equivalent CO₂ concentrations. A much larger layer of uncertainty is added when using the radiative forcing to calculate temperature.

Temperature changes are well understood by the general public. While not as broadly understood, concentration metrics offer the ability to “draw lines in the sand” used by policy makers to argue for emissions targets such as “a doubling in greenhouse gas concentrations since pre-industrial”.

Here we use four climate metrics. **Radiative forcing (W/m²)** is given as a change relative to preindustrial conditions in the year 1765 and includes all constituents in the model. **Temperature increase (°C)** is derived directly from the radiative forcing and given as a change relative to 1765. In contrast to radiative forcing and temperature increase, **equivalent CO₂ (CO₂eq, ppm)** is defined here as a function of the change in greenhouse gases only (CO₂ and CH₄ only, not NO_x, SO₂, PM, N₂O, or halogenated gases). Secondary chemistry (e.g., changes in halogenated gases as a function of methane concentrations) is not included. Referencing MAGICC6, in 2010 these values were 2.15 W/m² for radiative forcing, 0.8 °C for temperature increase, and 416 ppm for CO₂eq. Because emissions comparisons are also of interest in some applications, we also provide **carbon dioxide equivalent (CDE, million metric tons)** as a function of CO₂ and CH₄ emissions (100-year global warming potential of 21 (Myhre et al., 2013)).

To find the USA contribution toward CO₂eq in 2010, we used MAGICC6 for global emissions data (Meinshausen et al., 2011b) and national databases for USA emissions data (EPA, 2012; Boden et al., 2013). Total CO₂ annual average concentrations were 389 ppm in 2010; they were 278 ppm preindustrial. The USA is responsible for 24-26% of the CO₂ concentrations and 9% of CH₄ concentrations, with CO₂ values varying as a function of uncertainty in CO₂ lifetime (50-200 years, (EPA, 2012). Under this definition, the USA’s contribution to CO₂eq is thus roughly 30 ppm.

Appendix C: Detailed emission results

We used U.S. Department of Energy (DOE) forecasts of emissions and generation as the baseline for our analysis (see *Methods - Calculation of baseline emissions* in the main text). From this baseline, we replaced all coal plants with either natural gas or zero-emission plants, starting in 2016. The following are EIA's descriptions of the three baseline cases we used:

- **Reference case (Figure C.1):** baseline assumptions for economic growth (2.4 percent for 2012 - 2040), oil prices, and technology. Brent spot price rises to about \$141.50 per barrel (2012) in 2040
- **Low Oil and Gas Resource:** Estimated ultimate recovery per shale gas, tight gas, and tight oil well is 50% lower than in the Reference case. All other resource assumptions will remain the same as in the Reference case
- **High Oil and Gas Resource:** Estimated ultimate recovery per shale gas, tight gas, and tight oil well is 50% higher and well spacing is 50% lower (or the number of wells left to be drilled is 100% higher) than in the reference case. In addition, tight oil resources are added to reflect new plays or the expansion of known tight oil plays and the estimated ultimate recovery for tight and shale wells is increased 1% per year to reflect additional technological improvement. Also includes kerogen development, tight oil resources in Alaska, and 50% higher undiscovered resources in lower 48 offshore and Alaska than the Reference case

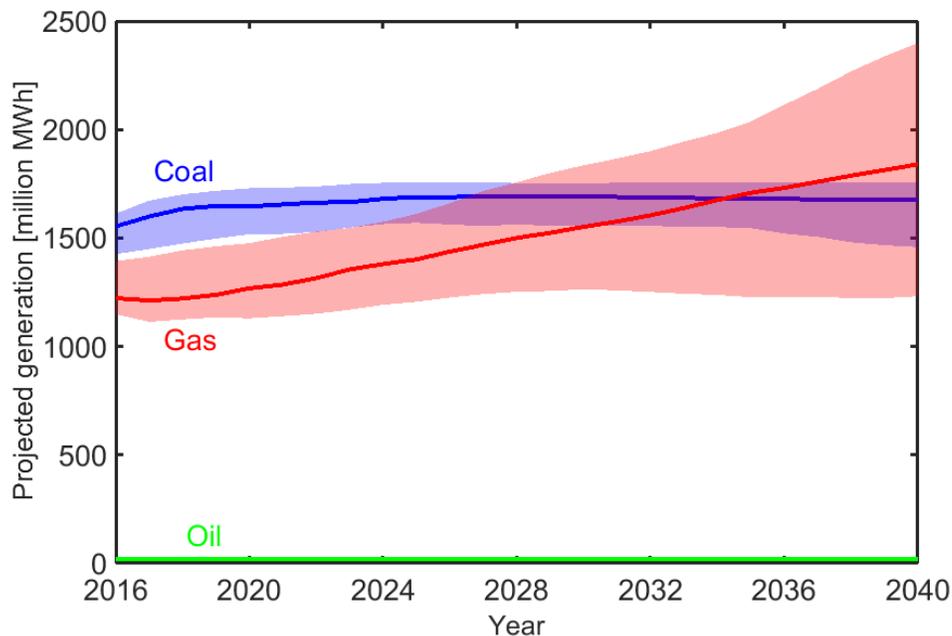


Figure C.1. EIA forecast of generation from coal, gas, and oil plants, 2016 – 2040. Solid lines are EIA Reference Case; ranges represent High Gas Resource Case and Low Gas Resource Case.

C.1 Change in emissions due to switching to zero emission plants

Figures C.2-C.5 compare the change in emissions due to switching from coal to gas to a scenario in which coal plants are switched to zero emission plants, either renewables or nuclear plants. We make several simplifying assumptions, including that zero emission plants can be built in the same location and with the same capacity as coal plants. We also assume that zero emission plants can provide firm, dispatchable power in the same manner as coal plants. In reality, intermittent renewables such as wind and solar would require storage in order to provide firm power.

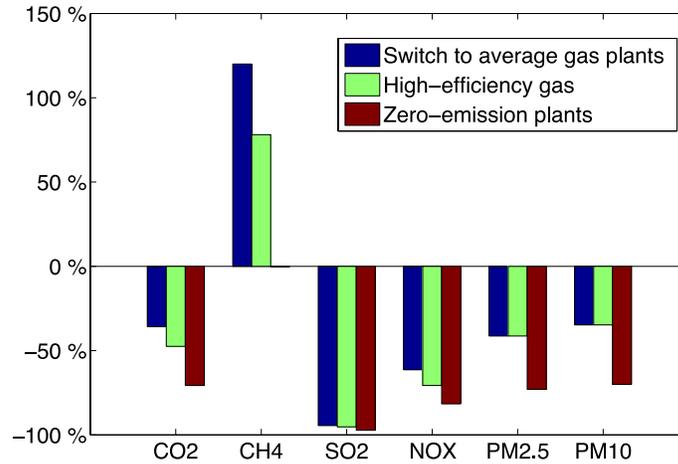


Figure C.2. Percent change in total electric power GHG emissions (CO₂ and CH₄, 3% fugitive CH₄ rate), and criteria pollutants from the EIA Reference Case in 2025. Reductions are constant across years 2016 – 2040.

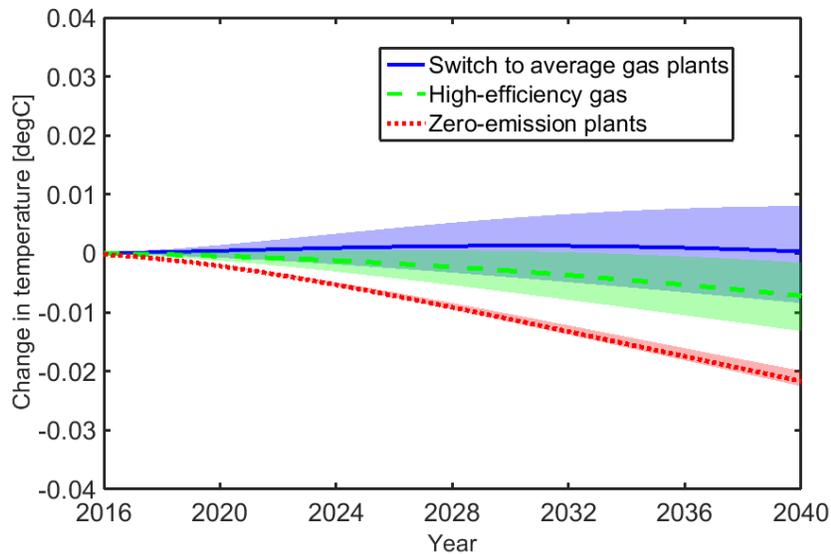


Figure C.3. Change in temperature from scenarios (A) high-efficiency gas, (B) average gas, and (C) zero emission plants minus change in temperature from business as usual. Temperature changes include contributions from CO₂ and CH₄ only. Solid line is 3% fugitive CH₄ rate for the EIA reference case; shaded area is

range across EIA reference case, high gas resource case, and low gas resource case. Assumed $GTP_{20_{CH_4}}$ of $68 \pm 75\%$.

