The Health Effects of a USA Switch from Coal to Gas Electricity Generation

Roger Lueken[†§], Kelly Klima[†‡], W. Michael Griffin[†], Jay Apt[†‡]*
[†]Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA 15213, USA
[‡]Tepper School of Business, Carnegie Mellon University, Pittsburgh, PA 15213, USA
[§]Present address: The Brattle Group, 1850 M Street Northwest #1200, Washington, DC 20036, USA

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 bounding analysis case, we analyzed a switch of all USA coal plants to natural gas plants, occurring in 2016. Although the climate change effects would be modest, the human health benefits of such a switch are substantial: SO_2 emissions are reduced by more than 90%, and NO_X emissions by more than 60%. The costs of building and operating new gas plants likely exceed the health benefits; retrofitting coal plants with emission control technology is likely to be more cost effective. Policymakers should not be distracted by the modest climate change benefits; annual health damages could be reduced by ~$20 billion in the United States if coal plants are either replaced with gas plants or fitted with flue gas desulfurization emission controls.

KEYWORDS
Natural gas, coal, criteria pollutants, human health

INTRODUCTION

Over the past decade shale gas development has increased USA domestic gas production by 20% [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. In June 2014 the Environmental Protection Agency proposed the Clean Power Rule under 111(d) that would reduce greenhouse gas emissions from the power sector 30% by 2030, compared to the levels in 2005 [2].

Recently, a growing body of research has questioned the ability of domestic natural gas to substantially reduce USA greenhouse gas (GHG) emissions. Natural gas power plants typically emit 50% - 60% less carbon dioxide (CO_2) 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, CH_4), itself a potent GHG, and may diminish these climate benefits. In general, GHG emissions associated with natural gas use comes from fugitive methane emissions or fuel combustion [4]. A number of GHG life cycle analyses (LCA's) have been published for conventional or average natural gas [5-11] and for unconventional natural gas modeled as average unconventional gas [5-9], or specific shale gas plays, e.g. Marcellus Shale [10-13] and Barnett Shale [11].

Weber and Clavin [14] reviewed many of these studies [5-11], reconciled differences in upstream data and assumptions, assured consistent boundary conditions, and conducted an uncertainty analysis of the GHG emissions for both shale and conventional natural gas production. They found that the likely upstream carbon footprint of both conventional and unconventional natural gas production to be similar, with overlapping 95% confidence ranges from 11.0–21.0 gCO2e/MJ for shale gas and 12.4–19.5 gCO2e/MJ for conventional gas. The upstream emissions represented less than 25% of the total emissions for producing heat, electricity, transportation services, or other functions.

Brandt et al. reviewed 20 years of technical literature to find emissions estimates of natural gas production [15]. They concluded that most official inventories underestimate methane emissions and a small number of super emitters might be responsible for a large fraction of the emissions. The authors suggested that the likely leakage rate is not large enough to negate the climate benefits of coal to gas switching. Recent measurement campaigns even when including production related methane emissions measurements from operations such as well production, completions, and liquids unloading [16-18], gathering facilities and processing plants [19] and compressor stations [20], agree with these assessments. Aerial measurements have suggested higher emissions rates [21-23] than the direct process measurement or those calculated via the life cycle studies.

Much research exists on the climate impact of fugitive methane emissions associated with natural gas use. Using a reduced form integrated assessment model, global average emissions factors, and conversion efficiencies, Hahoe et al. found initial higher temperatures with natural gas use [24] due to reduced sulfate aerosols. The impact lasted for up to 30 years depending on sulfur emissions controls, although by 2100 the reduction of carbon dioxide emissions led to a net decrease in temperature. The authors noted that methane emissions due to natural gas use were an "important factor" in determining the effectiveness of replacing coal by natural gas. Wigley confirmed this earlier analysis and extended the research by looking at supply chain fugitive emissions rates ranging from zero to 10% [25]. He modeled a coal replacement scenario (1.25% per year) along with replacement of any additional primary fossil energy with natural gas. Wigley concluded that methane emissions more than offset any gains from a coal to gas transition until after 2100 and that the overall methane leak rate must be kept below 2% to be an effective mitigation strategy. As was observed by Hayhoe et al. [24], temperature increased before the impact of reduced CO_2 emissions offset the warming due to reduced sulfur emissions. McJeon et al. used an ensemble of five integrated assessment models combined with MAGICC 6.0 to assess future scenarios with abundant natural gas [26]. The availability of low priced abundant natural gas displaced more than just coal fired electricity production as assumed in other studies, thus increasing economic activity in general. The combined effect resulted in no discernible reduction in fossil fuel GHG emissions to 2050. When adding the impact of a high fugitive emissions rate for natural gas production the climate forcing increased by more than 5% compared to the baseline analysis. Overall the climate modeling suggests that the fugitive emissions associated with natural gas production must be low to result in the net reduction of GHG emissions. Measurement studies tend to confirm the lower range of emissions rates suggested by LCA analysis but this level tends to be at the critical value suggest by climate modeling. Additional work is needed to further quantify these emissions and reconcile aerial basin measurement with facility level data. But one can tentatively conclude that there could be emissions reductions associated with natural gas substitution for coal use but the overall climate impact will likely be small.

The human health consequences of such a shift have not received as extensive a discussion as the GHG effects. Compared to coal plants without emission controls, natural gas plants emit less SO_2 and NO_x, precursors of particulate matter. Natural gas generation also has lower primary emissions of $PM_{2.5}$ and PM_{10} than does coal generation. Exposure to $PM_{2.5}$ has been linked to human mortality and morbidity [27-31]. EPA regulations, including the Clean Air Interstate Rule (CAIR), the Cross-State Air Pollution Rule, and Mercury and Air Toxics Standard (MATS), are designed to reduce these emissions [27, 32, 33]. These regulations have been one cause of a switch from coal to natural gas plants [34].

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 an instantaneous switch of all USA coal plants to natural gas plants, occurring in 2016. We quantified the reductions in total power sector emissions that would occur, as well as the associated health benefits.

Our intent was not to quantify the cost effectiveness of switching to gas or 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 health [35, 36] and climate implications [24, 26, 37, 38] of switching the USA fleet of coal generators to gas plants in that we attempted to quantify the maximum achievable benefit of this switch. In reality, the switch from coal to gas would take several years, and the pollution reduction benefits would be less than the upper bound we establish in the thought experiment we present here. Unlike these studies, we also directly compare the magnitude of the reduction in criteria pollutant emissions to that of GHG emissions.

METHODS

We used U.S. Department of Energy (DOE) forecasts of emissions and generation as the baseline for our analysis. From this baseline, we replaced all coal plants with natural gas plants, starting in 2016. We varied the fugitive methane emission rate from 0% - 7%, a range that includes estimates from existing literature [14]. The APEEP model [39] was used to compute the health benefits of such a switch.

Calculation of baseline emissions

We developed baseline emission scenarios for 2016 – 2040 based on the forecasts from the DOE's Energy Information Agency (EIA) [40]. EIA forecasts installed capacity by plant type, electricity generation by fuel type, and total NO_X and SO_2 emissions from the electric power sector. 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 the supporting information, Section 3. We assumed that any switching from coal to gas not forecast by the EIA would be due to future policies, not market forces.

Baseline NO_X and SO_2 emissions

EIA forecasts total electric power NO_X and SO_2 emissions to 2040. It does not forecast emissions by fuel type. We therefore separated out the NO_X and SO_2 emissions associated with coal, oil, and gas plants. We first calculated NO_X and SO_2 emissions from oil and gas plants. We used plant-level emission data from the EPA Air Market Program Database (AMPD) to identify 2012 capacity-weighted average emission rates for oil and gas plants in 27 eastern states regulated by the EPA Clean Air Interstate Rule (CAIR) [41].

Next, we multiplied these emission rates by EIA's forecast of electricity production to find total NO_X and SO_2 emissions from oil and gas plants. Finally, we calculated coal NO_X and SO_2 emissions as the difference between EIA's forecast of total NO_X and SO_2 emissions and total oil and gas plant emissions.

Baseline $PM_{2.5}$ and PM_{10} emissions

EIA does not forecast direct emissions of $PM_{2.5}$ and PM_{10} from power plants. We assumed that coal and oil plants emit 0.14 kg / MWh of $PM_{2.5}$ and PM_{10}, the limit imposed by the EPA's MATS [27]. Gas plants are not regulated by MATS, and therefore we used data from the 2005 National Emissions Inventory (NEI) [42] and eGRID 2005 [4] to identify gas plant $PM_{2.5}$ and PM_{10} 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 PM_{10}. For coal, oil and gas plants, we multiplied the assumed emission rates by EIA's forecast of annual electricity generation by each fuel.

Baseline greenhouse gas emissions

EIA does not forecast CO_2 or CH_4 emissions. We calculated CO_2 emissions by multiplying EIA's forecast of total electricity production from each fuel by the 2012 capacity-weighted average CO_2 emission rate of plants of that fuel type. We used plant-level emission data from AMPD to identify 2012 CO_2 emission rates for plants in CAIR states. These generators made up 70% of 2012 CO_2 emissions.

We calculated CH_4 emissions as the sum of combustion emissions and fugitive emissions from CH_4 production and transportation. Combustion CH_4 emissions for each fuel type are the capacity-weighted average CH_4 emission rates of plants in the EPA's Emissions & Generation Resource Integrated Database (eGRID), 2009 [4]. We parameterized the rate of fugitive CH_4 emissions in a range of 0 - 7%, covering estimates from existing literature [14]. We multiplied the fugitive rate by forecasts of total gas to calculate total fugitive CH_4 emissions. Total gas consumed was found by multiplying EIA's forecast of natural gas generation [40] by the capacity-weighted heat rate of existing gas plants in 2012 [4]. Other fugitive emissions (greenhouse gases, NO_x, SO_2, $PM_{2.5}$, PM_{10}) 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 [37].

