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

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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 power and a future low-carbon grid. We use existing national datasets and publicly available models to examine how a shift from coal to natural gas will affect climate change and damages to human health. Climate benefits of a USA coal-to-gas switch are limited. Even at a low fugitive methane emissions rate, a full switch from coal to gas provides only a few months' delay in reaching greenhouse gas levels that lead to dangerous climate impacts. On the other hand, human health benefits are substantial: reduced emissions of harmful criteria pollutants would further reduce annual health damages by ~$40 billion from anticipated 2015 levels. However, 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. While human health in the United States can greatly benefit from policies that continue the switch from coal to gas, natural gas should not sidetrack policy from the goal of reducing global greenhouse gas emissions.

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 2013 President Obama released the USA Climate Action Plan, which included "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 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, 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 SO_2 and NO_x, precursors of particulate matter. Natural gas also has lower primary emissions $PM_{2.5}$ and PM_{10} than coal. Exposure to $PM_{2.5}$ has been linked to human mortality and morbidity *(10)*. EPA regulations, including the Clean Air Interstate Rule (CAIR) and Mercury and Air Toxics Standard (MATS), are designed to reduce these emissions *(10, 11)*. These regulations have been one cause of a switch from coal to natural gas plants *(1, 12)*.

We investigated the potential for natural gas to reduce electric power emissions in the USA. To establish an upper bound on the potential benefits, we analyzed a switch of all USA coal plants to natural gas plants. We examined four scenarios (described below). We varied the fugitive methane emission rate from 0% - 7%, a range that includes estimates from existing literature *(9)*. Using MAGICC6 *(13)*, a reduced-form climate model, we estimated how switching from coal to gas would delay the time to reach a particular atmospheric GHG concentration in 2100. The APEEP model *(14)* computed the health benefits of such a switch.

METHODS

Calculation of baseline plant emission rates

We developed baseline 2015 emission rates for all USA fossil plants for a scenario in which coal plants remain in operation with their emissions of SO_2 and NO_X regulated under the EPA Mercury and Air Toxics Standards (MATS). We first identified 2009 emission rates for all USA plants, then updated emission rates to 2012 levels, and finally projected how emission rates may change from 2012 to 2015 under MATS.

2009 emission rates

The Emissions & Generation Resource Integrated Database (eGRID) *(3)* was used to identify 2009 data for all USA electricity plants. The database of all USA plants identifies location, annual generation, combustion emission rates of CO_2, NO_x, SO_2, CH_4 and heat rates. Annual fuel consumption for all plants was calculated by multiplying the total annual electricity generation by the plant's heat rate. From this dataset, we developed total emissions and natural gas consumption from all plants as they were in 2009 as a starting point.

We estimated $PM_{2.5}$ and PM_{10} combustion emissions rates from fossil fueled plants with the 2005 National Emissions Inventory (NEI) *(15)* and eGRID 2005 *(3)*. We derived emission rates for each plant by dividing total annual PM emissions by total annual generation. NEI provides PM emissions data for 40% of USA coal plants, 6% of gas plants, and 2% of oil plants. For plants not included in NEI data, we assumed emission rates equal to the average emission rate for plants of the same type, weighted by plant capacity. We calculated each plant's total 2009 $PM_{2.5}$ and PM_{10} emissions by multiplying the calculated PM emission rate by the plant's 2009 generation. We assumed PM emission rates were unchanged between 2005 and 2009.

2012 emission rates

Criteria pollutant emissions from USA generators dropped significantly from 2009 to 2012, largely due to increased electricity production from natural gas plants and new installations of emission control technologies (ECTs) at coal plants *(16)*. To account for this effect, we used plant-level emission data from the EPA Air Market Program Database (AMPD) to identify 2012 emissions of NO_x, SO_2, and CO_2, generation, and heat rates for plants in 27 eastern states regulated by the EPA Clean Air Interstate Rule (CAIR) *(16)*. Generators in CAIR made up 50% of total 2009 USA electricity generation, 80% of SO_2 emissions, and 70% of CO_2 emissions. MATS requires fossil plants not in CAIR states to reduce SO_2 and NO_X emissions. For these plants, we assumed changes in NO_X, SO_2, and CO_2 emission rates, heat rates, and power generation between 2009 and 2012 equal the generation-weighted average change of plants of the same type in CAIR states. Emission rates of CH_4, $PM_{2.5}$, PM_{10} were left unchanged from 2009 due to lack of data.

Baseline 2015 scenario emission rates under MATS

Further SO_2 emission reductions are anticipated under the baseline scenario in which MATS remains in effect. Emission reductions required by MATS are more stringent than those under CAIR *(17)*. EPA anticipates 2015 total annual emissions from coal and oil plants will be 2.1 million tons of SO_2 and 1.7 million tons of NO_X *(11)*. This represents a 32% reduction in SO_2 from our calculated 2012 coal and oil total, and a 5% increase in NO_X emissions. We adjusted emissions of SO_2 and NO_X equally for all coal and oil plants such that total emissions equaled the anticipated 2015 levels. Emissions of CH_4, $PM_{2.5}$, and PM_{10} were assumed unchanged due to lack of data.

In addition to combustion emissions, we analyzed upstream emissions associated with the production and transportation of coal and natural gas. We parameterized the rate of fugitive CH_4 emissions during production and transportation of natural gas in a range of 0 - 7%, covering estimates from existing literature *(9)*. Other fugitive emissions (greenhouse gases, NO_x, SO_2, $PM_{2.5}$, PM_{10}) from the production and transportation of coal and natural gas do not qualitatively change our results and were excluded from this analysis.

Our estimate of the quantity of power produced began with the eGRID 2009 production for each U.S. plant. AMPD provided the 2012 power produced by all CAIR state plants; for other states we assumed generation followed the same trend. We assumed no load growth between 2012 and 2015, in agreement with the EIA *(21)*. Assuming modest growth will not qualitatively change our results. For the climate analysis, generation growth assumptions are built into the representative concentration pathways, by fuel type.

Calculation of replacement plant emission rates

We modeled four scenarios to investigate the benefits of switching from coal to other fuels. Scenario a) retired all coal plants and built new, high-efficiency 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 or Siemens Frame-H *(18, 19)*. The CO_2 emission rate was calculated by multiplying the heat rate by the carbon content of natural gas. To calculate emission rates of NO_x, SO_2, CH_4, $PM_{2.5}$, and PM_{10} we used the EPA's National Electric Energy Data System (NEEDS), Version 5.13 *(20)*, which lists the characteristics of 450 existing NGCC plants. We assumed the emission rates of these pollutants equaled the load-weighted average emission rate of the 450 existing plants in the 2015 baseline MATS scenario (Equation 1). This assumption somewhat overstates emission rates, as emission rates of new, high-efficiency NGCC will likely be lower than the existing NGCC fleet average.

$$\textit{Load weighted emission rate} = \frac{\sum_{generators} \textit{Annual generation} * \textit{Emission rate}}{\sum_{generators} \textit{Annual generation}} \quad \text{(Equation 1)}$$

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. 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.