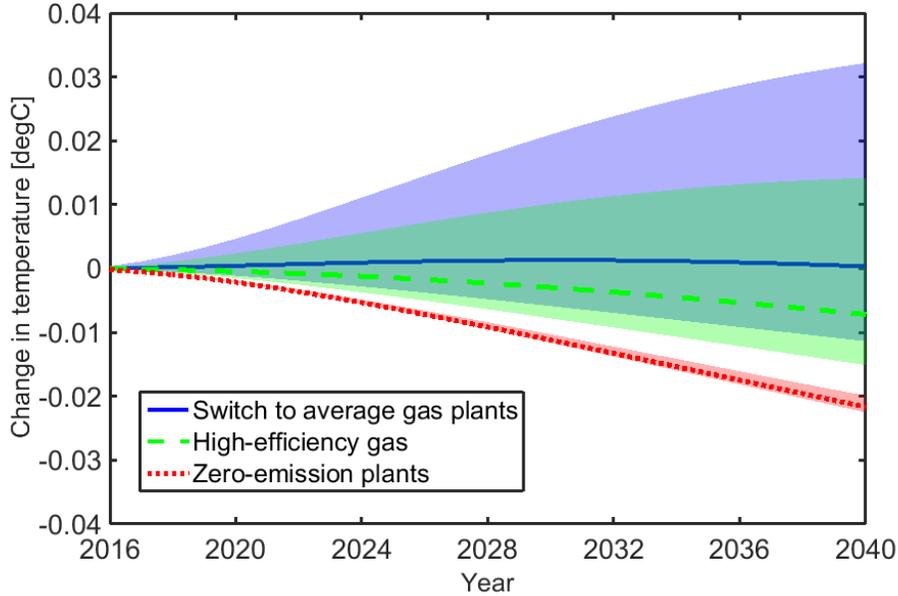


Figure C.4. Effect of fugitive CH_4 rate uncertainty. Change in temperature from scenarios (A) high-efficiency gas, (B) average gas, and (C) zero-emission plants minus change in temperature from business as usual. Temperature changes include contributions from CO_2 and CH_4 only. Solid line is 3% fugitive CH_4 rate for the EIA reference case; shaded area is represents uncertainty across EIA reference case, high gas resource case, and low gas resource case and 0% - 7% fugitive CH_4 rate. Assumed $GTP_{20_{CH_4}}$ of $68 \pm 75\%$.

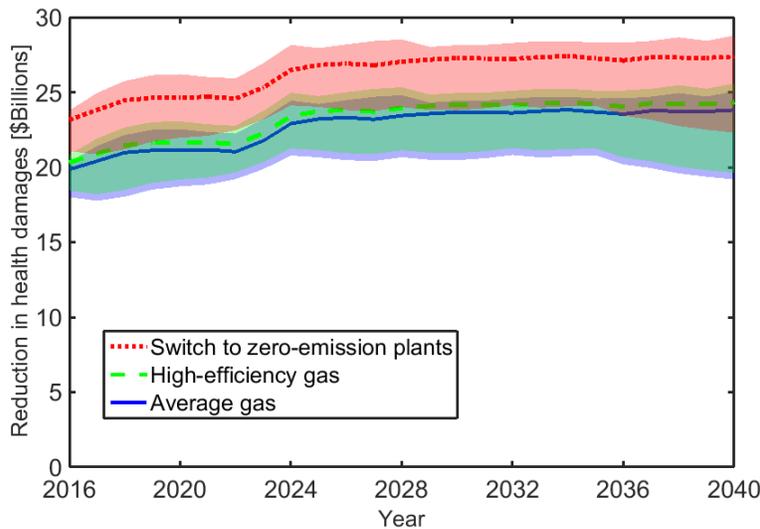


Figure C.5. Reduction in annual health damages due to switching from coal. \$6 million value of statistical life. Solid line is EIA reference case; shaded area is the range across EIA reference case, high gas resource case, and low gas resource case.

C.2 Change in each pollutant, by year

Figures C.6-C.11 provide the change in each pollutant by year for the cases described above.

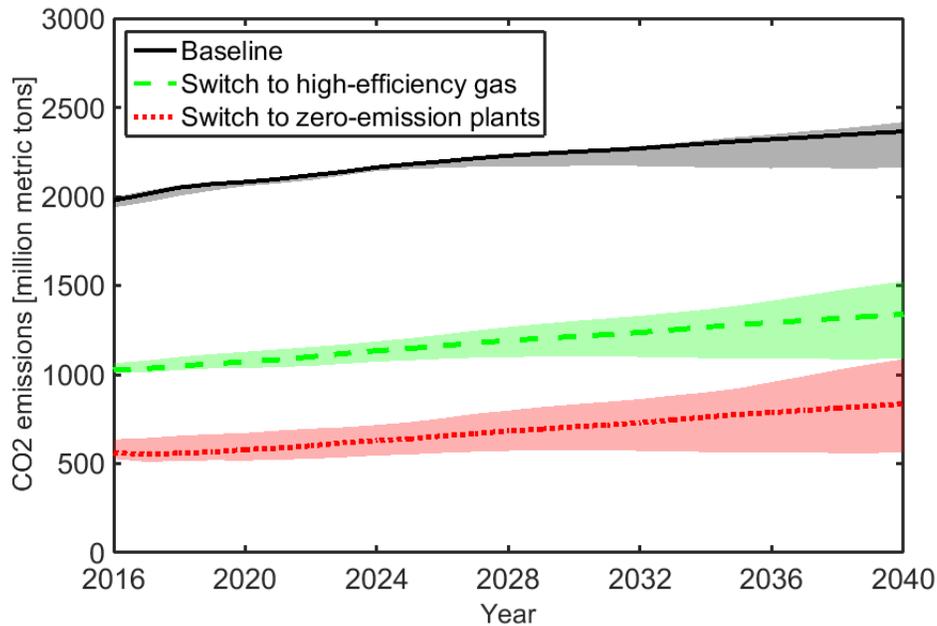


Figure C.6. CO₂ emissions. Solid line is EIA Reference Case; shaded area is range across EIA Reference Case, High Gas Resource Case, and Low Gas Resource Case.

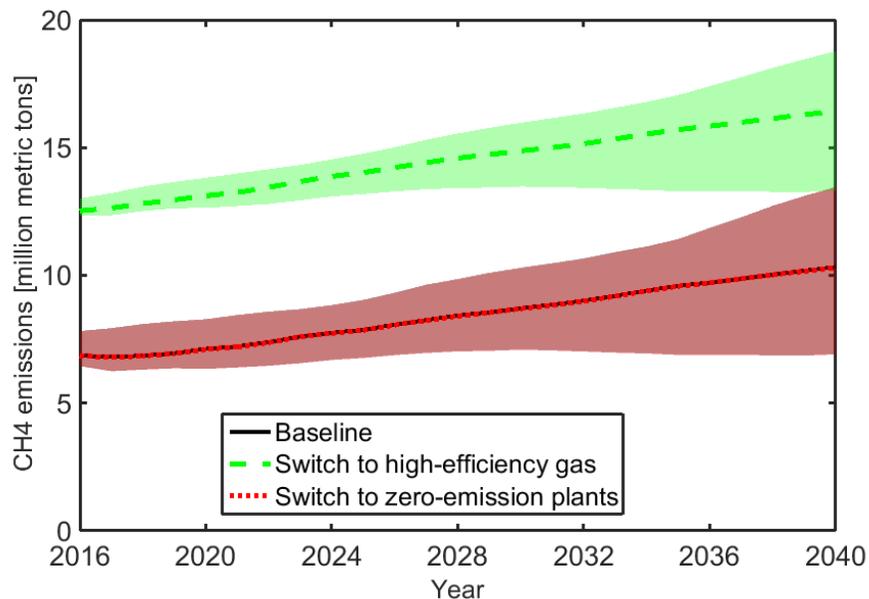


Figure C.7. CH₄ emissions. Solid line is EIA Reference Case; shaded area is range across EIA Reference Case, High Gas Resource Case, and Low Gas Resource Case. Note: Baseline and zero-emission cases are nearly identical.