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 natural gas combined cycle (NGCC) plants. New NGCC plants were assumed to have a heat rate of 5,700 Btu/MWh achieved by state-of-the-art GE Flex-60 and Siemens Frame-H [43, 44]. The CO_2 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 [45]. 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 SO_2 emission rates were based on 2012 emission rates (AMPD); CH_4 emission rates were from eGRID [3]; $PM_{2.5}$ and PM_{10} emission rates were based on NEI [42].

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, CO_2, NO_X and SO_2 emission rates were based on 2012 data (AMPD); CH_4 emission rates were from eGRID [3]; $PM_{2.5}$ and PM_{10} emission rates were based on NEI [42]. This scenario isolates the benefits of fuel switching from the benefits of switching to high-efficiency plants (Scenario a). Load-weighted emission rates were calculated per Equation 1; load-weighted heat rates were calculated similarly.

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 (supporting information, Figures S3 – S6). 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.

Calculation of health effects

Switching from coal to gas reduces emissions of SO_2, NO_X, $PM_{2.5}$, and PM_{10}. We monetized the benefit to human health and the environment caused by this switch using the Air Pollution Emission Experiments and Policy (APEEP) model [39]. The model 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, SO_2, $PM_{2.5}$, PM_{10}, volatile organic compounds (VOCs), and ammonia (NH_3) from each county in the USA. We excluded damages due to VOC and NH_3 from our analysis due to uncertainty in the atmospheric science surrounding these pollutants, and the relatively small damages they cause compared to SO_2, NO_X, and PM [46, 47].

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) [39]. APEEP was used in the National Academies' *Hidden Costs of Energy* report [35]; similar health models exist [36, 48] and have been used by the EPA to as technical support for major pollution regulations [27]. The APEEP model and our analysis exclude damages associated with emissions in Alaska and Hawaii.

Because the damages caused by emissions vary by location, we estimated individual coal plant emissions of SO_2, NO_X, $PM_{2.5}$, and PM_{10}. Although EIA forecasts total NO_X and SO_2 emissions, plant-level emissions out to 2040 are highly uncertain. We assumed the fraction of total coal SO_2 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 PM_{10} [32].

Switching all coal plants to gas would have a significant effect on criteria pollutants, and it might be argued that APEEP's 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 SO_2 and NO_X is linear with reduced emissions, with no threshold [49]. Major cohort studies have found $PM_{2.5}$ concentration-response functions and mortality are linear with no threshold [50-52]. 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 SO_2 emissions.

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 CO_2 emissions by half; switching to high-efficiency gas reduces CO_2 emissions by ⅔. Both average and high-efficiency gas plants emit an order of magnitude less SO_2 and NO_X than coal plants.

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

Change in Emissions

Figure 1 shows emission reductions due to switching from coal to gas. The switch reduces SO_2 emissions by more than 90%, NO_X emissions by more than 60%, and PM emissions by 40% from the EIA's reference case (supporting information, Figures S7 – S12). Annual electric power CO_2 emissions are reduced by 35% - 47%; CH_4 emissions would increase by 80% - 120%, assuming a 3% fugitive CH_4 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 CH_4 reductions are highly sensitive to the assumed fugitive CH_4 emission rate. Emission reductions are similar for the EIA Reference Case, High Gas Resource Case, and Low Gas Resource Case (see supporting information, section 3).

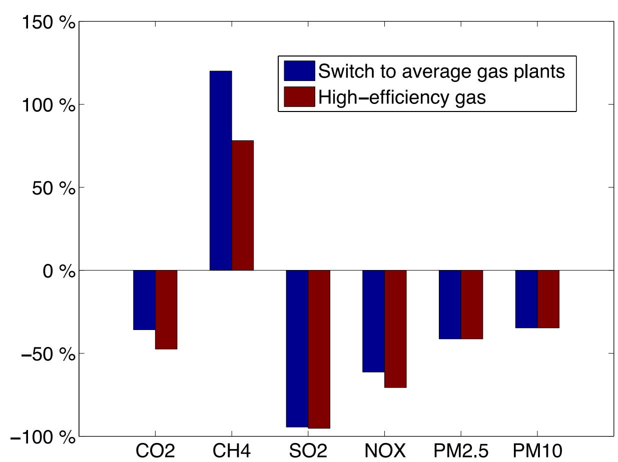

Figure 1: Effect of coal-to-gas switching as a percent change in total USA electric power GHG emissions (CO_2 and CH_4, the latter using a 3% fugitive CH_4 rate), and criteria pollutants from the EIA Reference Case in 2025. Reductions are constant across years 2016 – 2040.

Table 2: Sensitivity of CH_4 emissions in 2025 to fugitive CH_4 emission rate, EIA Reference Case.

	Percent change in CH_4 emissions			
Scenario	**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

Effect on human health

Switching from coal to gas would significantly reduce SO_2, NO_X, and PM emissions (Figure 1). The monetized annual health and environmental damages of emissions, via the APEEP model, are shown in Figure 2. Damage reductions are \$20 billion - \$24 billion per year if switching to either high-efficiency gas or average gas plants. Damage reductions increase from 2016 – 2025, as the EIA forecasts increasing coal generation over that time period. More than 75% of damage reductions are due to reductions in SO_2; reductions in NO_X and $PM_{2.5}$ each make up 10% of damage reductions. Health and environmental damages vary regionally (Figure 3). Most damages occur in the Ohio River Valley and Southeast due to the high concentration of coal plants and significant downwind population.

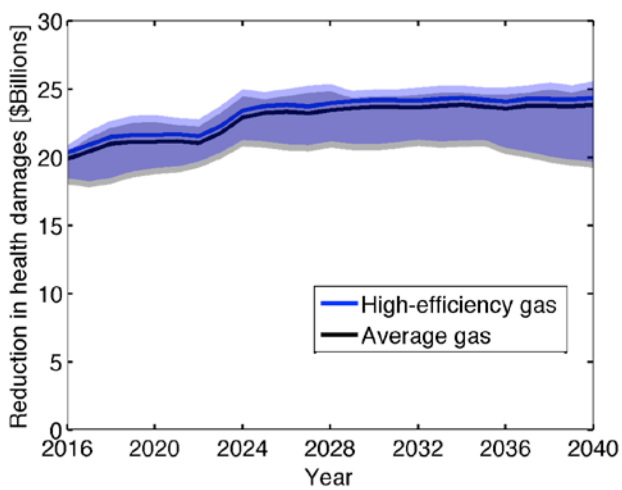

Figure 2: Reduction in annual health damages due to switching from coal, using a \$6 million value of statistical life. Solid line is EIA reference case; shaded area is the range across EIA reference case, high gas resource case, and low gas resource case.

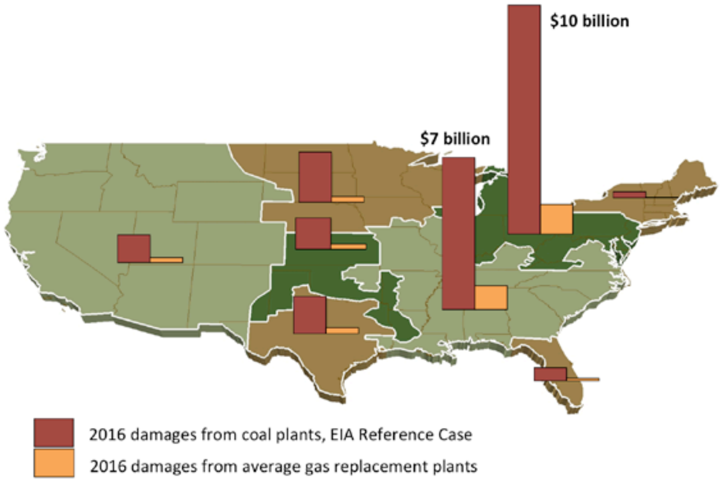

Figure 3: 2016 annual health and environmental damages due to emissions of criteria pollutants from coal plants, by NERC region. Replacing coal plants with average gas plants (Scenario b) reduces damages most significantly in the Midwest and Southeast.

Costs of reducing SO_2 emissions from coal

Although replacing all USA coal generation with new, high-efficiency NGCC plants would create health benefits of $20 - $24 billion annually, the costs of constructing and operating such plants are approximately twice as large as the created health benefits. The annual capital cost of replacing all 375 GW of USA coal capacity would be $35 - $65 billion, assuming new NGCC plants cost $1,000/kW - $1,300/kW, a facility life of 20 years [53] and a blended cost of capital of 7% - 12% [54].

Replacing coal plants with gas is only one option to mitigate SO_2 emissions, the primary source of health damages. Flue gas desulfurization and direct sorbent injection are two emission control technologies (ECTs) used to mitigate SO_2 in existing coal plants. Table 3 compares the costs and effectiveness of each ECT to building a new NGCC. ECTs have the potential to be a more cost effective SO_2 mitigation option than building new gas plants. Large deployments of these ECTs are anticipated by 2015, as utilities retrofit coal plants to comply with MATS [27, 34].

Table 3: Cost and effectiveness of different SO_2 control technologies. New NGCC costs and all fuel costs from [53]; FGD and DSI costs for a representative 500 MW coal unit [34]. Assumes natural gas cost of $4.50/MMBtu and coal cost of $1.70/MMBtu

SO_2 control technology	Capital cost ($/kW)	Fixed O&M ($/MW-yr)	Variable O&M ($/MWh)	Fuel cost ($/MWh)	SO_2 reduction
Build new NGCC	$1,000 - $1,300	$5,500 - $6,200	$2 - $3.5	$24 - $25	99%
Flue gas desulfurization (FGD)	$500	$8,100	$1.8	$15 - $20	98%
Direct sorbent	$40	$590	$7.9	$15 - $20	50%

injection (DSI)					

DISCUSSION

As several groups have shown, the climate benefits of a coal-to-gas switch are modest. We should not forget that 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; SO_2 emissions would be reduced by more than 90%. Retrofitting existing coal plants with emissions control technology is more cost effective at reducing SO_2 than building gas plants in most cases (Table 3). It is likely that a combination of switching coal to gas and installations of ECT on coal plants will be the primary way utilities comply with MATS. Annual health damages could be reduced by ~$20 billion if coal plants are either replaced with gas plants or fitted with flue gas desulfurization emission controls.