Scenario c) retired coal plants and increased generation from existing natural gas plants. This scenario models a world in which it is more economical for utilities to run existing plants for more hours than to build new gas plants. We performed separate replacement analyses for each of the eight NERC regions, Alaska, and Hawaii to account for transmission constraints within the grid. We first calculated the total annual energy generated by coal and gas plants in each region. We then assigned this total annual generation to the region's gas plants, in order of increasing heat rate. We assumed each generator is run up to a 100% capacity factor; once a generator reaches maximum capacity we moved to the next generator. If insufficient gas capacity exists in a region to completely offset coal, we incrementally increased the size of all regional gas generators by 0.1% until there was sufficient capacity. Because we assume existing gas plants expand to meet demand, our emission results are independent of the assumed capacity factor.

Scenario d) retired all coal plants and built new plants that have zero emissions of all pollutants, either renewable or nuclear plants. We assumed the replacement plants can provide firm baseload power; in reality, variable renewables such as wind would need storage to serve as baseload.

Scenarios a), b), and d) assume 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. The location of renewable plants may be constrained by the availability of renewable resources (wind or solar). Scenario c) assumes the size of existing gas plants increase as needed to offset coal generation. 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 climate effects

We modeled climate change effects with the publicly available MAGICC6 model *(13)* a simple/reduced complexity climate model including an ocean, an atmosphere, a carbon cycle, and indirect aerosol effects. For scenarios a) – d), and fugitive methane rates of 0% - 7%, we modeled changes from business as usual at decadal intervals from 2010 to 2100 using MAGICC6's default emissions for representative concentration pathways (RCPs) 4.5, 6.0, and 8.5 *(13, 22)*. We assumed that all particulate matter ($PM_{2.5}$ and PM_{10}) could be considered black carbon, and all SO_2 could be considered SO_X. Additionally, we assumed NO_X is made of 90% NO and 10% NO_2 by mass *(23)*. Total emissions were not allowed to drop below zero.

The RCPs are new projections of future emissions to 2100 for the Intergovernmental Panel on Climate Change's fifth assessment report *(24)*. The four RCPs 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 *(22, 25)*. While the RCPs provide values for land use, dust, and nitrate aerosol forcing, these are not included in the radiative forcing estimates *(25)*. To reduce complexity stemming from policy, technology, land-use, and climate assumptions in the RCPs, we assumed all existing USA coal plants were instantaneously converted in 2015 (baseline MATS scenario). This is a best-case implementation scenario for the climate; a switch would likely take years to implement and the climate benefits would be smaller than what we calculate. 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 (the Supporting Information (SI) shows results of other assumptions). However, the RCPs do not report their primary coal energy usage by country or region, so we cannot account for future policies, technologies, or retirement changes.

MAGICC6 takes as inputs emissions scenarios (e.g., GtC, MtS, MtN, etc). The model computes concentrations, radiative forcings, and temperatures. To test our scenarios a) – d), we slightly modified the included RCP scenarios. Since the RCP2.6 case appears unreasonably optimistic compared to the trajectory we are now on, as well as to commercial energy outlooks (SI), we chose to examine the upper three RCPs (RCP4.5, RCP6.0, and RCP8.5). Model validation against published literature is given in the SI.

We measure changes in USA GHG emissions in units of carbon dioxide equivalent (CDE). CDE is the mass of CO_2 that would have the same global warming potential as the mass of other GHG species when measured over a specified timescale. We measure changes in global GHG concentrations in units of equivalent CO_2, or CO_2eq. CO_2eq is the concentration of carbon dioxide that would have the same radiative forcing as the concentration in question when measured over a specified timescale.

Calculation of health effects

Damages to human health and the environment caused by emissions of SO_2, NO_X, $PM_{2.5}$, and PM_{10} were calculated with the Air Pollution Emission Experiments and Policy (APEEP) model *(14)*. 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 *(26, 27)*.

Health effects, 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) *(14)*. APEEP was used in the National Academies' *Hidden Costs of Energy* report *(28)*; similar health models exist *(29, 30)* and have been used by the EPA to as technical support for major pollution regulations *(10)*. The APEEP model and our analysis exclude damages associated with emissions in Alaska and Hawaii.

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 *(31)*. Major cohort studies have found $PM_{2.5}$ concentration-response functions and mortality are linear with no threshold *(32 – 34)*. Since we find NO_X made up 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

In 2009 there were 560 coal plants in the USA with a capacity of 375 GW, 33% of total generation capacity. These plants generated 45% of electricity in 2009. Table 1 shows the load-weighted average emission rates and heat rates of coal plants in 2009, 2012, and the anticipated 2015 levels under MATS. Also shown are the emission rates and heat rates for the coal replacement plants in scenarios a) – d).

Table 1: **Load-weighted average heat rates and emission rates for USA coal plants in 2009, 2012, and anticipated in 2015 under MATS, as well as replacement plants for scenarios a) – d).**

Plant type	**Heat rate (Btu/kWh)**	**Combustion emission rates (kg/MWh)**					
		CO_2	**NO_x**	**SO_2**	**CH_4**	**$PM_{2.5}$**	**PM_{10}**
Coal – 2009	10,400	970	0.95	2.9	0.011	0.28	0.34
Coal – 2012	9,800	910	0.89	1.7	0.011	0.28	0.34
Coal – 2015 MATS*	9,800	910	0.94	1.1	0.011	0.28	0.34
Scenario a): High-efficiency gas	5,700	300	0.09	0.02	0.008	0.06	0.07
Scenario b): Average gas	8,700	450	0.17	0.02	0.009	0.06	0.07
Scenario c): Existing gas	9,100	470	0.28	0.02	0.010	0.06	0.07
Scenario d): Zero emission plants	n/a	0	0	0	0	0	0

* EPA anticipates 2015 NO_X emissions will be 5% higher than 2012 levels *(12* ***Error! Bookmark not defined.****)*.

Effect on greenhouse gas emissions & atmospheric concentrations

Change in emissions

In 2009, the carbon dioxide equivalent mass (CDE) of CO_2 and CH_4 (100-year global warming potential of 21 *(35)*) from the electric power sector was 36% of the USA total of 6,600 million metric tons *(36)*. Between 2009 and 2012, GHG emissions from the electric power sector fell 6%. We find that MATS is unlikely to induce significant further GHG reductions, a finding supported by EPA's analysis of MATS *(11)*.

A USA policy of switching all coal plants to natural gas would reduce total USA GHG emissions by 3% - 18% from 2011 levels, depending on the replacement scenario and assumed fugitive CH_4 emissions rate. Switching to zero emission plants would reduce emissions 24% - 26% (Figure 1). These reductions exceed the expected emissions reduction of 0% - 2% in the base scenario.