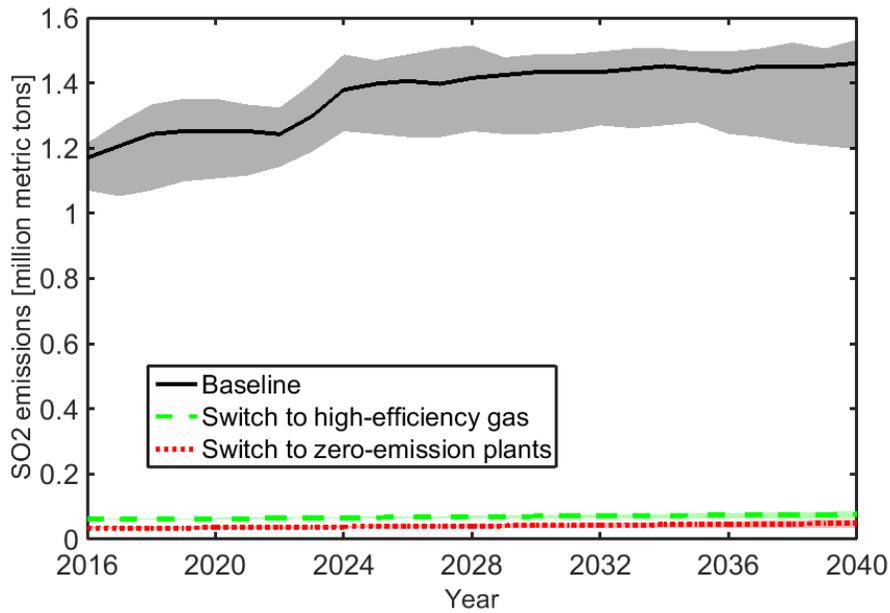


Figure C.8. SO₂ emissions. Solid line is EIA Reference Case; shaded area is range across EIA Reference Case, High Gas Resource Case, and Low Gas Resource Case.

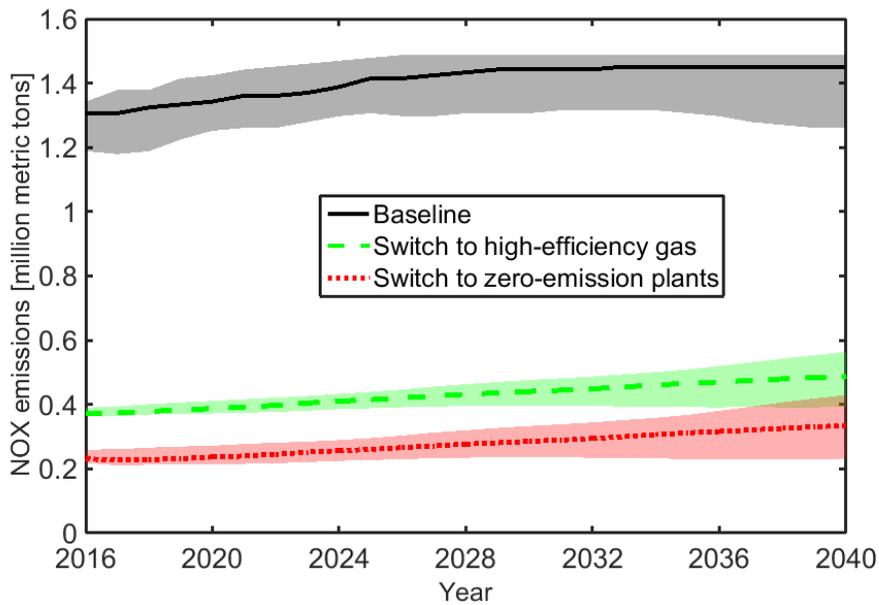


Figure C.9. NO_x emissions. Solid line is EIA Reference Case; shaded area is range across EIA Reference Case, High Gas Resource Case, and Low Gas Resource Case.

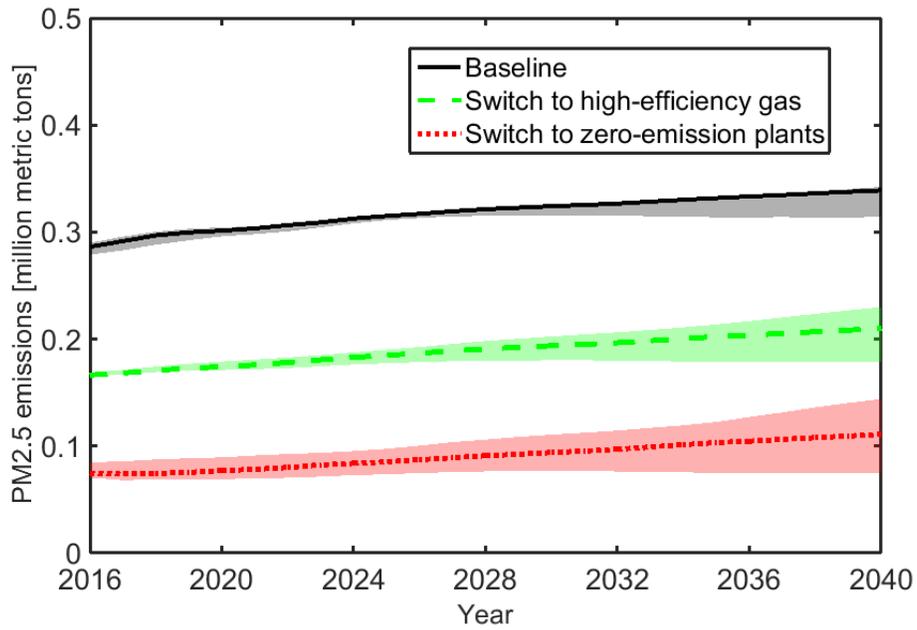


Figure C.10. PM_{2.5} emissions. Solid line is EIA Reference Case; shaded area is range across EIA Reference Case, High Gas Resource Case, and Low Gas Resource Case.

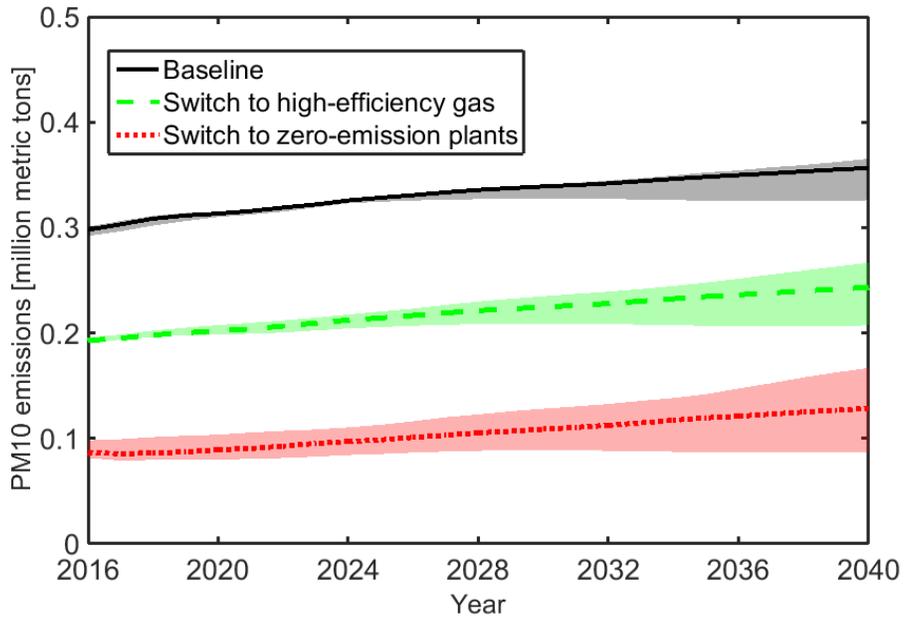


Figure C.11. PM₁₀ emissions. Solid line is EIA Reference Case; shaded area is range across EIA Reference Case, High Gas Resource Case, and Low Gas Resource Case.