AUTHOR INFORMATION

Corresponding Author

*Phone: 412-268-2299; e-mail: wmichaelgriffin@cmu.edu.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The authors acknowledge support from the Carnegie Mellon Climate and Energy Decision Making Center (CEDM) formed through a cooperative agreement between the NSF and CMU (SES-0949710). We thank Jessica Barnebei for her graphics expertise. We also thank Peter Adams, Albert Presto, Jinhyok Heo, M. Granger Morgan, and David Luke Oates for helpful discussions.

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Supplementary Data for The health effects of a USA switch from coal to gas electricity generation

Roger Lueken[†§], *Kelly Klima*[†‡], *W. Michael Griffin*[*†], *Jay Apt*[†‡]
[†]*Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA 15213, USA*
[‡]*Tepper School of Business, Carnegie Mellon University, Pittsburgh, PA 15213, USA*
[§]*Present address: The Brattle Group, 1850 M Street Northwest #1200, Washington, DC 20036, USA*

* Corresponding Author. wmichaelgriffin@cmu.edu Phone: (412) 268-2299. Fax: (412) 268-3757

This Supplementary Data contains:
1) Methods overview, 2) Definitions, 3) Detailed emissions results, 4) Climate model to 2100, 5) References

1. 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) [1]. In particular, we identify total annual combustion emissions of carbon dioxide (CO_2), CH_4, nitric oxide and nitrogen dioxide (NO_x), sulfur dioxide (SO_2), and 2.5 micrometer and 10 micrometer particulate matter ($PM_{2.5}$ & PM_{10}) 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%, a range that includes estimates from existing literature [2].

We use the publicly available APEEP model with its empirical health damages as a function of particulate type and location [3] to value the reductions in damages to human health and the environment associated with NO_x, SO_2, $PM_{2.5}$, and PM_{10}. We calculate the change in temperatures in two ways as described in the Supporting Information Section 4(a) below: 1) using a global temperature potential model under different EIA scenarios, and 2) using the publicly available MAGICC6 climate model [4] under different representative concentration pathways (RCPs).

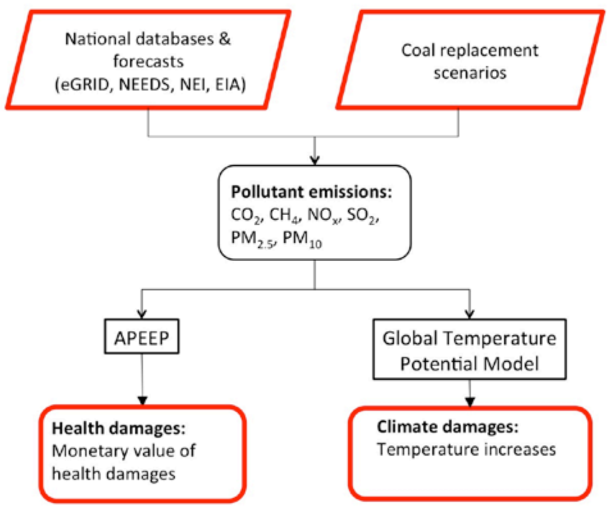

Figure S1. Graphical representation of the model used in this work. Thick red parallelograms denote inputs we varied. Thick red ovals indicate outputs.

2. 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.

2.1. What do 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:

$$CDE = \sum_n GWP_n m_n \qquad \text{(Equation S1)}$$

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 CO_2, or carbon dioxide equivalent concentrations (CO_2eq), 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:

$$CO_2eq = C_o e^{\frac{RF}{\alpha}} \qquad \text{(Equation S2)}$$

where *Co* 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/m^2).

CDE and CO_2eq 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 CO_2, CH_4, N_2O, and halogenated gases regulated under the Kyoto protocol. MAGICC's "CO2EQ" is a function of CO_2, CH_4, N_2O, and halogenated gases regulated under both the Montreal and the Kyoto protocol. Another choice is to use CO_2eq as a function of CO_2 and CH_4 only. In other possible choices, these values also include aerosols.

2.2. Climate metrics

Radiative forcing, CO_2eq, and temperature have quite different uncertainties. A climate model such as MAGICC6 requires as input specifications the emissions of different constituents (e.g., CO_2, CH_4, 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 CO_2 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/m^2)** 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 CO_2 (CO_2eq, ppm)** is defined here as a function of the change in greenhouse gases only (CO_2 and CH_4 only, not NOx, SO_2, PM, N_2O, 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/m^2 for radiative forcing, 0.8 °C for temperature increase, and 416 ppm for CO_2eq. Because emissions comparisons are also of interest in some applications, we also provide **carbon dioxide equivalent (CDE, million metric tons)** as a function of CO_2 and CH_4 emissions (100-year global warming potential of 21 [5]).

To find the USA contribution toward CO_2eq in 2010, we used MAGICC6 for global emissions data [3] and national databases for USA emissions data [6, 7]. Total CO_2 annual average concentrations were 389 ppm in 2010; they were 278 ppm preindustrial. The USA is responsible for 24-26% of the CO_2 concentrations and 9% of CH_4 concentrations, with CO_2 values varying as a function of uncertainty in CO_2 lifetime (50-200 years, [6]). Under this definition, the USA's contribution to CO_2eq is thus roughly 30 ppm.

3. DETAILED EMISSIONS 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:** 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.

3.1. Change in emissions due to switching to zero emission plants

Figures S3 – S6 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.

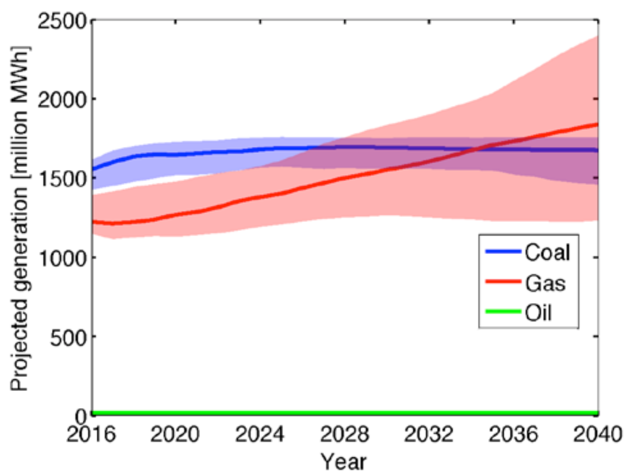

Figure S2. EIA forecast of generation from coal, gas, and oil plants, 2016 – 2040. Solid lines are EIA Reference Case; ranges represent High Gas Resource Case and Low Gas Resource Case.

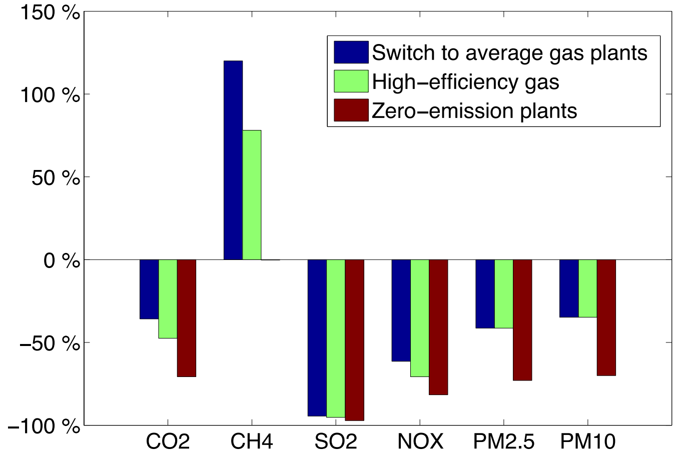

Figure S3. Percent change in total electric power GHG emissions (CO_2 and CH_4, 3% fugitive CH_4 rate), and criteria pollutants from the EIA Reference Case in 2025. Reductions are constant across years 2016 – 2040.

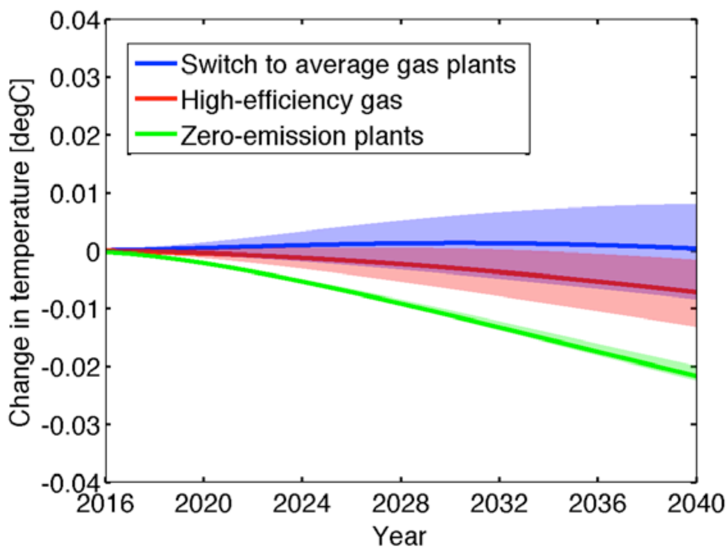

Figure S4. Change in temperature from scenarios a) high-efficiency gas, b) average gas, and c) zero emission plants minus change in temperature from business as usual. Temperature changes include contributions from CO_2 and CH_4 only. Solid line is 3% fugitive CH_4 rate for the EIA reference case; shaded area is range across EIA reference case, high gas resource case, and low gas resource case. Assumed $GTP20_{CH4}$ of 68 ± 75%.