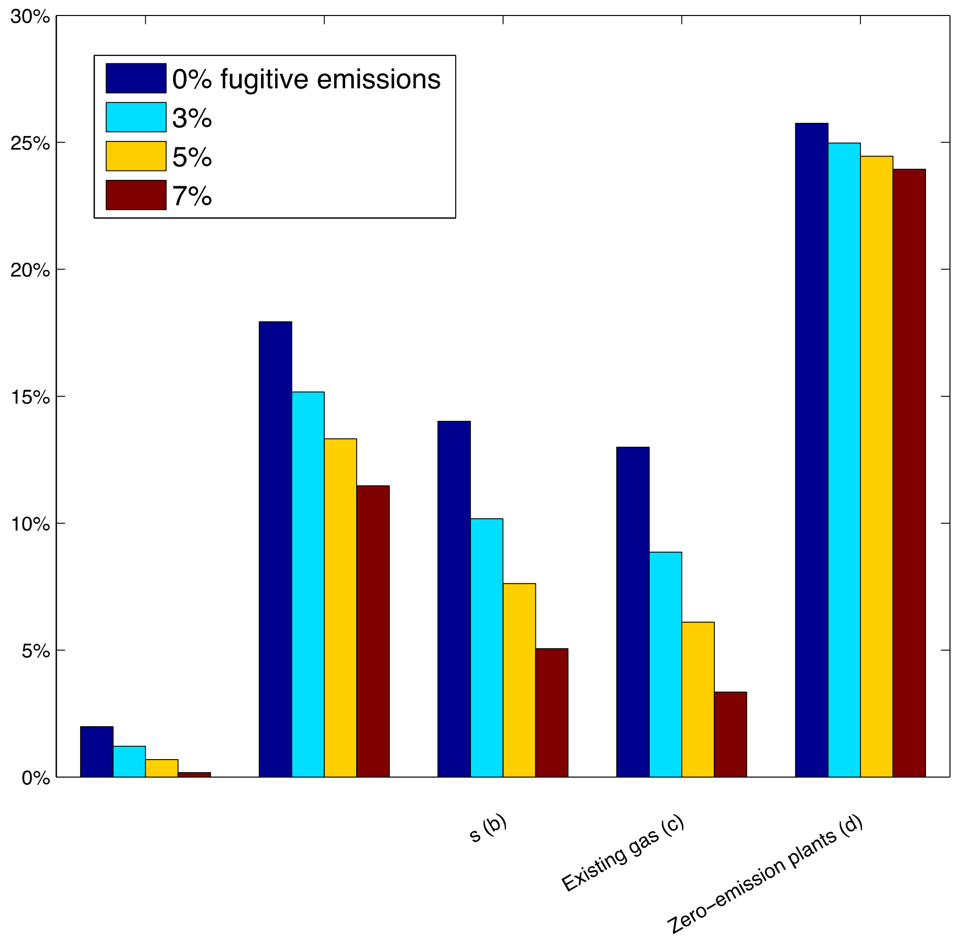

Figure 1: Percent reduction in total annual USA GHG emissions from 2011 levels, carbon dioxide equivalent

Climate effects

In agreement with published literature (*4 – 9*), we find that climate benefits for a USA policy of switching from coal to natural gas are limited. Fuel switching increases carbon dioxide equivalent concentrations (CO_2eq) in the short term due to reduction in aerosols and increased fugitive methane emissions, and decreases CO_2eq by 2100 due to reduction in CO_2. The length of this "concentration 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 2 shows the change in CO_2eq from business as usual for the USA policy for scenarios a) -d). All of the coal to natural gas scenarios and RCPs are similar; scenario a) is best at reducing CO_2eq concentrations, while scenario c) is least effective. The zero emissions scenario d) is roughly 2-3 times more effective at reducing CO_2eq as the gas scenarios. While a USA policy reduces the nation's contribution of CO_2 and CH_4 from its 2010 CO_2eq of 30 ppm by, in some cases, over 33%, the reduction values are small compared to global values (current anthropogenic CO_2 and CH_4 concentration is ~140 ppm CO_2eq).

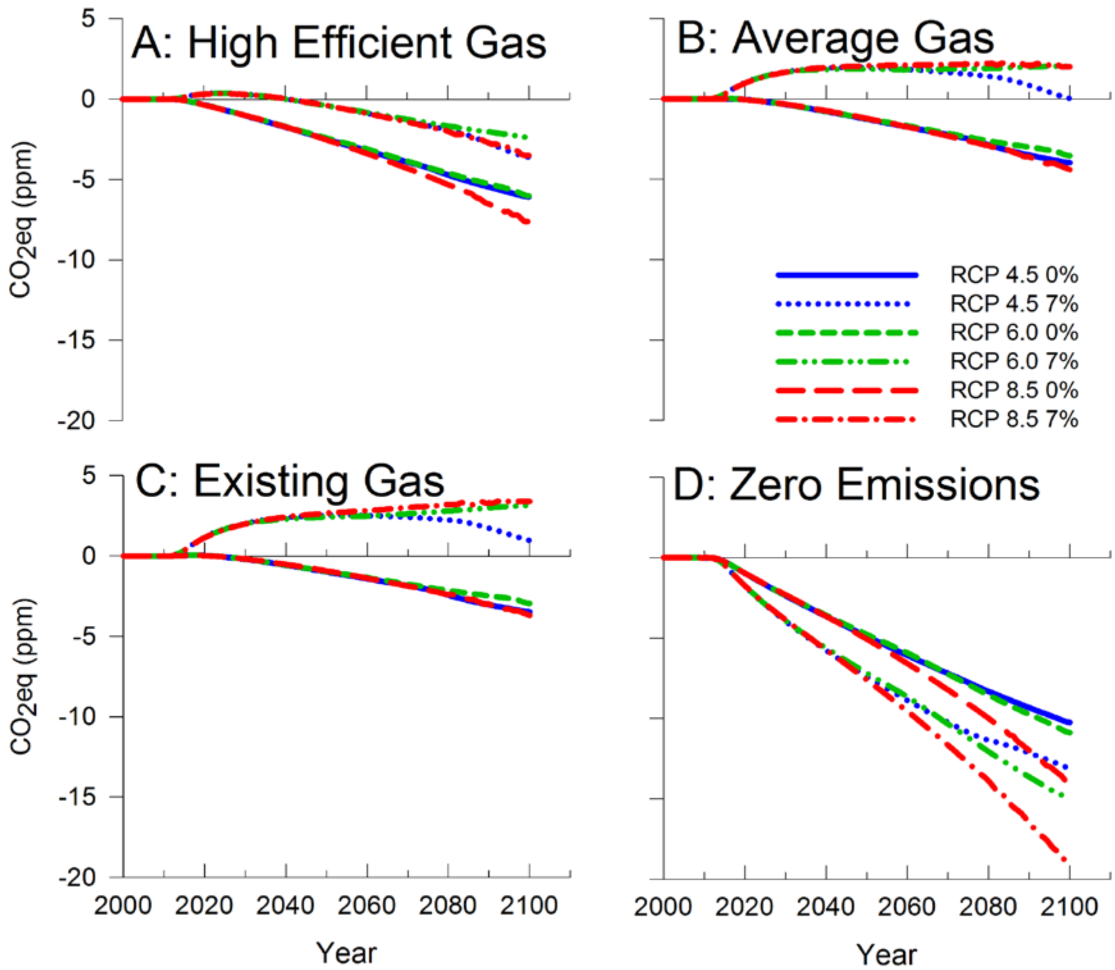

Figure 2: Change in CO_2eq from Business as usual for the USA Policy for scenarios (A) High-efficient Gas, (B) Average Gas, (C) Existing Gas, (D) zero emissions. We note that CO_2eq is defined as a concentration, and for our purposes includes CO_2 and CH_4 only.