C.3 Global Warming Potential

We calculated the Global Warming Potential (GWP) as described in Appendix B of CO₂ and CH₄ emissions in Figure C.12-C13. Fossil methane, including climate change feedbacks, has a GWP over 20 years (or GWP20) of $85 \pm 25\%$, and a GWP100 of $30 \pm 35\%$.

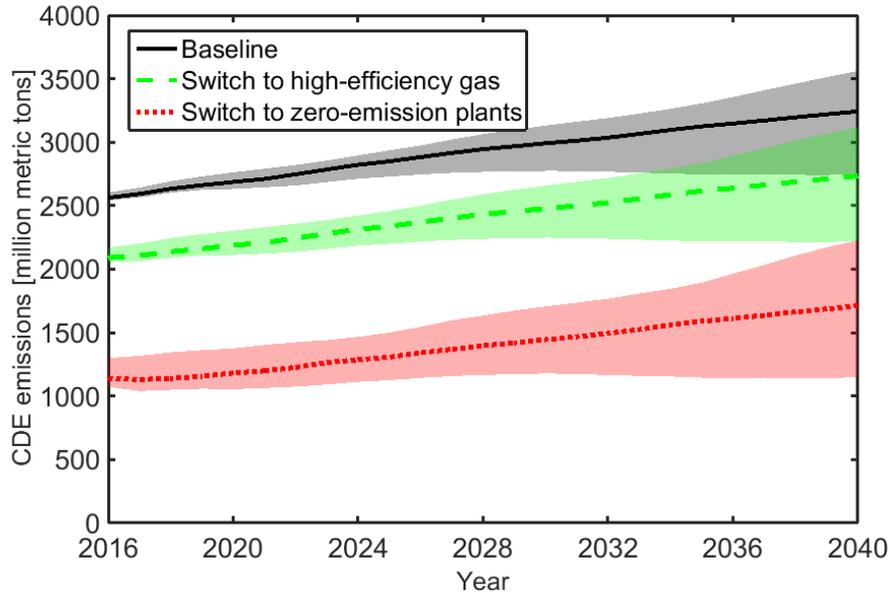


Figure C.12. Carbon dioxide equivalent emissions, CO₂ and CH₄ (20-year GWP of 85), 2016 - 2040. Solid line is EIA Reference Case; shaded area is range across EIA Reference Case, High Gas Resource Case, and Low Gas Resource Case. Assumed fugitive CH₄ rate of 3%.

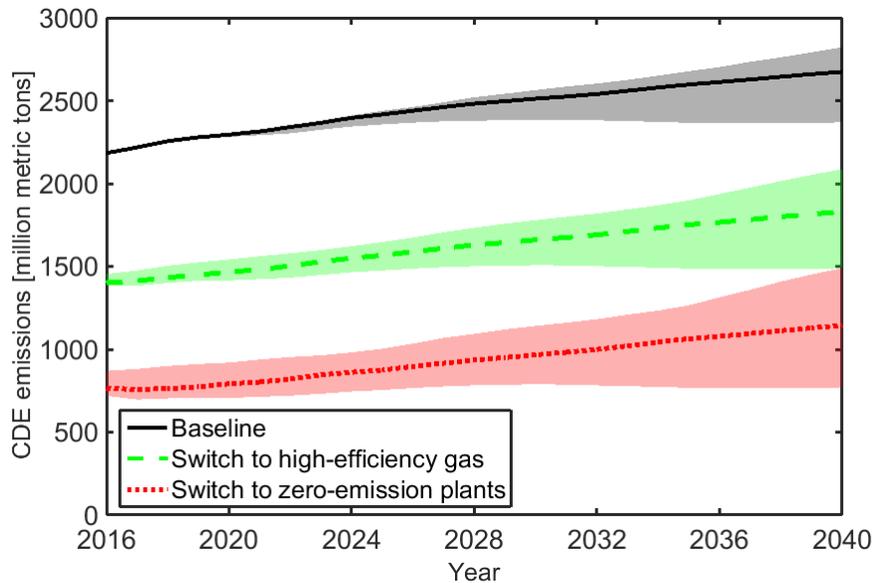


Figure C.13. Carbon dioxide equivalent emissions, CO₂ and CH₄ (100-year GWP of 30) 2016 - 2040. Solid line is EIA Reference Case; shaded area is range across EIA

Reference Case, High Gas Resource Case, and Low Gas Resource Case. Assumed fugitive CH₄ rate of 3%.

C.4 Fugitive emissions

We analyzed the upstream fugitive emissions of CO₂, NO_x, SO₂, and CH₄ associated with the production and transportation of coal and natural gas (Table C.1). Fugitive emissions (sometimes used synonymously with leakage) can have different meanings in different contexts. Here we define fugitive emissions as the sum of intentional and unintentional releases of the modeled gases to the atmosphere. Because fugitive emissions are highly uncertain, we calculated both a low and high estimate. Fugitive emissions of NO_x and SO₂ for both coal and natural gas are taken from (Jaramillo et al., 2007). Upstream greenhouse gas (GHG) emissions from coal, in units of carbon dioxide equivalent mass (CDE), are the 5% and 95% confidence values reported by (Venkatesh et al., 2012a).

Upstream GHG emissions for natural gas plants come from two sources: electricity used in the fuel’s transportation (Jaramillo et al., 2007), and fugitive methane emissions from production and transportation. Of the two, fugitive methane dominates (Jaramillo et al., 2007). Because the amount of fugitive methane is highly uncertain, we parameterized the fugitive emission rate between 0 – 7%, a range that includes estimates from other researchers (Weber and Clavin, 2012; Allen et al., 2013). Total annual CH₄ fugitive emissions were calculated by multiplying the fugitive emissions rate with the total gas consumption of all plants.

Other than potential CH₄ fugitive emissions from natural gas, all fugitive emissions are small when compared to combustion emissions. We therefore exclude all fugitive emissions except CH₄ fugitives from natural gas from our analysis.

Table C.1. Upstream fugitive emission factors

Emission rate (Low estimate, high estimate) [kg/MMBtu fuel produced]	Coal	Gas
CDE	(1.055, 16.774)	(0.068, 0.068) (upstream electricity for transporting CH ₄ only)
CH ₄	0	(0, 1.347) (0% - 7% fugitive emissions rate)
NO _x	(0.014, 0.243)	(0.004, 0.243)
SO ₂	(0.003, 0.013)	(0.003, 0.014)

Appendix D: Climate Model to 2100:

To model the complex chemistry associated with aerosols, SO_x, NO_x, BC, and OC, we needed to use a climate model. This section first describes the process used to model climate effects, and then provides the results. .

D.1 RCPs and their comparison to published data

The representative concentration pathways (RCPs) are new projections of future emissions to 2100 for the Intergovernmental Panel on Climate Change's fifth assessment report (Van Vuuren et al., 2011a). The four scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) represent the range of global radiative forcing estimates by 2100, as low as 2.5 W/m² to between 8 and 9 W/m² and higher (Meinshausen et al., 2013; Van Vuuren et al., 2011b). While the RCPs provide values for land use, dust, and nitrate aerosol forcing, these are not included in the radiative forcing estimates (Van Vuuren et al., 2011b).

The RCP authors caution that users must be careful to avoid over-interpreting the data. The RCPs were developed by four independent modeling groups (Van Vuuren et al., 2011c; Thomson et al., 2011; Masui et al., 2011; Riahi et al., 2011). While integrated assessment models were used (IMAGE, MiniCAM, AIM, and MESSAGE)¹, the scenarios were created without consideration for changes in policy, technology, land-use, or climate. Thus, differences between the scenarios should be attributed in part to differences between models and to scenario assumptions (scientific, economic, and technological). Additionally, the authors caution that users should not attempt to parse out individual countries' contributions over time. This means we can examine only a snapshot in 2010 of the USA electric power fleet. Thus, we must instantaneously change generators in 2010 to those required in each scenario. This is not a limitation for the global RCPs that do report the primary energy sources individually in future years. So our global models examine for each RCP changing all future power plants as well as existing ones.