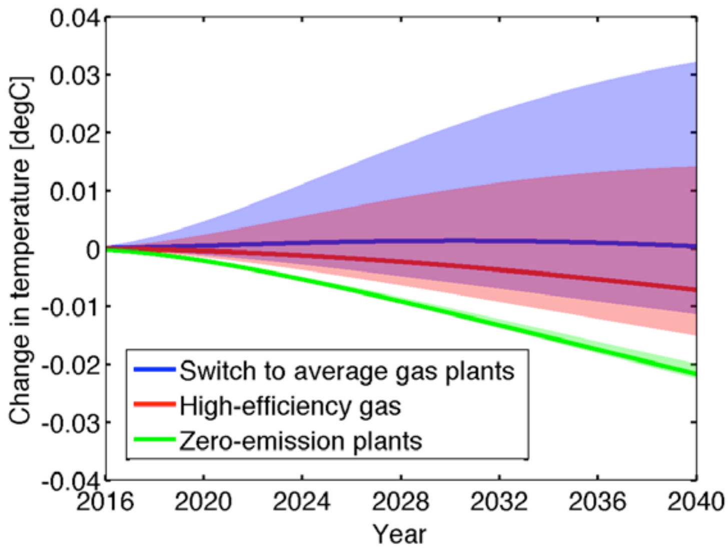

Figure S5. Effect of fugitive CH_4 rate uncertainty. Change in temperature from scenarios a) high-efficiency gas, b) average gas, and c) zero-emission plants minus change in temperature from business as usual. Temperature changes include contributions from CO_2 and CH_4 only. Solid line is 3% fugitive 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 $GTP20_{CH4}$ of 68 ± 75%.

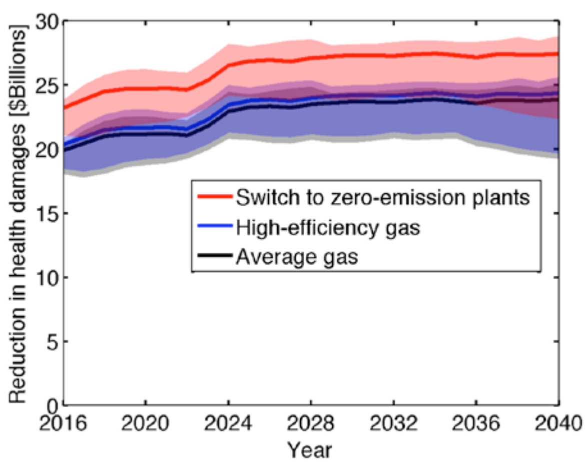

Figure S6. Reduction in annual health damages due to switching from coal. $6 million value of statistical life. Solid line is EIA reference case; shaded area is the range across EIA reference case, high gas resource case, and low gas resource case.

3.2. Change in each pollutant, by year

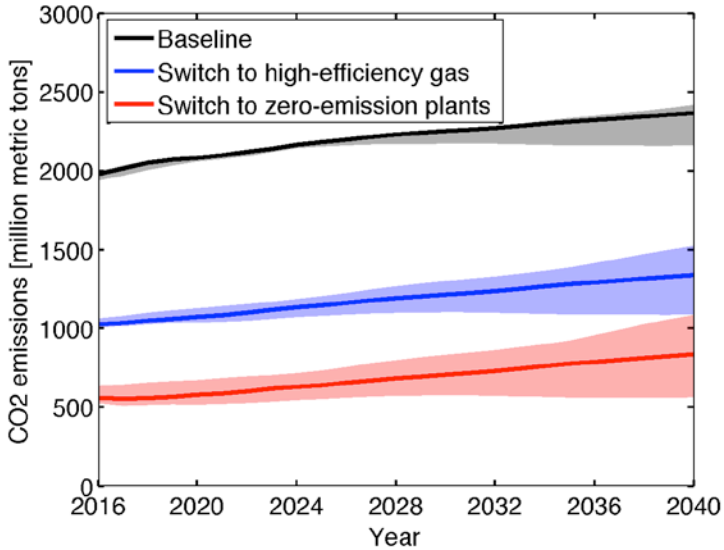

Figure S7. CO_2 emissions. Solid line is EIA Reference Case; shaded area is range across EIA Reference Case, High Gas Resource Case, and Low Gas Resource Case.

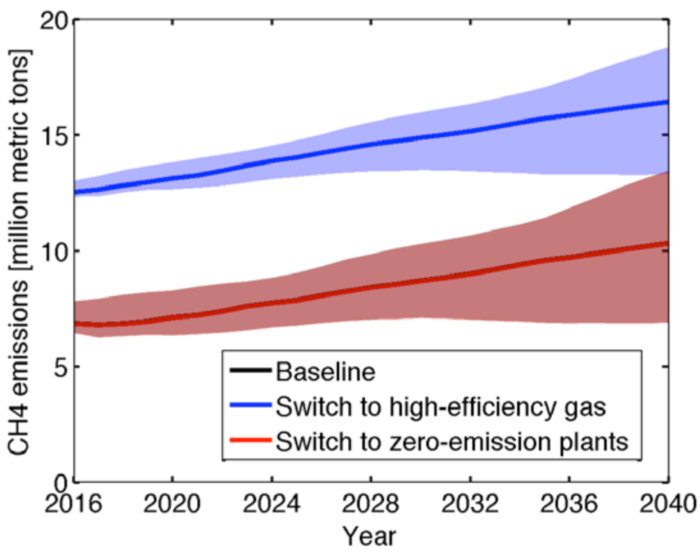

Figure S8. CH_4 emissions. Solid line is EIA Reference Case; shaded area is range across EIA Reference Case, High Gas Resource Case, and Low Gas Resource Case. Note: Baseline and zero-emission cases are nearly identical.

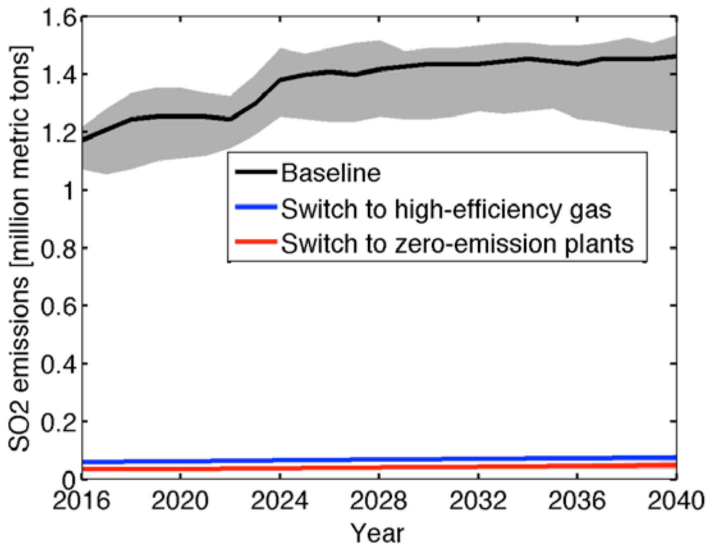

Figure S9. SO_2 emissions. Solid line is EIA Reference Case; shaded area is range across EIA Reference Case, High Gas Resource Case, and Low Gas Resource Case.

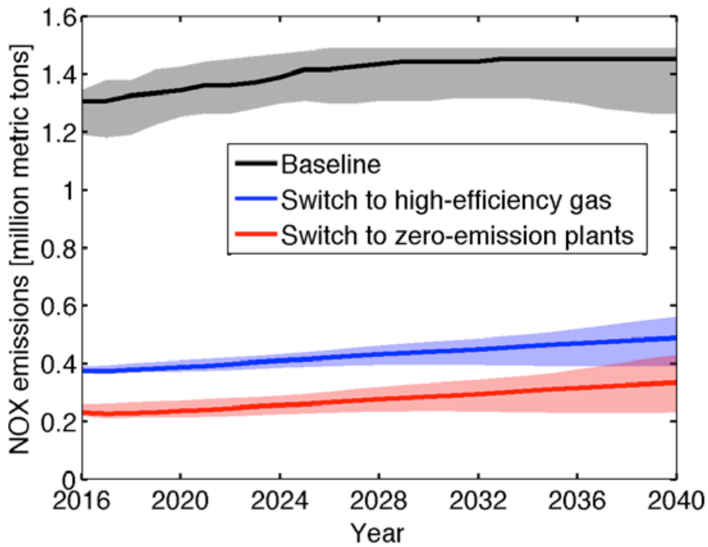

Figure S10. NO_X emissions. Solid line is EIA Reference Case; shaded area is range across EIA Reference Case, High Gas Resource Case, and Low Gas Resource Case.

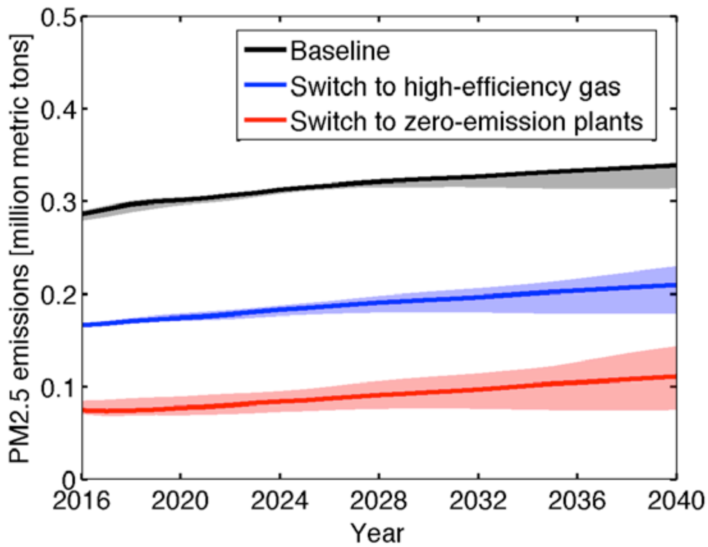

Figure S11. $PM_{2.5}$ emissions. Solid line is EIA Reference Case; shaded area is range across EIA Reference Case, High Gas Resource Case, and Low Gas Resource Case.