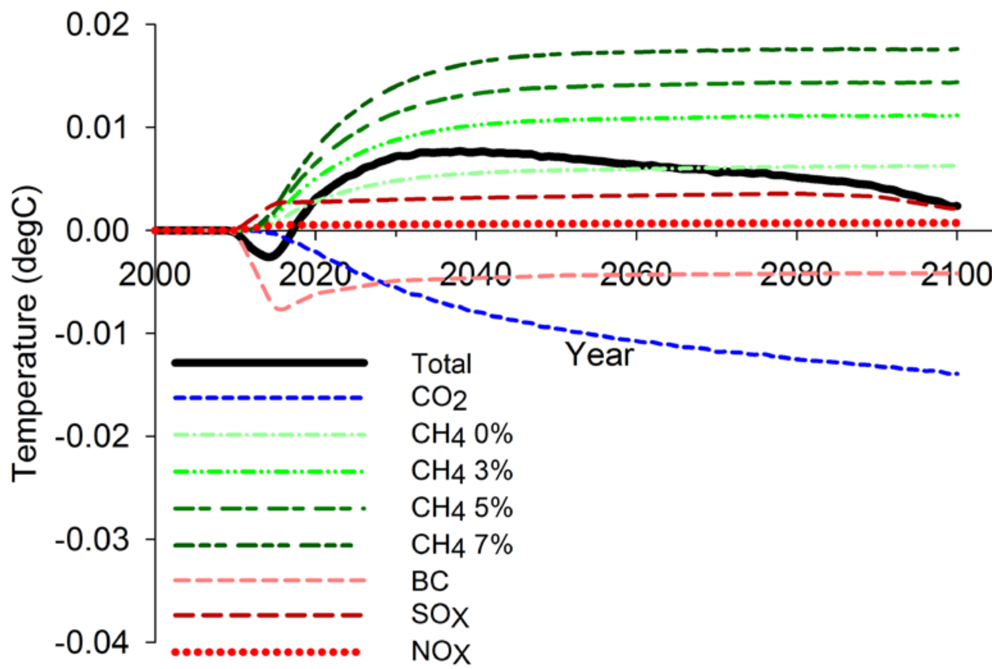

Figure 3: Change from Business as usual for the USA Policy for Scenario b): Average Gas for RCP8.5 for temperature contribution (°C) by individual constituents. The total, shown as the solid black line, is for 3% fugitive methane emissions.

Figure 3 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 *(37)* 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 (*6*). In our analysis, the baseline fleet in 2015 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 (Figure 3), 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 *(38)*. 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.

Effect on criteria pollutants and human health

Figure 4 illustrates the changes in emissions of SO_2, NO_X, $PM_{2.5}$, and PM_{10} that have occurred from 2009 to 2012, as well as anticipated 2015 levels under MATS and coal replacement scenarios. The significant reduction in SO_2 and NO_X emissions between 2009 and 2012 was primarily due to reductions in emission rates from coal and gas plants. In coal plants, new installations of emission control technologies reduced SO_2 emission rates by 41% and NO_X emission rates by 6%. Gas plants SO_2 rates fell 70% and NO_X rates fell 22%, due to reduced co-firing with coal or oil. By 2015, total national emissions of SO_2 are anticipated to drop a further 32% to meet the MATS requirements; NO_X emissions are anticipated to rise 5%. We likely overstate direct emissions of $PM_{2.5}$ and PM_{10} from coal and oil plants; due to lack of data, 2005 emission rates are assumed. However, implementation of the MATS rule is anticipated to reduce PM emissions from coal plants through the installation of fabric filters or upgrades to existing electrostatic precipitators *(11)*.

Switching from coal to gas would further reduce SO_2 emissions by more than 95% when compared to the base 2015 MATS emission levels; NO_X emissions would fall by 50% - 80% depending on the type of gas plant used to replace coal (scenarios a – c). Switching to zero emission sources would reduce SO_2 emissions by more than 98% and NO_X emissions by 86%.

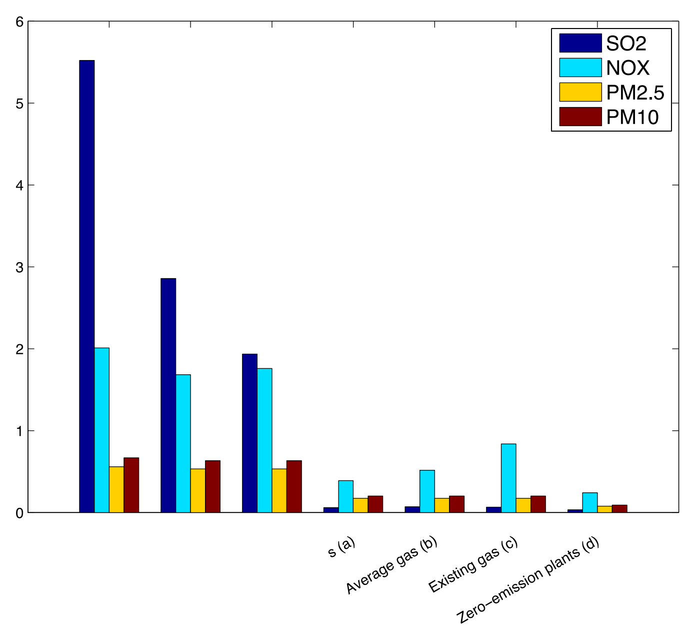

Figure 4: Emissions of criteria pollutant emissions pollutants in 2009, 2012, anticipated 2015 levels under MATS, and levels under four coal replacement scenarios.

The monetized annual health and environmental damages of emissions, via the APEEP model, are shown in Figure 5. Historically, SO_2 has been the predominant source of health damages from the electric power sector. Annual damages due to SO_2 are expected to fall by 2/3 from 2009 levels in 2015 from \$80 to \$27 billion due to implementation of MATS. Replacing coal with gas would further reduce annual damages by \$36 - \$38 billion from 2015 values, to \$7 - \$9 billion, depending on the replacement technology used. Replacing coal with zero emission sources would reduce annual damages by \$41 billion to \$4 billion. Health and environmental damages vary regionally (Figure 6). Most damages occur in the Ohio River Valley and Southeast due to the high concentration of coal plants and significant downwind population.

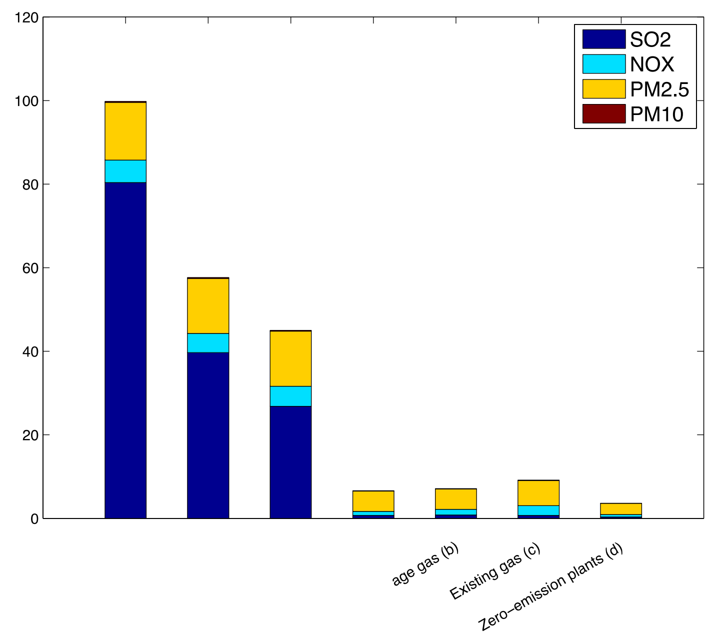

Figure 5: Annual health and environmental damages due to emissions of criteria pollutants in 2009, 2012, anticipated 2015 levels under MATS, and levels under four coal replacement scenarios.