Observed CO₂ emissions are larger than the RCP 8.5 values (Sanford et al., 2014). Figure D.1-D.2 compare the RCPs to published primary energy usage outlooks from BP (BP, 2013) and ExxonMobil (ExxonMobil 2013). BP's predicted primary energy usage of coal is similar to RCP8.5, the scenario with the highest emissions and strongest radiative forcing. ExxonMobil's predicted primary energy usage of coal is intermediate between RCP6.0 and RCP8.5 until 2040; after that date ExxonMobil predicts substantial reductions in coal usage. The total primary energy usage modeled by ExxonMobil is similar to RCP6.0 through ~2025.

¹ Contact Information: RCP 2.6 (IMAGE): Detlef van Vuuren (detlef.vanvuuren@pbl.nl); RCP 4.5 (MiniCAM): Allison Thomson (Allison.Thomson@pnl.gov); RCP 6.0 (AIM): Toshihiko Masui (masui@nies.go.jp); RCP 8.5 (MESSAGE): Keywan Riahi (riahi@iiasa.ac.at); Data and VOC details: Jean-Francois Lamarque (lamar@ucar.edu)

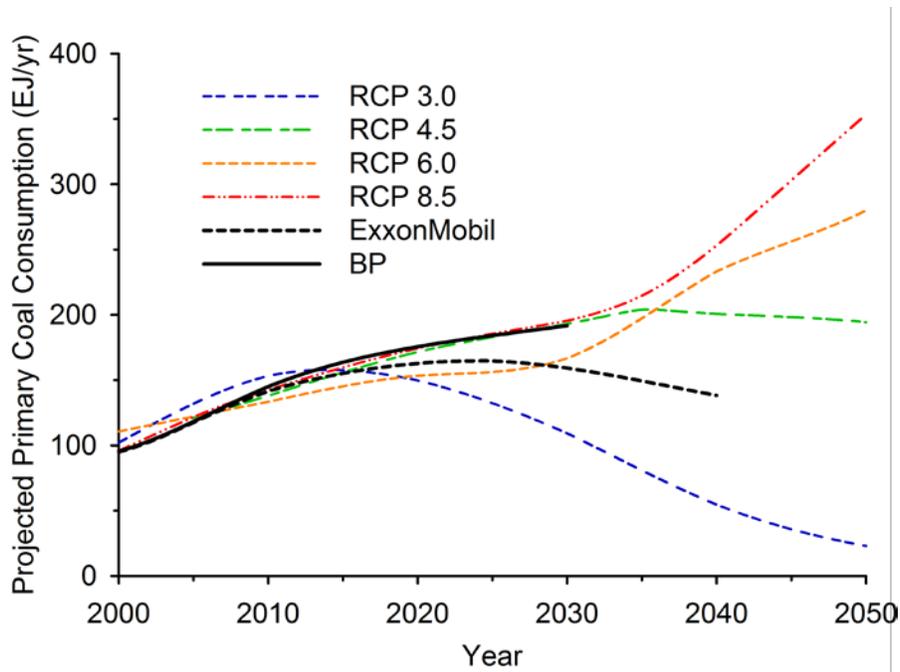


Figure D.1. Primary energy usage of coal, 2000-2040. BP's outlook matches that of RCP 8.5. ExxonMobil's outlook is in between RCP6.0 and RCP8.5 until 2025, at which time they predict substantial reductions in coal usage; its total primary energy usage is in line with RCP6.0.

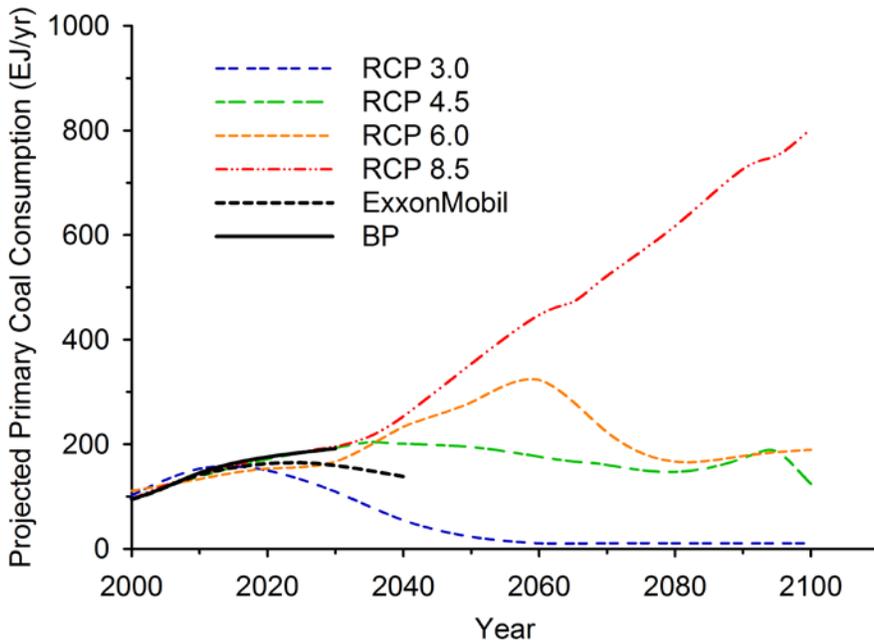


Figure D.2. Primary energy usage of coal, 2000-2100. BP's outlook matches that of RCP 8.5. ExxonMobil's outlook is between RCP6.0 and RCP8.5 until 2025, at which time they predict substantial reductions in coal usage; its total primary energy usage is in line with RCP6.0.

D.2 Climate Model Benchmarking

We modeled climate change effects with the publicly available MAGICC6 model (Meinshausen et al., 2011b). MAGICC6 is a simple/reduced complexity climate model including an ocean, an atmosphere, a carbon cycle, and indirect aerosol effects.

MAGICC6 takes as inputs emissions scenarios (e.g., GtC, MtS, MtN, etc). The model outputs concentrations, radiative forcings, and temperatures. The MAGICC6 authors have converted the RCP scenarios to inputs for running in the model. To test our scenarios a) through c), we slightly modified the included RCP scenarios.

Unfortunately, since the model is calibrated to run at higher emissions scenarios (e.g., RCP6.0 and RCP8.5), we were not able to run reductions from the lowest scenario, RCP2.6. Since the RCP2.6 case appears unreasonably optimistic compared to the trajectory we are now on, as well as to ExxonMobil's and BP's energy outlooks, we chose to examine the upper three RCPs (RCP4.5, RCP6.0, and RCP8.5).

Table D.1 lists other climate models used in the literature to examine the problem. MAGICC6 builds on several of these models, resulting in the most comprehensive model used thus far to examine this problem. Other models approach the problem differently by applying estimates of lifecycle emissions (Jaramillo et al., 2007; Venkatesh et al., 2012b) or by applying a Monte Carlo analysis of values published in the literature (Weber and Clavin, 2012).

Table D.1. Climate models used in recent literature we cite.

Model	Type	Climate Feedback, λ	Ocean	Chemistry
Hayhoe et al., 2002	Energy-Balance Model	1.25 Wm ² /K (2.5°C degree rise for a doubling in CO ₂)	Vertically-resolved upwelling-diffusion deep ocean	Gas cycle models
Myhrvold and Caldeira, 2012	Energy-Balance Model	1.25 Wm ² /K	4 km thick, diffusive slab with a vertical thermal diffusivity 10 ⁻⁴ m ² /s	Basic
Wigley, 2011; Smith and Mizrahi, 2013; Meinshausen et al., 2011b.	Simple/reduced complexity climate model	Central value of 1.50 Wm ² /K; varies in model	Upwelling-diffusion-entrainment (UDE) ocean	Carbon cycle, indirect aerosol effects

D.3 Climate Model Validation

To validate our use of MAGICC6, we compared it to the closest published model used for a coal to natural gas switch, Wigley's Figure 2.b. (Figure D.3). Scenario values are listed in Table D.2. and our temperature differences from business as usual is in Figure D.4. We find that we can replicate Wigley's CO₂ and CH₄ radiative forcings quite closely. While we can replicate the general trend of the SO_x closely, our increase in global temperature from 2040-2060 is not as pronounced as he finds (Figure D.4). It is likely that Wigley may have applied the SO_x reduction slightly differently than we did.