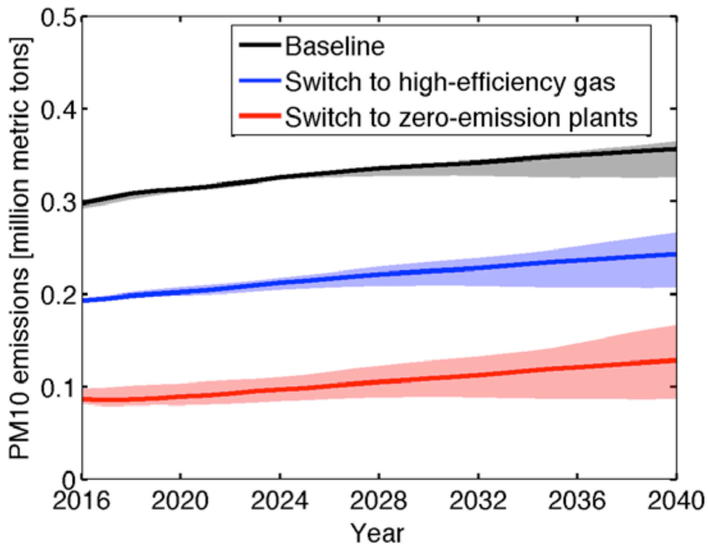

Figure S12. PM_{10} emissions. Solid line is EIA Reference Case; shaded area is range across EIA Reference Case, High Gas Resource Case, and Low Gas Resource Case.

3.3. Global warming potential

We calculated the Global Warming Potential (GWP) of CO_2 and CH_4 emissions. GWP is defined as "the time-integrated radiative forcing due to a pulse emission of a given component, relative to a pulse emission of an equal mass of CO_2" [8]. Thus while GWP represents the total energy added to the climate system by a component relative to that added by $CO_{2,}$ it does not provide information on radiative forcing or temperature changes. Fossil methane, including climate change feedbacks, has a GWP over 20 years (or GWP20) of 85 ± 25%, and a GWP100 of 30 ± 35%.

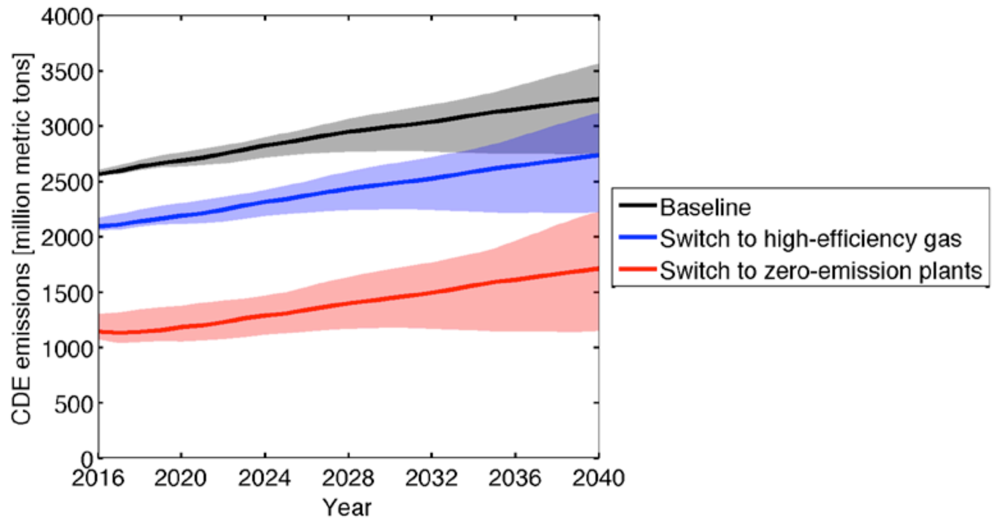

Figure S13. Carbon dioxide equivalent emissions, CO_2 and CH_4 (20-year GWP of 85), 2016 - 2040. Solid line is EIA Reference Case; shaded area is range across EIA Reference Case, High Gas Resource Case, and Low Gas Resource Case. Assumed fugitive CH_4 rate of 3%.

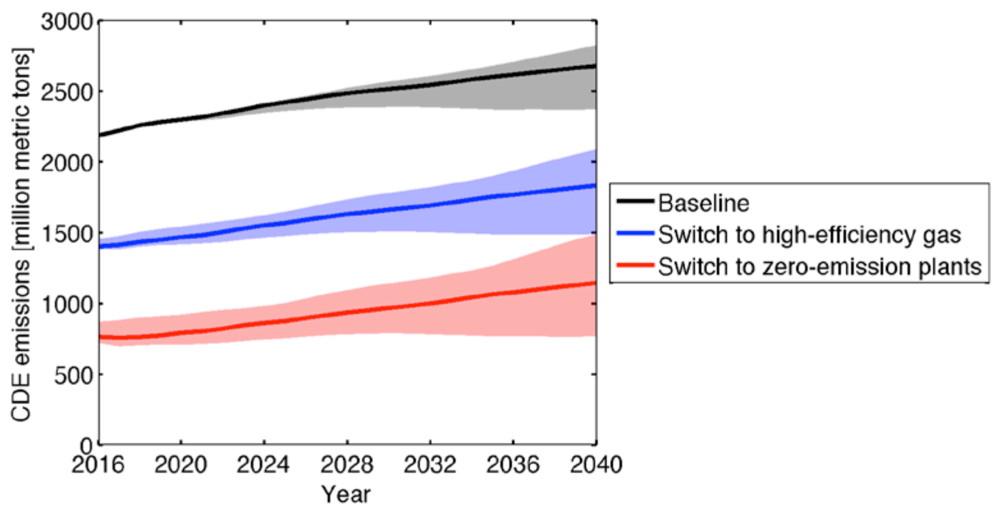

Figure S14. Carbon dioxide equivalent emissions, CO_2 and CH_4 (100-year GWP of 30) 2016 - 2040. Solid line is EIA Reference Case; shaded area is range across EIA Reference Case, High Gas Resource Case, and Low Gas Resource Case. Assumed fugitive CH_4 rate of 3%.

3.4. Fugitive Emissions

We analyzed the upstream fugitive emissions of CO_2, NO_x, SO_2, and CH_4 associated with the production and transportation of coal and natural gas (Table S1). 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 SO_2 for both coal and natural gas are taken from [9]. Upstream greenhouse gas (GHG) emissions from coal, in units of carbon dioxide equivalent mass (CDE), are the 5% and 95% confidence values reported by [10].

Upstream GHG emissions for natural gas plants come from two sources: electricity used in the fuel's transportation [9], and fugitive methane emissions from production and transportation. Of the two, fugitive methane dominates [9]. 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 [2, 11]. Total annual CH_4 fugitive emissions were calculated by multiplying the fugitive emissions rate with the total gas consumption of all plants.

Other than potential CH_4 fugitive emissions from natural gas, all fugitive emissions are small when compared to combustion emissions. We therefore exclude all fugitive emissions except CH_4 fugitives from natural gas from our analysis.

Table S3. 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)

4. CLIMATE MODEL TO 2100

We calculated the climate effects in two ways.

First, using the Global Temperature Potential (GTP), 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 forecasts emissions and generation. Here w*e only examined the global temperature potential for carbon dioxide (CO_2) and methane (CH_4). While this simple model can allow the user to intuitively understand the changes in CO_2 and CH_4, it does not take into account the effects of NO_x, SO_x, black carbon (BC), and organic carbon (OC). Previous literature has shown that a shift from coal to gas would significantly reduce SO_2, offsetting both the climate forcing from the reduction in black carbon and some of the GHGs [12]. However, this literature also assumes the base coal fleet emits a large amount of SO_2, whereas in our analysis, the baseline forecasts of SO_2 emissions account for mandated SO_2 emissions due to the MATS standard, and therefore already have low SO_2 emissions. Thus, we do not expect to see large temperature changes from NO_x, SO_x, or BC.

Second, 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.

4.1. Methods

4.1.1. Global Temperature Potential

We calculated resulting temperature changes using a metric used by the IPCC, Global Temperature Potential (GTP) [13, 14]. GTP is defined as the ratio between the global mean surface temperature change (ΔT) at a given future time horizon (TH) following an emission (pulse or sustained) of a compound x relative to an equivalent mass of CO_2 [36], or:

$$\mathrm{GTP}_x^{TH} = \frac{\Delta T_x^{TH}}{\Delta T_{CO2}^{TH}}$$

Since power plant emissions are typically given at annual intervals, the total change in temperature (ΔT) due to emissions of all pollutant types [14] over the entire time horizon (TH) years can be approximated as:

$$\Delta T = \sum_{x=1}^{X} \sum_{t=1}^{TH} \mathrm{GTP}_x(t) * \Delta T_{CO_2}(t) * M_x(t)$$

where M is the mass of the pollutant x emitted in year t (kg) and ΔT_{CO2} 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_{CO2} can be represented through empirical analysis [15]. 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 ± 75%); the most recent IPCC report fully characterizes GTP_{CH4}^{TH} over a century [15]. A discussion of the global warming potential of CO_2 and CH_4 emissions can be found above in the Supplementary Data, Section 2.

4.1.2. Climate model

4.1.2.1. 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 [16]. 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/m^2 to between 8 and 9 W/m^2 and higher [17, 18]. While the RCPs provide values for land use, dust, and nitrate aerosol forcing, these are not included in the radiative forcing estimates [18].