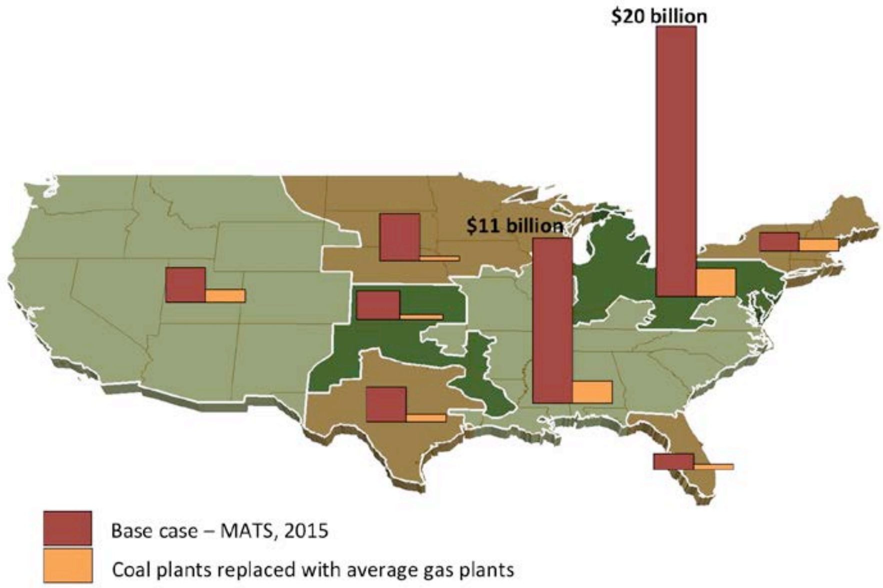

Figure 6: Variation in annual health and environmental damages due to emissions of criteria pollutants, by NERC region. Replacing coal plants with average gas plants (scenario b) most significantly reduces damages in the Midwest and Southeast.

Costs of reducing SO_2 emissions from coal

Although replacing all USA coal generation with new gas plants would create benefits of nearly $40 billion annually compared to the 2015 MATS scenario, the costs of constructing and operating such plants are approximately the same as the created health benefits (and may be larger). 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 *(39)* and a blended cost of capital of 7- 12% *(40)*.

Replacing coal plants with gas is only one option to mitigate SO_2 emissions. Flue gas desulfurization and direct sorbent injection are two emission control technologies (ECTs) used to mitigate SO_2 in existing coal plants. Table 2 compares the costs and effectiveness of each ECT to building a new NGCC. ECTs have the potential to be a more cost effective mitigation option than building new gas plants.

Table 2: Cost and effectiveness of different SO_2 control technologies. New NGCC costs and all fuel costs from *(39)*; FGD and DSI costs for a representative 500 MW coal unit *(12)*. 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 injection (DSI)	$40	$590	$7.9	$15 - $20	50%

DISCUSSION

The bounty of relatively inexpensive natural gas in North America should be viewed as a way to significantly improve public health. Replacing all USA coal plants with natural gas plants provides only a few months' delay in reaching GHG levels that lead to dangerous anthropogenic effects on the climate. Switching all USA coal plants to gas would reduce domestic greenhouse gas emissions by 3% - 18% from 2011 levels. Although this would represent a significant reduction in the nation's carbon footprint, it is insufficient to significantly delay anticipated warming effects by 2100. Wind, solar, and other zero emission electric power sources are three times as effective at reducing GHG pollution as switching to gas, but even switching the USA to zero emission sources delays reaching a target global CO_2eq by only a year or two.

Robust international action on GHG mitigation is required, and the USA and a few other major GHG polluters must come to an agreement. There are excellent pathways to a low carbon future, and a global natural gas switch may be a step on that path. However, natural gas should not sidetrack policy in the United States from the goal of reducing global GHGs.

Human health in the United States can greatly benefit from policies that continue the reduction of pollutants from coal plants, by switching to gas or installing emissions controls. Since 2009, the installation of emission control technology at coal plants has created substantial health benefits, and further improvements are anticipated by 2015 due to MATS. Retrofitting existing coal plants with ECT is more cost effective than building gas plants in most cases (Table 2). 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 further by ~$40 billion if coal plants are either replaced with gas plants or fitted with emissions controls.

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

Supporting Information

Table of Contents

1. Methods overview

A graphical representation of the model used in this work is shown in Figure S1. We use existing national datasets to identify emissions from all USA power plants. 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}) from each plant. We estimate emissions for 2009, 2012, and projected 2015 emissions under the EPA Mercury and Air Toxics Standard (MATS). We then examine the benefits of four 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; c) coal is displaced by increasing generation from existing gas plants, expanding their capacity where insufficient gas capacity exists; and d) 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 with its empirical health damages as a function of particulate type and location *(1)* 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 use the publicly-available MAGICC6 climate model *(2)* under different representative concentration pathways (RCPs; see section 4(a) below) to find the years of delay to global climate change such a switch would induce, considering emissions of CO_2, CH_4, NO_X, SO_2, $PM_{2.5}$, and PM_{10}.

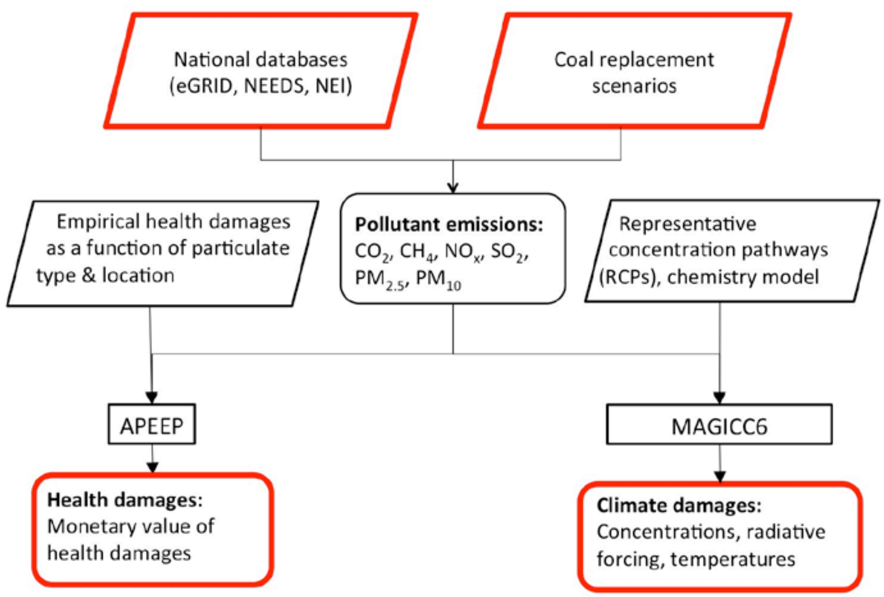

Figure S1: Graphical representation of the model used in this work. Thick red parallelograms denote inputs we varied. Thick red ovals indicate outputs.

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.

a. 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:

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

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.

b. 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 *(3)*).