Table D.2. Model description used in Wigley’s model and our choices to perform validation with MAGICC6.

Item	Wigley	This work
Baseline emissions scenario	standard “no-climate-policy”	RCP 8.5
Scenario	Replaces coal with natural gas as given in his Figure 1. For every 1EJ of coal replaced by gas, reduce coal GtC by 0.027GtC/EJ and increase gas GtC by $0.027\text{GtC/EJ} * 0.299 = 0.008073$.	Same
Fugitive emissions	5%, or 66.6 TgCH ₄ /GtC of natural gas	Same
SO _x	Assume a value of 12 TgS/GtC for the present (2010) declining linearly to 2 TgS/GtC by 2060 and remaining at this level thereafter.	Same
BC	No change in input to model. BC’s radiative forcing reduces the SO _x radiative forcing by 30%.	Replace MAGICC6 output with Wigley assumption.

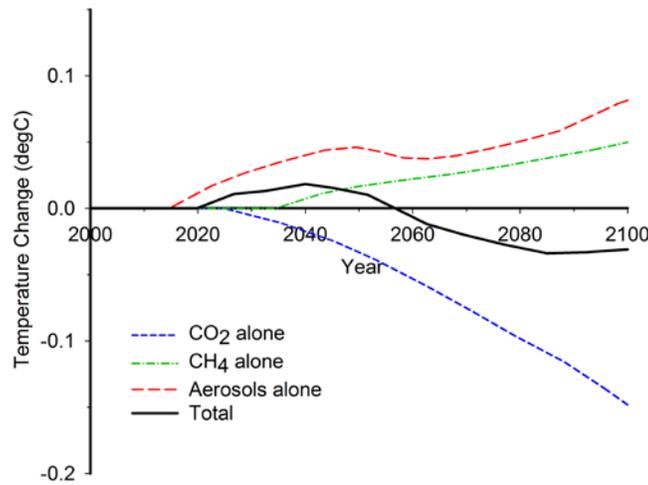


Figure D.3. Temperature changes from Wigley, 2011, Figure 2b

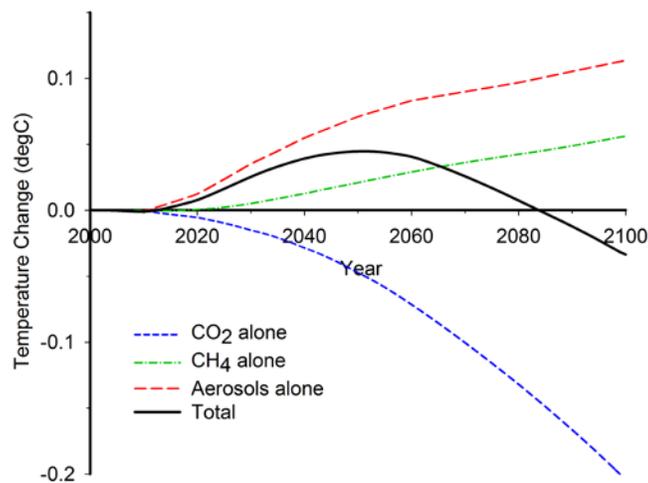


Figure D.4. Temperature changes recreating the Wigley, 2011 estimates

D.4 Climate Results: Radiative forcing and temperature

Finally we examined the effects of a US switch as described in the main text in the MAGICC6 Model. For scenarios a) – c) and fugitive methane rates of 0% - 7%, we modeled changes from business as usual using MAGICC6's default emissions for representative concentration pathways (RCPs) 4.5, 6.0, and 8.5 (Meinshausen et al., 2011a; Venkatesh et al., 2012b). Since the MAGICC6 climate model can allocate total emissions by region, we allocated all changes to the OECD region and assumed no changes in other regions). For each RCP, we assumed that, to first order that we could use the appropriate EIA Case Scenario: Low for RCP4.5, Reference for RCP 6.0, and High for RCP8.5. While the RCPs are not meant to be used this way, we believe this is an okay assumption. For 2000-2040, we used annual intervals of changes from business as usual as described in our main text; starting in 2040, we assumed the changes remained constant to 2100. We assumed all SO₂ could be considered SO_x. Additionally, we assumed NO_x is made of 90% NO and 10% NO₂ by mass (Hanrahan, 1999). Based on recent publications examining coal power plant particulate matter, we assumed that all particulate matter (PM_{2.5} and PM₁₀) is 12% organic carbon, 4% black carbon, with the rest not relevant for the climate (Wang et al., 2013; Goodarzi, 2006). Total emissions were not allowed to drop below zero.

In agreement with published literature (Hayhoe et al., 2002; Jaramillo et al., 2007; Wigley, 2011; Venkatesh et al., 2012b; Myhrvold and Caldeira, 2012; Weber and Clavin, 2012), we find that climate benefits for a USA policy of switching from coal to natural gas are limited. Fuel switching increases temperature in the short term due to reduction in aerosols and increased fugitive methane emissions, and decreases temperatures by 2100 due to reduction in CO₂. The length of this “temperature delay” in 2100 is dependent on the amount of coal switched. Varying the methane fugitive emissions rate from 0-7% can alter changes from business as usual by as much as ±25%.

Figure D.5 shows the change in temperature from business as usual for the USA policy for scenarios a) -c). All of the coal to natural gas scenarios and RCPs are similar; scenario a) is best at reducing temperature concentrations, while scenario b) is least effective. The zero emissions scenario c) is roughly 2-3 times more effective at reducing temperature as the gas scenarios. While a USA policy reduces the nation's contribution to global temperatures in 2100 by, in some cases, over 33% as shown in the Main Text, the reduction values are small compared to global values. For reference, Figure D.6 shows the relation between radiative forcings and temperatures.

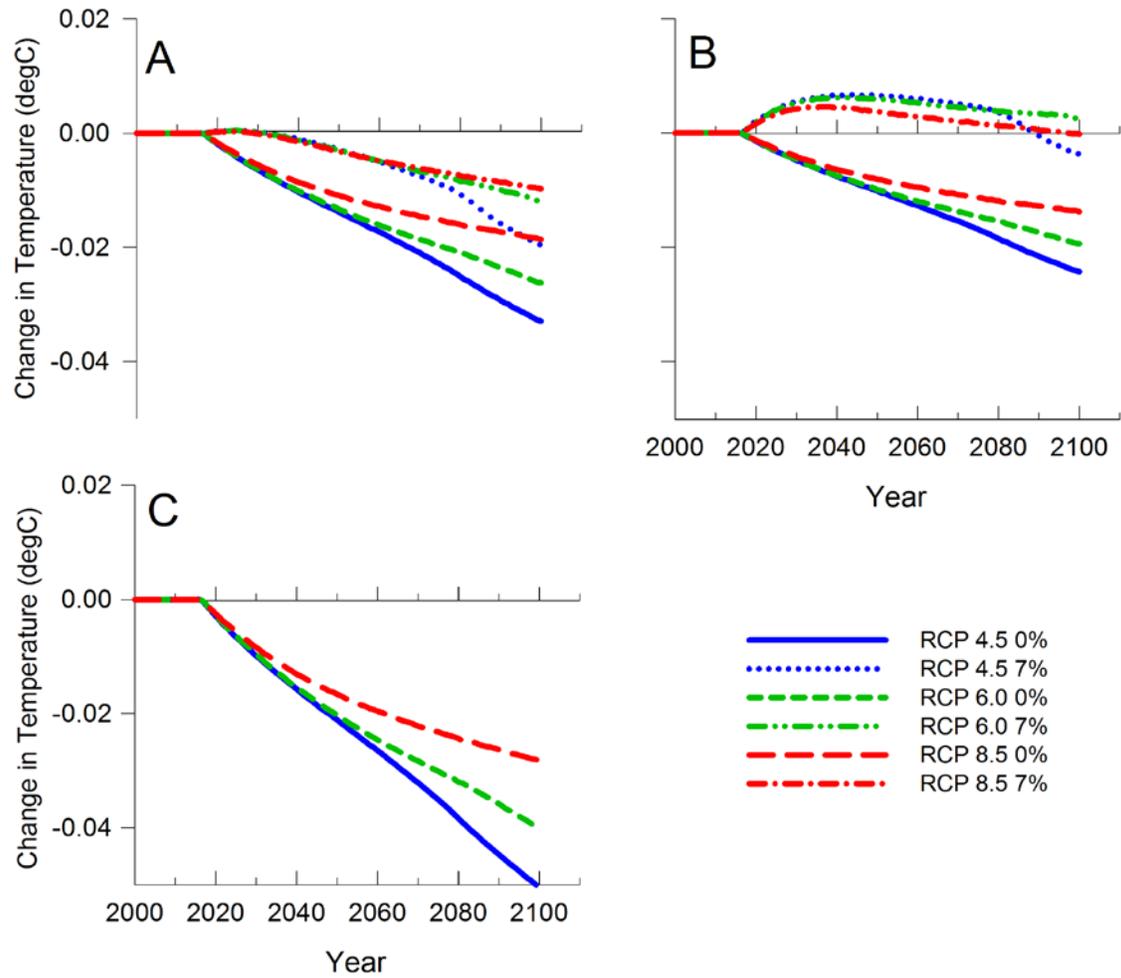


Figure D.5. Change in Temperature from Business as usual for the USA Policy for scenarios (A) High efficiency Gas, (B) Average Gas, (D) zero emissions. We note that this graph is meant to compare with the GTP value, and thus for our purposes includes changes from CO₂ and CH₄ only.