The RCP authors caution that users must be careful to avoid over-interpreting the data. The RCPs were developed by four independent modeling groups [19 – 22]. 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 CO_2 emissions are larger than the RCP 8.5 values [23]. Figure S15 and Figure S16 compare the RCPs to published primary energy usage outlooks from BP [24] and ExxonMobil [25]. 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.

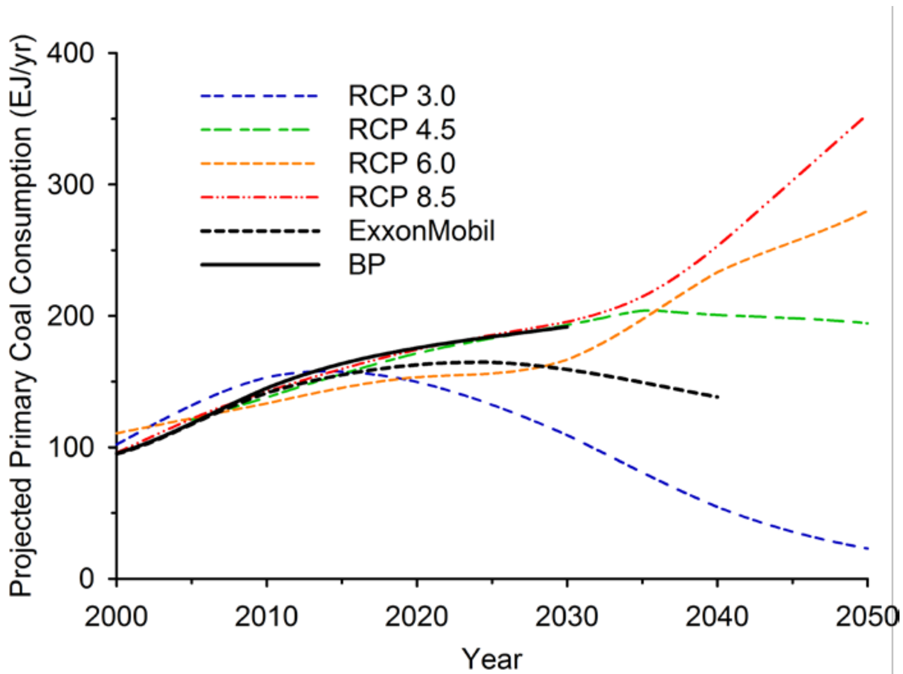

Figure S15. Primary energy usage of coal, 2000-2040. BP's outlook matches that of RCP 8.5. ExxonMobil's outlook is in between RCP6.0 and RCP8.5 until 2025, at which time they predict substantial reductions in coal usage; its total primary energy usage is in line with RCP6.0.

[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)

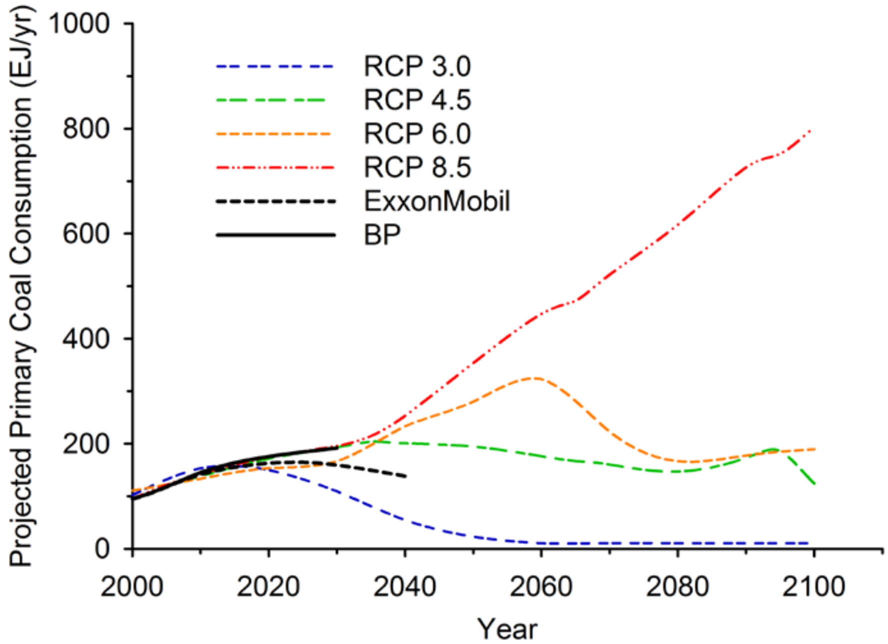

Figure S16. Primary energy usage of coal, 2000-2100. BP's outlook matches that of RCP 8.5. ExxonMobil's outlook is between RCP6.0 and RCP8.5 until 2025, at which time they predict substantial reductions in coal usage; its total primary energy usage is in line with RCP6.0.

4.1.2.2. Climate model benchmarking

We modeled climate change effects with the publicly available MAGICC6 model [4]. 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 S2 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 [9, 26] or by applying a Monte Carlo analysis of values published in the literature [2].

4.1.2.3. 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 Figure2.b. (Figure S17). Scenario values are listed in Table S3 and our temperature differences from business as usual is in Figure S18. We find that we can replicate Wigley's CO_2 and CH_4 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 S18). It is likely that Wigley may have applied the SO_X reduction slightly differently than we did.

Table S4. Climate models used in recent literature we cite.

Model	**Type**	**Climate Feedback, λ**	**Ocean**	**Chemistry**
Hayhoe et al. [27]	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 & Caldeira [28]	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 [12], Smith & Mizrahi [29], MAGICC6 [30]	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

Table S5. 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 0.027GtC/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 SOx radiative forcing by 30%.	Replace MAGICC6 output with Wigley assumption.

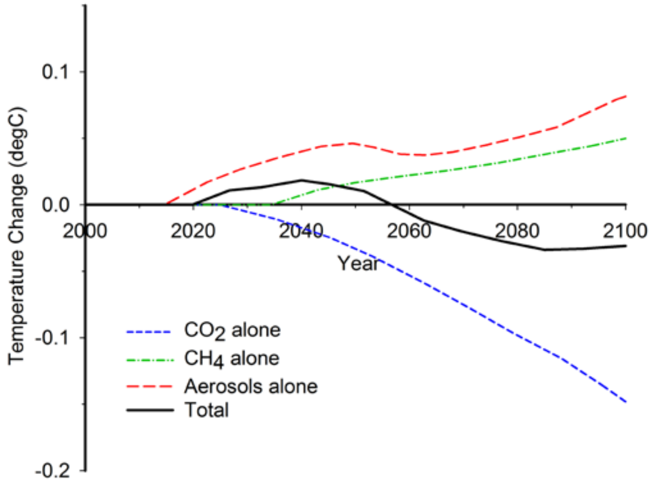

Figure S17. Temperature changes from Wigley, Figure 2b (Adapted from [12]).

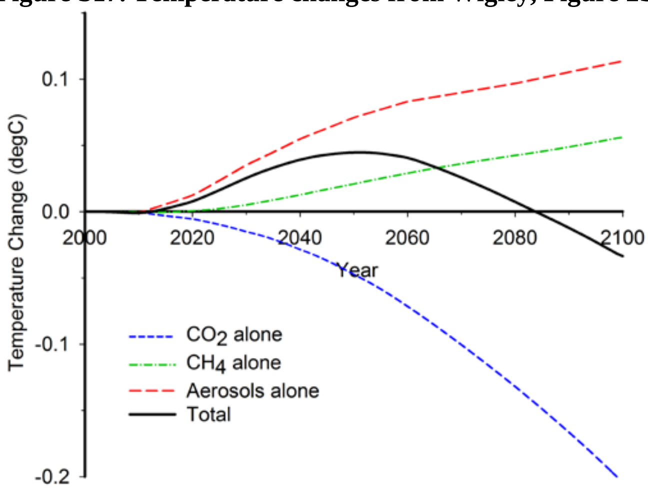

Figure S18. Temperature changes recreating the Wigley estimates

4.2. Climate results: Radiative forcing and temperature

We provide results for both the global temperature potential and the MAGICC6 runs.

4.2.1. Global temperature potential

In agreement with published literature *[9,12,26-28]*, 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 other major polluters reducing their GHG emissions. Figure S19 and Figure S20 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 ^{o}C and + 0.03 ^{o}C, depending on the assumed fugitive CH_4 rate. Differences in temperature changes are insensitive to the baseline EIA case assumed. As shown below in the Supplementary Data (Section 4.2.2), 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 S4 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 $GTP20_{CH4}$ of 68, as well as the $GTP20_{CH4}$ uncertainty range of ± 75%. Assuming $GTP20_{CH4}$ 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.

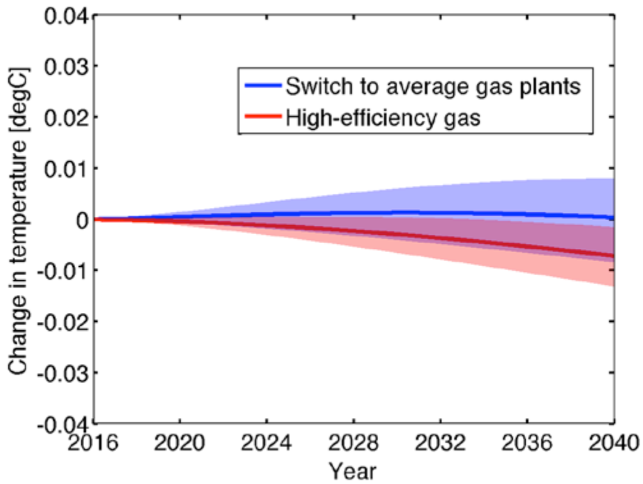

Figure S19. Change in temperature from scenarios a) high-efficiency gas and b) average gas minus change in temperature from business as usual. Temperature changes include contributions from CO_2 and CH_4 only. Solid line is 3% fugitive CH_4 rate for the EIA reference case; shaded area is range across EIA reference case, high gas resource case, and low gas resource case. Assumed $GTP20_{CH4}$ of 68 ± 75%.