To find the USA contribution toward CO_2eq in 2010, we used MAGICC6 for global emissions data *(2)* and national databases for USA emissions data *(4, 5)*. 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, *(4)*). Under this definition, the USA's contribution to CO_2eq is thus roughly 30 ppm.

3. 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 *(6)*. Upstream greenhouse gas (GHG) emissions from coal, in units of carbon dioxide equivalent mass (CDE), are the 5% and 95% confidence values reported by *(7)*.

Upstream GHG emissions for natural gas plants come from two sources: electricity used in the fuel's transportation *(6)*, and fugitive methane emissions from production and transportation. Of the two, fugitive methane dominates *(6)*. 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 *(8, 9)*. 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 S1: 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

This section describes the process used to model climate effects and the results.

a. 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 *(10)*. 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 *(11, 12)*. While the RCPs provide values for land use, dust, and nitrate aerosol forcing, these are not included in the radiative forcing estimates *(12)*.

The RCP authors caution that users must be careful to avoid over-interpreting the data. The RCPs were developed by four independent modeling groups *(13, 14, 15, 16)*. While integrated assessment models were used (IMAGE, MiniCAM, AIM, and MESSAGE)[i], 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

[i] 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)

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.

Figure S2 and Figure S3 compare the RCPs to published primary energy usage outlooks from BP *(17)* and ExxonMobil *(18).* 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.

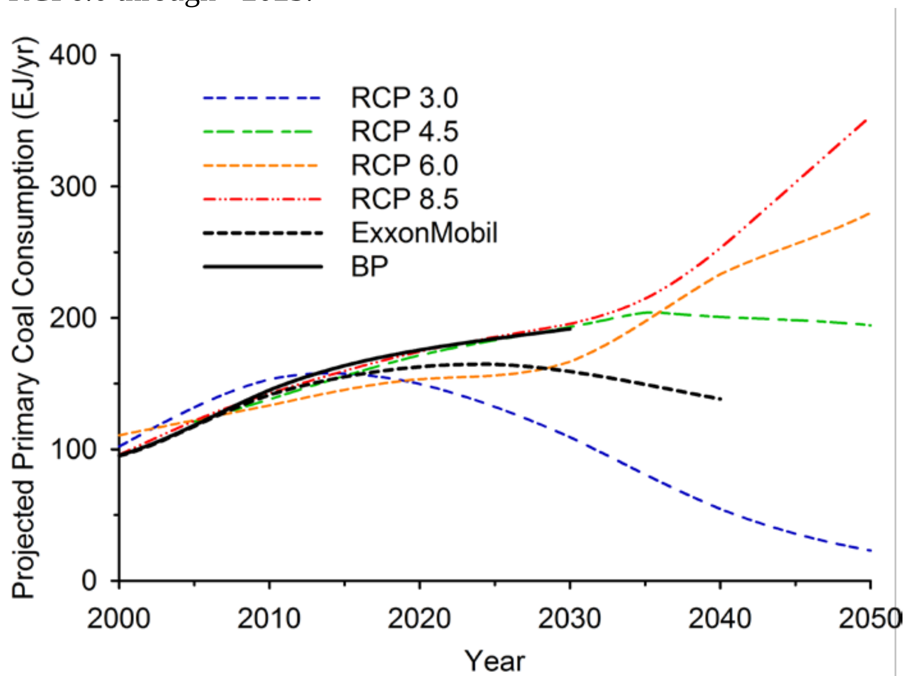

Figure S2: Primary energy usage of coal, 2000-2040. BP's outlook matches that of RCP 8.5. ExxonMobil's outlook is in between RCP6.0 and RCP8.5 until 2025, at which time they predict substantial reductions in coal usage; its total primary energy usage is in line with RCP6.0.

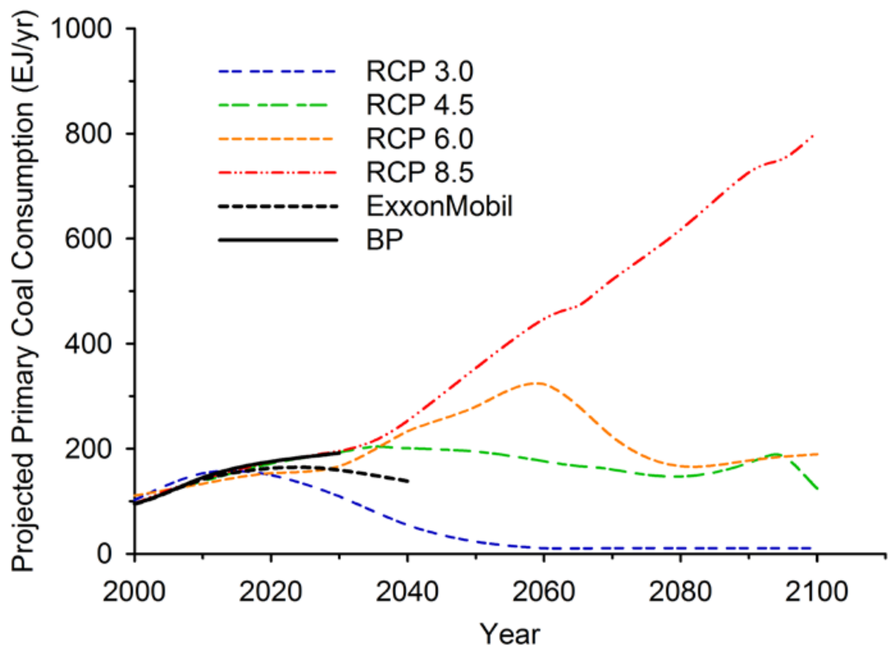

Figure S3: Primary energy usage of coal, 2000-2100. BP's outlook matches that of RCP 8.5. ExxonMobil's outlook is between RCP6.0 and RCP8.5 until 2025, at which time they predict substantial reductions in coal usage; its total primary energy usage is in line with RCP6.0.

b. Climate Model Benchmarking

We modeled climate change effects with the publicly available MAGICC6 model *(2)*. 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 d), 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 *(19, 20)* or by applying a Monte Carlo analysis of values published in the literature *(8)*.

Table S2: Climate models used in recent literature we cite.

Model	Type	Climate Feedback, λ	Ocean	Chemistry
Hayhoe et al. *(21)*	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 *(22)*	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 *(23)*, Smith & Mizrahi *(24)*, MAGICC6 *(25)*	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

c. 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 S4). Scenario values are listed in

Table S3 and our temperature differences from business as usual is in Figure S5. 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. It is likely that Wigley may have applied the SO_X reduction slightly differently than we did.

Table S3: **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.

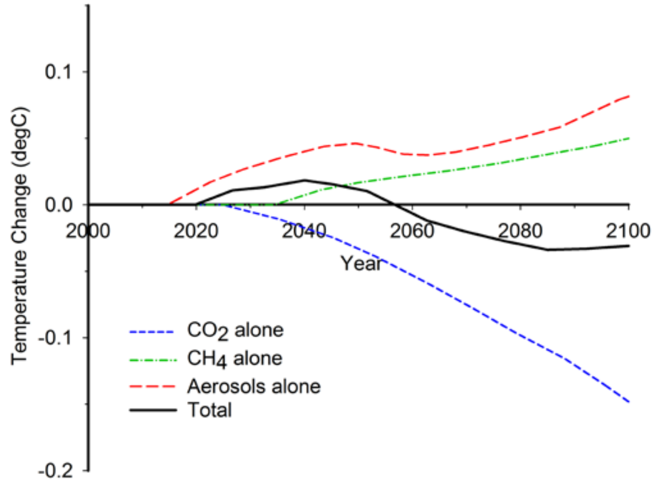

Figure S4: Temperature changes from Wigley, Figure 2b (Adapted from *(23)*).