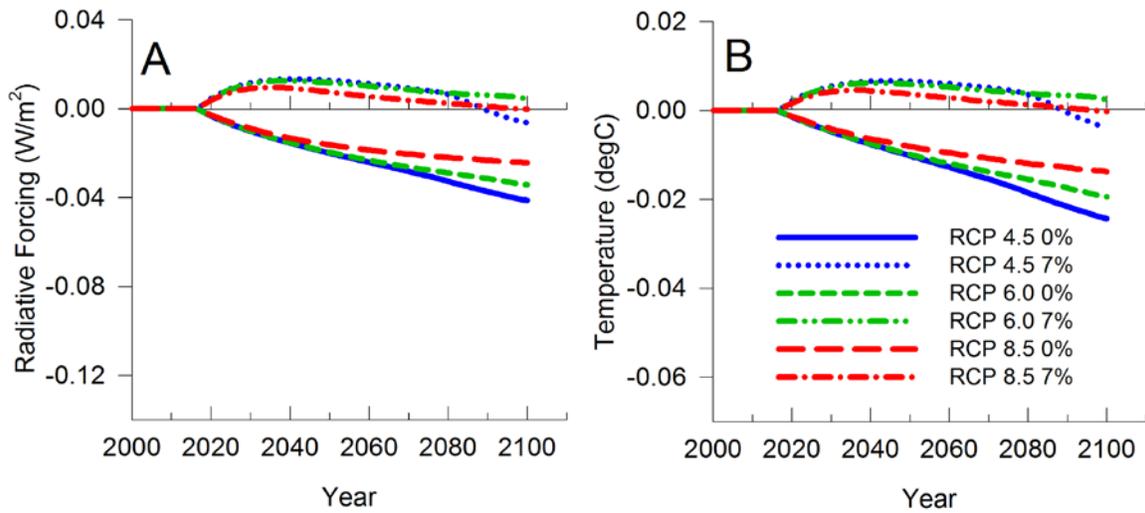


Figure D.6. Change from Business as usual for the USA Policy for Scenario b): Average Gas for (A) radiative forcings (W/m^2) and (B) temperature ($^{\circ}C$)

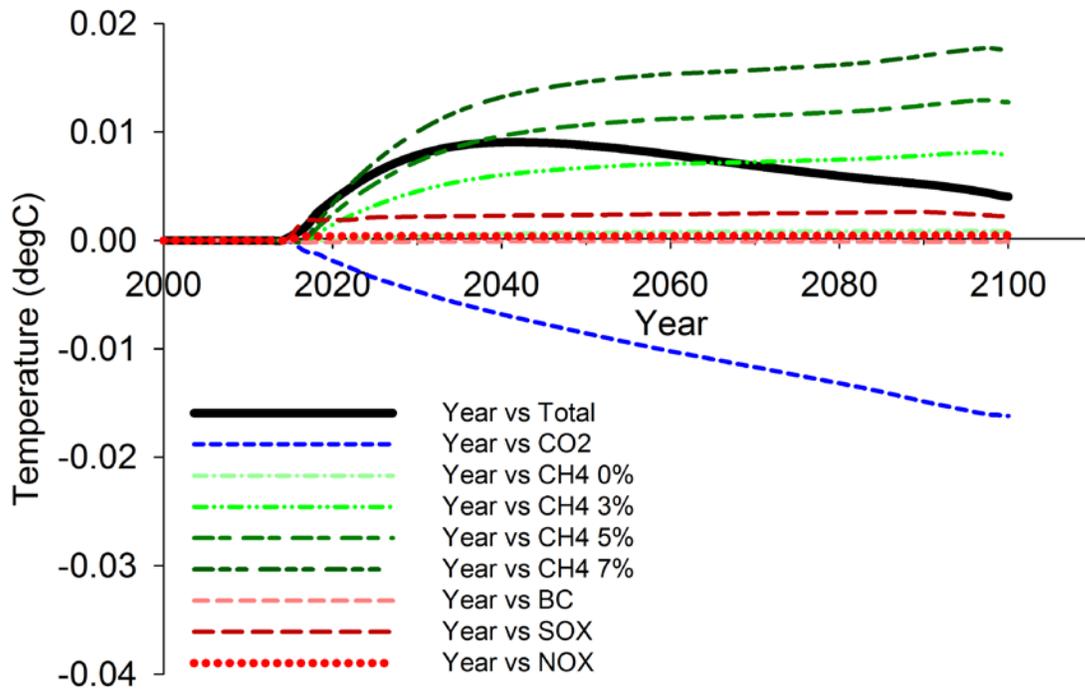


Figure D.7. Change from Business as usual for the USA Policy for Scenario b): Average Gas for RCP8.5 for temperature contribution ($^{\circ}C$) by individual constituents. The total, shown as the solid black line, is for 3% fugitive methane emissions.

Figure D.7 includes the effect of aerosols and shows the temperature contribution by individual constituents for RCP8.5. While highly uncertain, the direct effect of aerosols in MAGICC6 is to cool the climate, so decreasing aerosols increases the temperature in the short term. Their lifetime is short, so aerosol contributions decrease quickly. Reductions remain small compared to global values. We note that aerosol forcing has large uncertainties (Bond et al., 2013) that may be of the same size as that for methane leakage.

Previous literature assumes the base coal fleet emits a large amount of SO₂. Therefore, a shift from coal to gas would significantly reduce SO₂, offsetting both the climate forcing from the reduction in black carbon and some of the GHGs (Wigley, 2011). In our analysis, the baseline fleet in 2016 has been updated to reflect the MATS standard, and therefore already has low SO₂ emissions. Thus the avoided SO₂ emissions in scenarios a-d are no longer large enough to offset the changes from the reduction in black carbon. This effect means that for some scenarios, a coal to gas shift would result in an initially sharp decrease in radiative forcings followed by an increase as the longer-lived methane dominates.

We note that MAGICC6's chemistry model has many interesting secondary effects we have not reported with these data, e.g., the lifetime of halogenated gases decreases as methane concentrations increase. As part of their work examining a coal to natural gas shift, Smith and Mizrahi calculate the change in radiative forcing from business as usual for gases regulated under the Kyoto protocol (Smith and Mizrahi, 2013). Our analysis agrees with Smith and Mizrahi: depending on scenario and policy, we find the gases regulated under the Kyoto protocol result in an additional 20-30% reduction in radiative forcing in 2100. While this additional reduction suggests that a shift from coal to natural gas might be better for the climate than we suggest, the additional reduction is small compared to total reduction values and less than the model uncertainty.

D.5 Global replacement scenario

We next analyzed what would be the effect of switching all current and future coal power plants to natural gas. Here we assumed all global existing and future power plants are switched. The RCP scenarios provide estimates of future primary energy use of coal. Using 2005 data, we estimated that 77% of the primary energy usage of coal is in the form of coal power plants (Cullen and Allwood, 2010). While this percent is likely to change slightly from year to year, we assumed it was constant out to 2100. We then calculated the total electricity generation from the coal used for electric power. Finally, we assumed the coal plants generating this electricity were retired and replaced with natural gas or zero emission plants (Scenarios a-c)). Note that we assumed that all coal plants and replacement generators in the global scenarios have the same heat rates and emission rates as those in the USA scenarios.