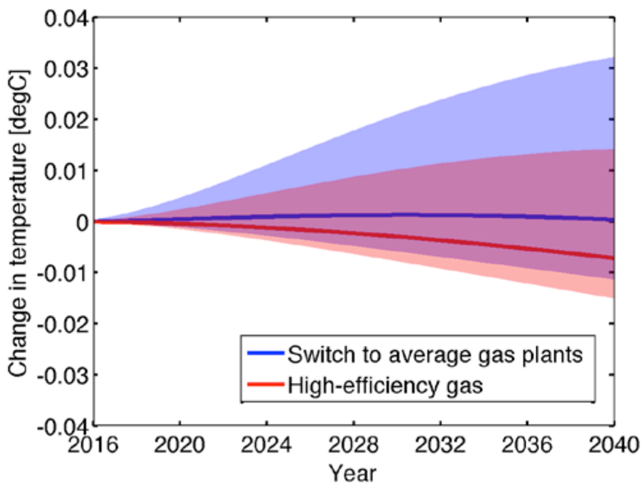

Figure S20. Effect of fugitive CH_4 rate uncertainty. Change in temperature from scenarios a) high-efficiency gas and b) average gas minus change in temperature from business as usual. Temperature changes include contributions from CO_2 and CH_4 only. Solid line is 3% fugitive CH_4 rate for the EIA reference 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 $GTP20_{CH4}$ of 68 ± 75%.

Table S6. 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 CO_2 and CH_4 only. Reductions are constant across 2016 – 2040. Assumed $GTP20_{CH4}$ of 68; uncertainty range of ± 75% in parenthesis.

	Change in warming contributed by U.S. electric power sector, 2040			
Scenario	0% fugitive CH_4	3% fugitive CH_4	5% fugitive CH_4	7% fugitive CH_4
A) Switch to high-	**-47%**	**-18%**	**-5%**	**+5%**

efficiency gas		(-38%, -3%)	(-33%, +11%)	(-28%, +21%)
B) Switch to average gas	**-35%**	**+1%** (-24%, +18%)	**+16%** (-18% +36%)	**+28%** (-12%, +49%)

Section 5 of the Supplementary Data 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 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 expected [31, 32].

4.2.2. MAGICC6

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 [17, 26]. 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 re 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 SO_2 could be considered SO_X. Additionally, we assumed NO_X is made of 90% NO and 10% NO_2 by mass [33]. Based on recent publications examining coal power plant particulate matter, we assumed that all particulate matter ($PM_{2.5}$ and PM_{10}) is 12% organic carbon, 4% black carbon, with the rest not relevant for the climate [31, 32]. Total emissions were not allowed to drop below zero.

In agreement with published literature [2, 9, 12, 26 - 28], 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 CO_2. 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 S21. 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 2010 by, in some cases, over 33% as shown in the Main Text, the reduction values are small compared to global values. For reference, Figure S22 shows the relation between radiative forcings and temperatures.

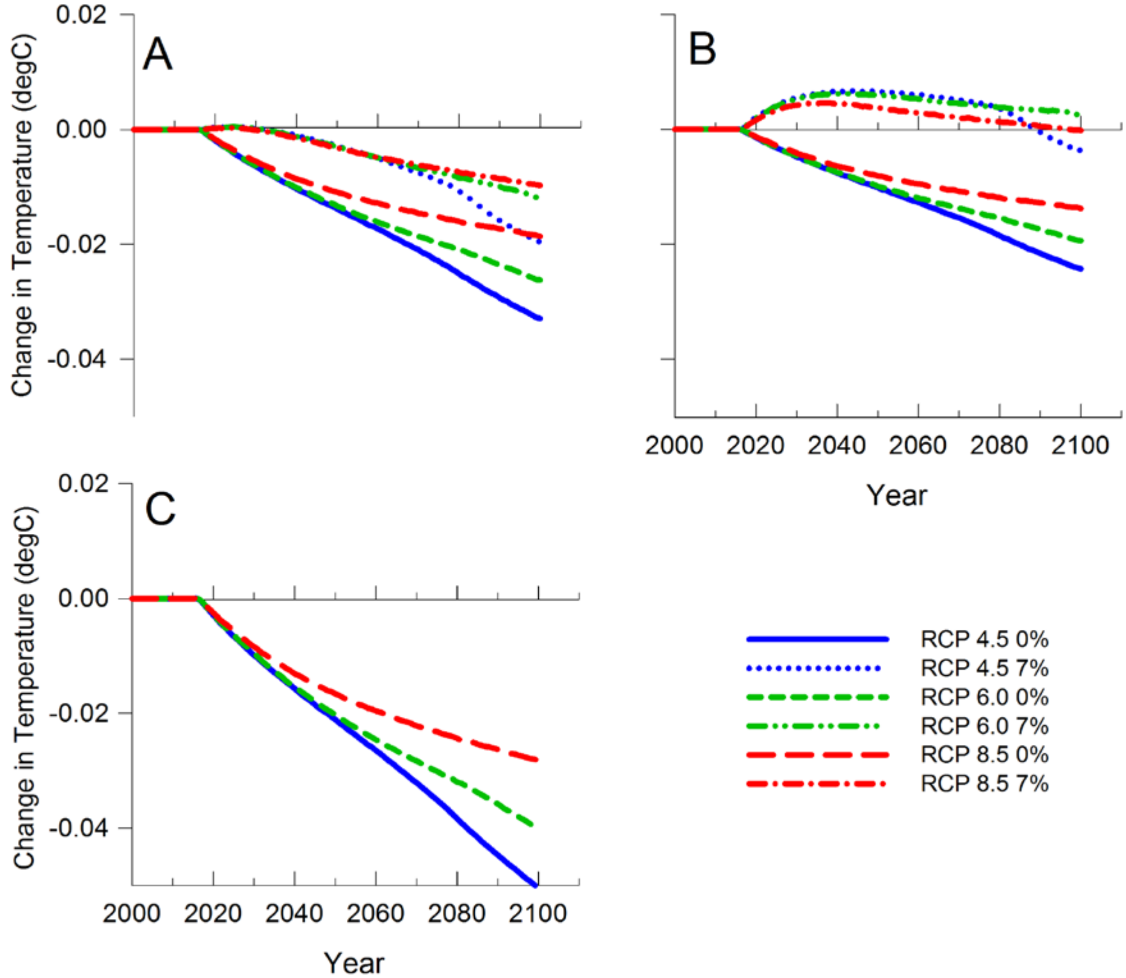

Figure S21. Change in Temperature from Business as usual for the USA Policy for scenarios a) High efficiency Gas, b) Average Gas, c) zero emissions. We note that this graph is meant to compare with the GTP value, and thus for our purposes includes changes from CO_2 and CH_4 only.

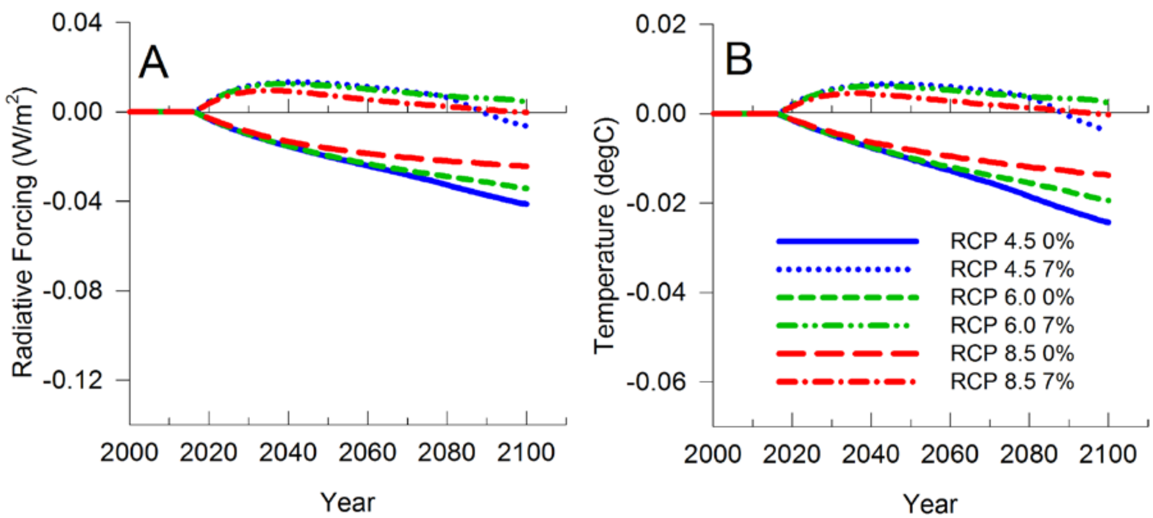

Figure S22. Change from Business as usual for the USA Policy for Scenario b): Average Gas for a) radiative forcings (W/m^2) and b) temperature (°C)