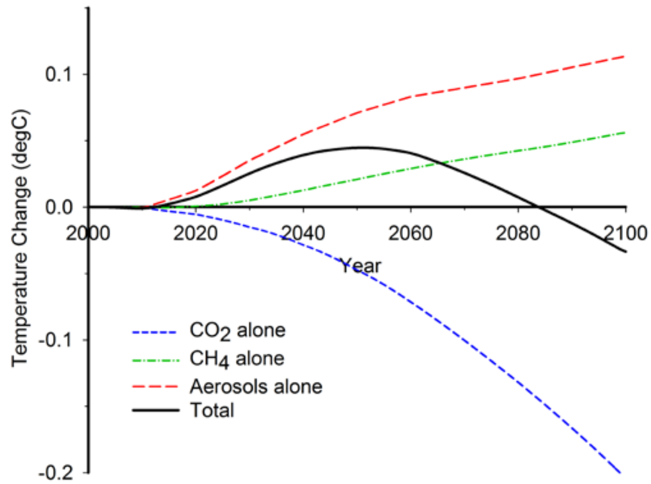

Figure S5: Temperature changes recreating the Wigley estimates

d. Climate results - radiative forcing and temperature results

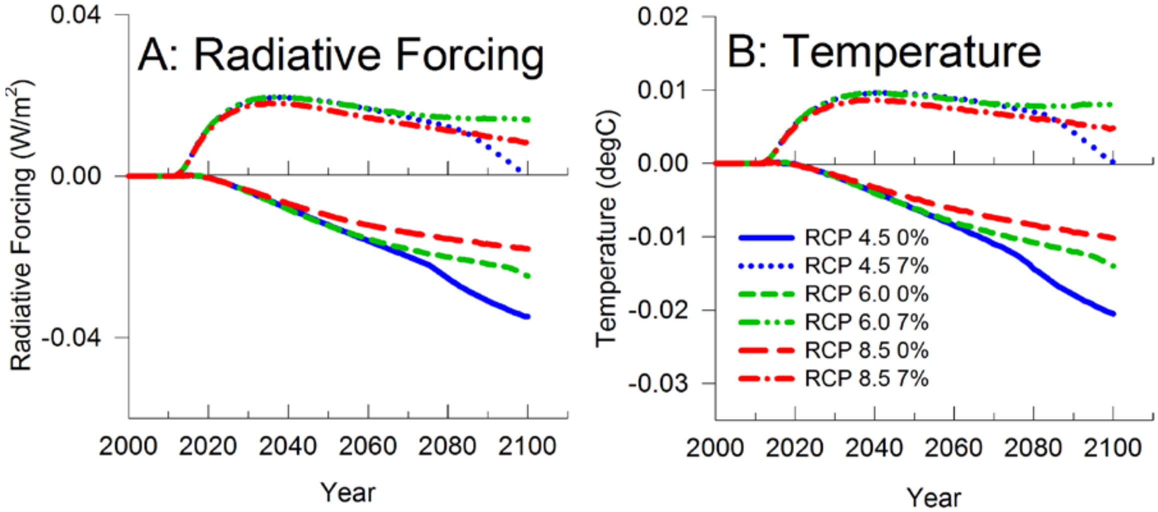

Figure S6: Change from Business as usual for the USA Policy for Scenario b): Average Gas for (A) radiative forcings (W/m^2) and (B) temperature (°C)

e. 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 *(26)*. 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)-d)). 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 S7). Switching to zero emission plants reduces emissions 26% assuming RCP 6.

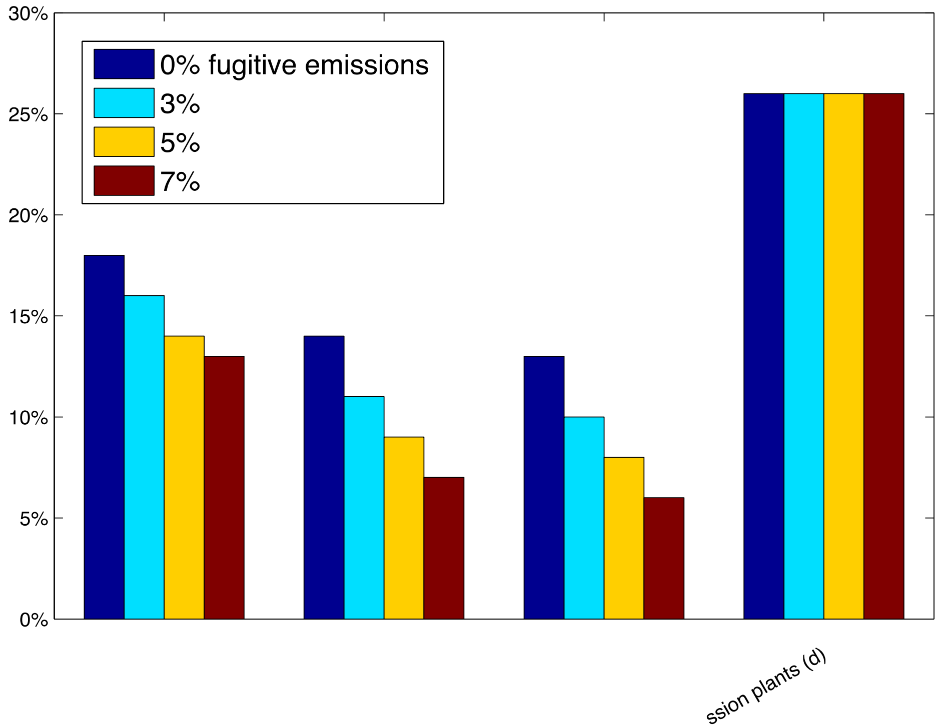

Figure S7: Reduction in total cumulative GHG emissions (CDE) to 2100 due to a global switch from coal, RCP 6