A global policy of switching all coal plants to natural gas would reduce total cumulative global GHG emissions to 2100 by 4% - 21% depending on the replacement scenario, assumed fugitive CH₄ emissions rate, and RCP. Scenario b with a 5% fugitive emissions rate and RCP 6 would reduce global GHG emissions by 9% (see Figure D.8). Switching to zero emission plants reduces emissions 26% assuming RCP 6.

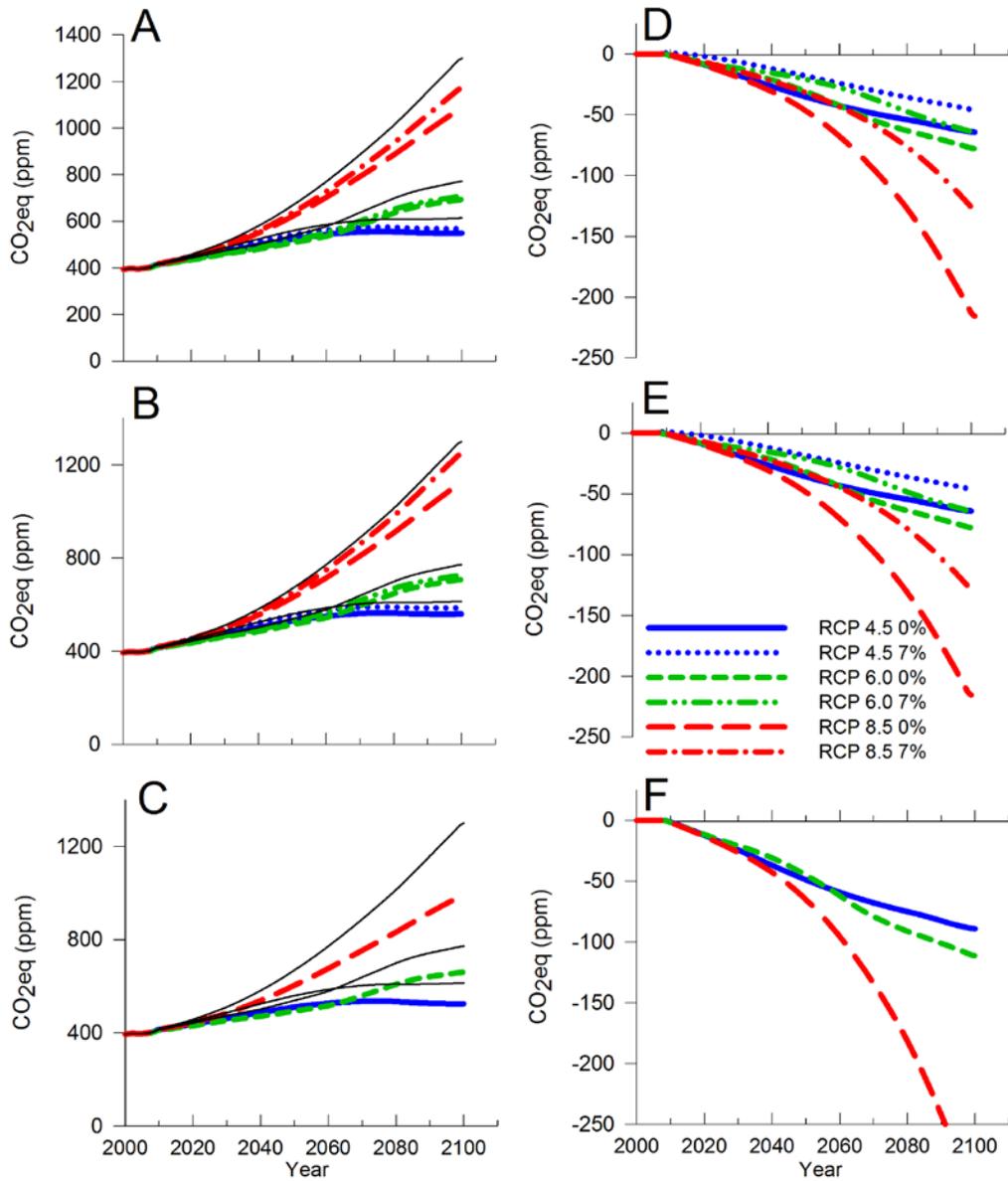


Figure D.8. Total CO₂eq (A-C) and Change in CO₂eq from Business as usual (D-F) for, from top to bottom, the Global Policy for Scenario a): High efficiency gas, Scenario b): Average, Scenario c): ZEG. Solid black lines indicate the business as usual scenario for 3% methane leakage.

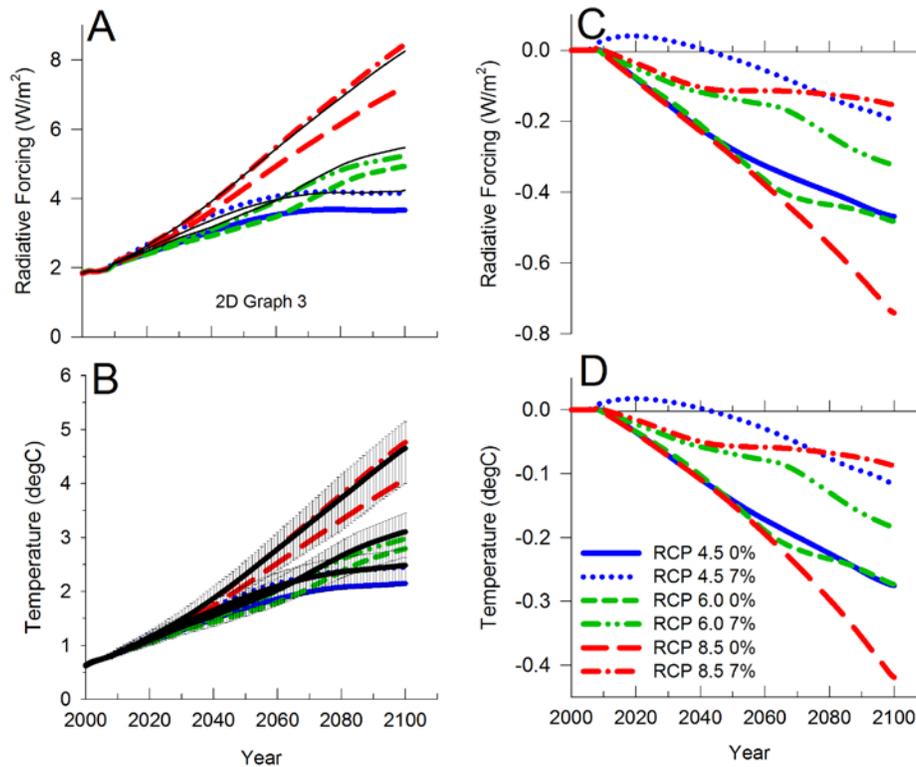


Figure D.9. Total (A-B) and change from Business as usual (C-D) for the Global Policy for Scenario b): Average for radiative forcings (A, C) and temperature (B, D). Solid black lines indicate the business as usual scenario for 3% methane leakage, and the error bars in B indicate the 66% confidence interval for a MAGICC6 multi-modal run where 171 Scenarios are run with all combinations of 19 AOGCM calibrations and 9 carbon cycle model calibrations.

Figure D.9 shows the total CO₂eq and change in CO₂eq from business as usual for the Global Policy for scenario a)-d). A global policy of switching from coal to natural gas could delay CO₂eq in 2100 by 5-25 years. All of the coal to natural gas scenarios are very similar; it appears that scenario a) is best at reducing CO₂eq concentrations, while scenario c) is the worst. Scenario d) is roughly 2-3 times as effective at reducing CO₂eq. Results vary with RCPs due to assumptions about future coal usage; since RCP8.5 assumes a large number of new coal power plants will be added to the fleet, it shows the largest decrease in concentrations.

Figure D.9 includes the effect of aerosols, and shows the radiative forcing and temperature for scenario b). The direct effect of aerosols is to cool the climate, so decreasing aerosols increases the temperature in the short term. Their lifetime is short, so this effect quickly disappears. Reductions remain small compared to global values and model uncertainty.

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