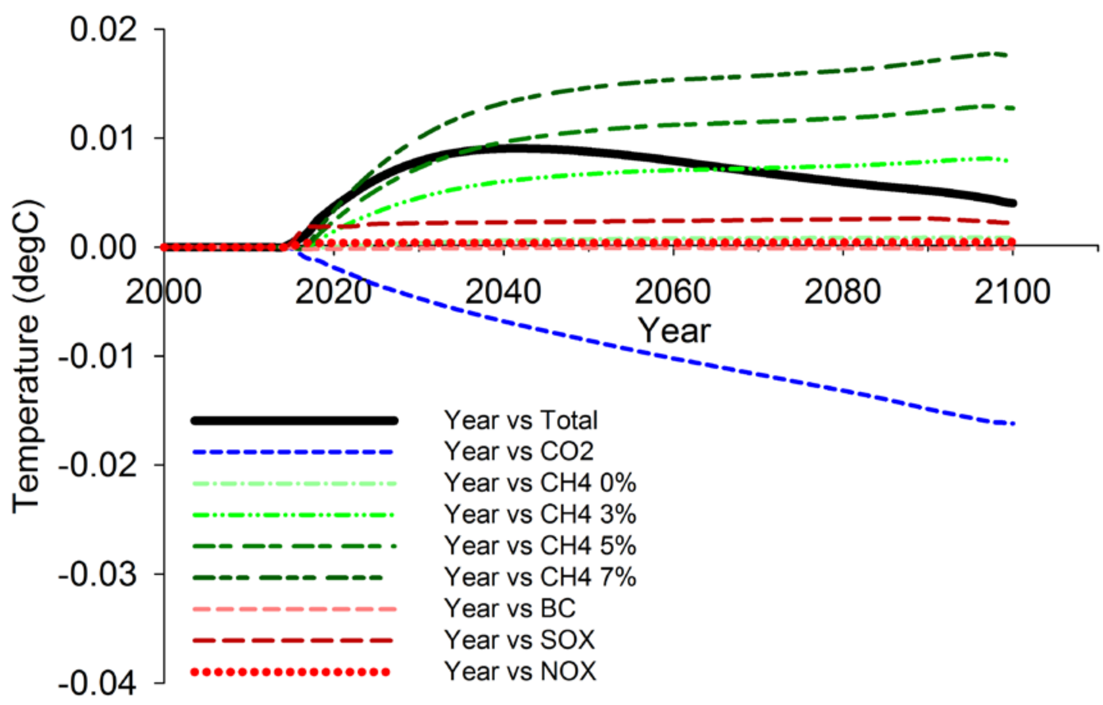

Figure S23. Change from Business as usual for the USA Policy for Scenario b): Average Gas for RCP8.5 for temperature contribution (°C) by individual constituents. The total, shown as the solid black line, is for 3% fugitive methane emissions.

Figure S23 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 [34] that may be of the same size as that for methane leakage.

Previous literature assumes the base coal fleet emits a large amount of SO_2. Therefore, a shift from coal to gas would significantly reduce SO_2, offsetting both the climate forcing from the reduction in black carbon and some of the GHGs [12]. In our analysis, the baseline fleet in 2016 has been updated to reflect the MATS standard, and therefore already has low SO_2 emissions. Thus the avoided SO_2 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 [29]. 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.

4.3. 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 [35]. 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 CH_4 emissions rate, and RCP. Scenario b with a 5% fugitive emissions rate and RCP 6 would reduce global GHG emissions by 9% (see Figure S24). Switching to zero emission plants reduces emissions 26% assuming RCP 6.

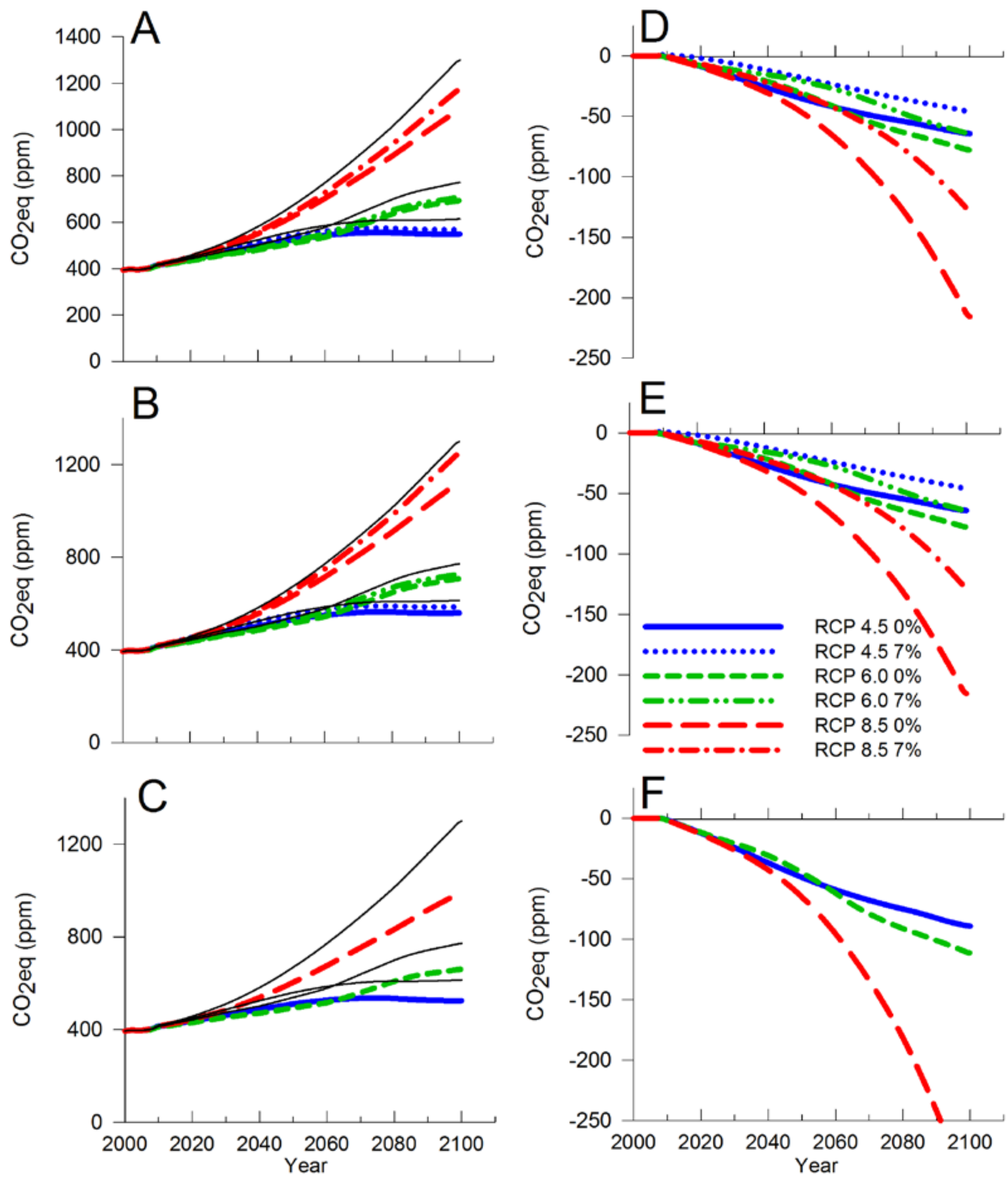

Figure S24. Total CO_2eq (a-c) and Change in CO_2eq from Business as usual (d-f) for, from top to bottom, the Global Policy for Scenario a): High efficiency gas, Scenario b): Average, Scenario c): ZEG. Solid black lines indicate the business as usual scenario for 3% methane leakage.

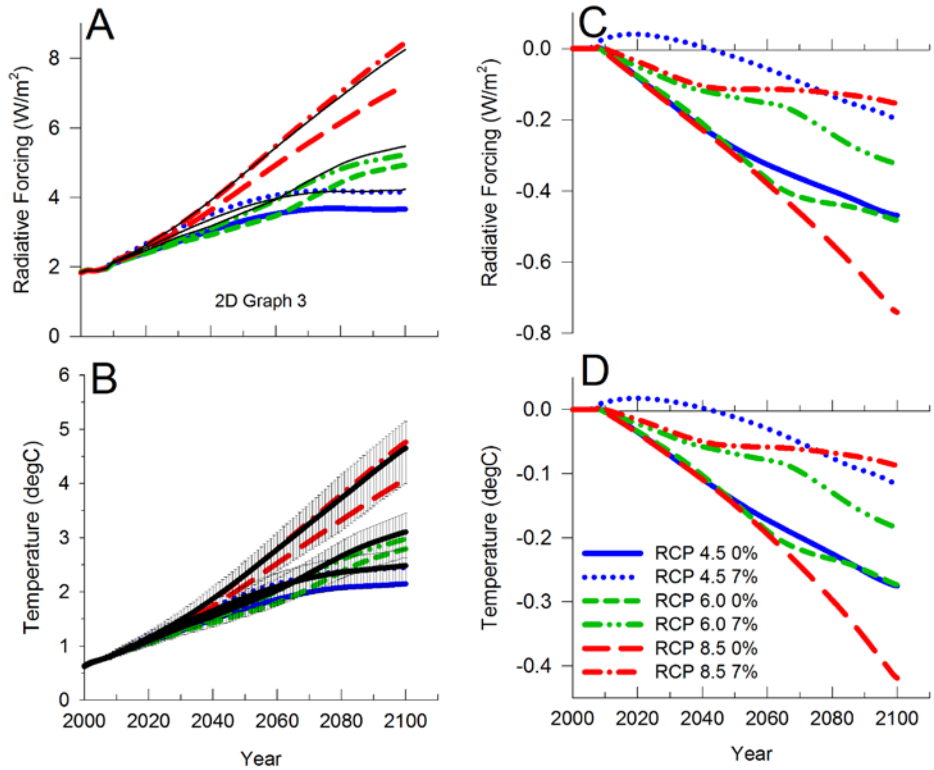

Figure S25. Total (a-b) and change from Business as usual (c-d) for the Global Policy for Scenario b): Average for radiative forcings (a, c) and temperature (b, d). Solid black lines indicate the business as usual scenario for 3% methane leakage, and the error bars in B indicate the 66% confidence interval 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 S24 shows the total CO_2eq and change in CO_2eq from business as usual for the Global Policy for scenario a)-c). A global policy of switching from coal to natural gas could delay CO_2eq 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 CO_2eq concentrations, while scenario b) is the worst. Scenario c) is roughly 2-3 times as effective at reducing CO_2eq. 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 S25 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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