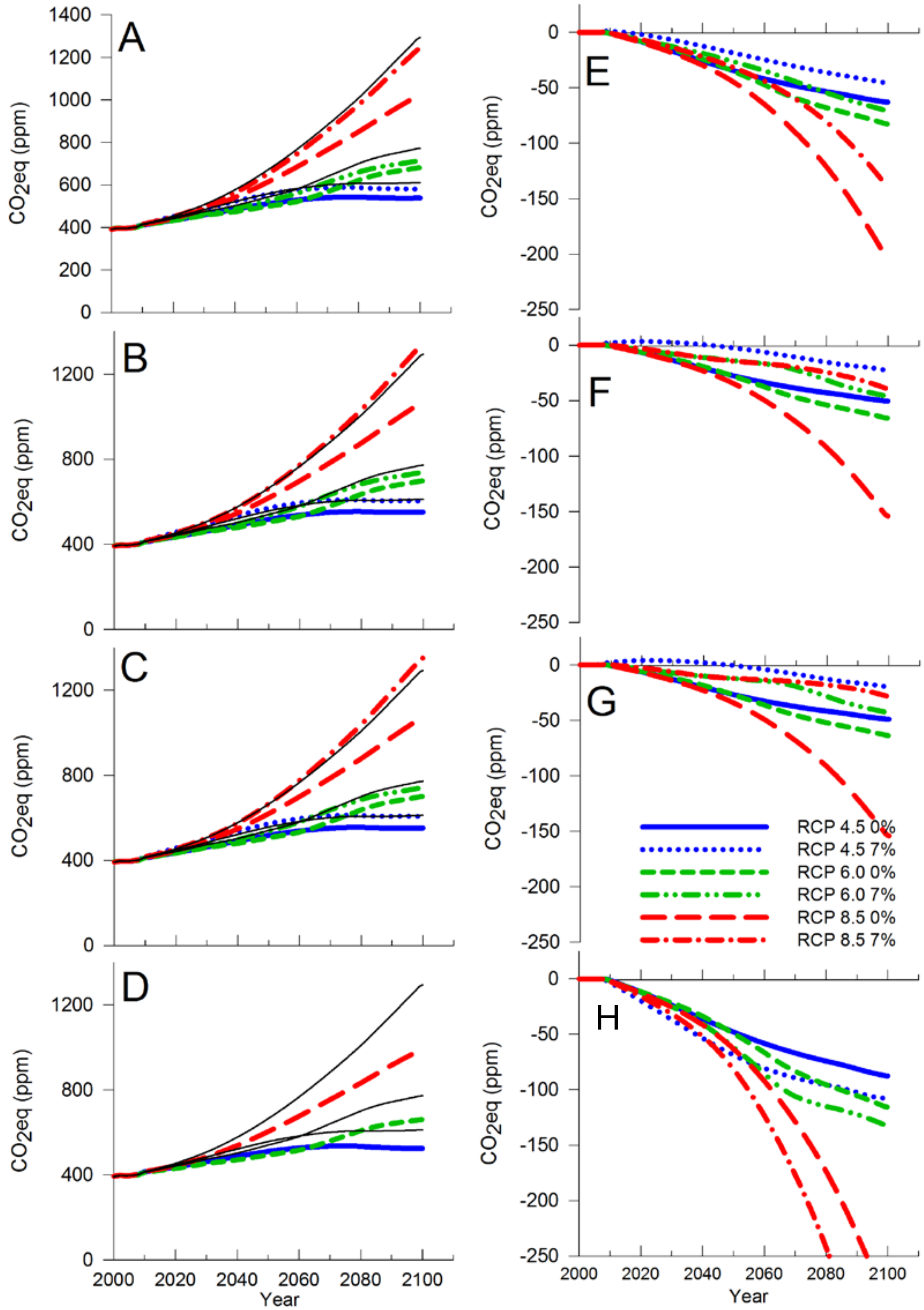

Figure 8: Total CO_2eq (A-D) and Change in CO_2eq from Business as usual (E-H) for, from top to bottom, the Global Policy for Scenario a): NGCC, Scenario b): Average, Scenario c): Existing, Scenario d): ZEG. Solid black lines indicate the business as usual scenario for 3% methane leakage..

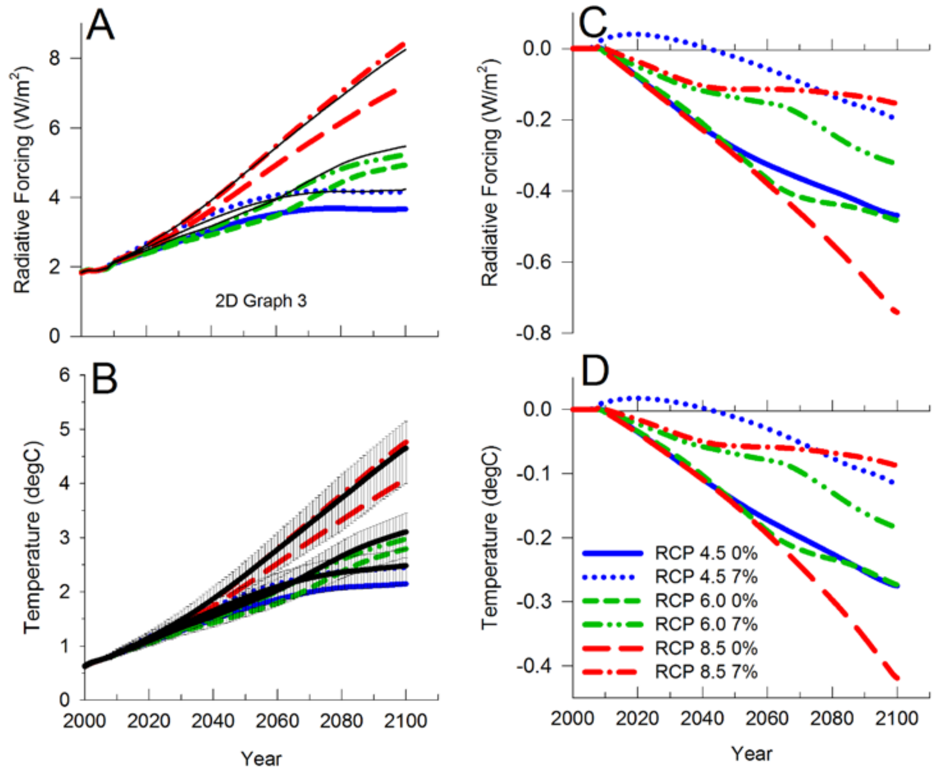

Figure 9: Total (A-B) and change from Business as usual (C-D) for the Global Policy for Scenario b): Average for (radiative forcings (A, C) and (B) temperature (B, D). Solid black lines indicate the business as usual scenario for 3% methane leakage, and the error bars in B indicate the 66% confidence 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 8 shows the total CO_2eq and change in CO_2eq from business as usual for the Global Policy for scenario a)-d). 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 c) is the worst. Scenario d) 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 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.

5. Emission and Health Results

shows calculated total USA emissions and health damages associated with all scenarios we analyze.

Table S4: Emissions of pollutants and associated health damages in scenarios we analyze

	Annual emission totals [million metric tons]									Annual health damages [$ Billions]				
						CH_4 (combustion + fugitives)								
Scenario	SO_2	NO_X	$PM_{2.5}$	PM_{10}	CO_2	0% fugitives	3% fugitives	5% fugitives	7% fugitives	SO_2	NO_X	$PM_{2.5}$	PM_{10}	Total
2009	5.5	2.0	0.6	0.7	2,200	5	9	12	15	80	5	14	0	100
2012	2.9	1.7	0.5	0.6	2,000	7	14	18	23	40	5	13	0	58
Base case – MATS, 2015	1.9	1.8	0.5	0.6	2,100	7	14	18	23	27	5	13	0	45
Scenario a) Switch to existing gas	0.1	0.8	0.2	0.2	1,400	17	34	45	56	1	2	6	0	9
Scenario b) Switch to avg gas	0.1	0.5	0.2	0.2	1,300	16	32	43	53	1	1	5	0	7
Scenario c) Switch to clean gas	0.0	0.4	0.2	0.2	1,100	13	26	34	43	1	1	5	0	6
Scenario d) Switch to zero emission plants	0.0	0.2	0.1	0.1	600	7	14	18	23	0	1	3	0	4

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