

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

Roger Lueken<sup>†</sup>, Kelly Klima<sup>†</sup>, W. Michael Griffin<sup>†</sup>, Jay Apt<sup>†,§</sup>

<sup>†</sup>Department of Engineering and Public Policy and <sup>§</sup>Tepper School of Business, Carnegie Mellon University, Pittsburgh, PA 15213-3890, United States

### 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<sub>2</sub>) 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<sub>4</sub>), 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<sub>2</sub> and NO<sub>x</sub>, precursors of particulate matter. Natural gas also has lower primary emissions PM<sub>2.5</sub> and PM<sub>10</sub> than coal. Exposure to PM<sub>2.5</sub> 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<sub>2</sub> and NO<sub>x</sub> 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<sub>2</sub>, NO<sub>x</sub>, SO<sub>2</sub>, CH<sub>4</sub> 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<sub>2.5</sub> and PM<sub>10</sub> 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<sub>2.5</sub> and PM<sub>10</sub> 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<sub>x</sub>, SO<sub>2</sub>, and CO<sub>2</sub>, 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<sub>2</sub> emissions, and 70% of CO<sub>2</sub> emissions. MATS requires fossil plants not in CAIR states to reduce SO<sub>2</sub> and NO<sub>x</sub> emissions. For these plants, we assumed changes in NO<sub>x</sub>, SO<sub>2</sub>, and CO<sub>2</sub> 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<sub>4</sub>, PM<sub>2.5</sub>, PM<sub>10</sub> were left unchanged from 2009 due to lack of data.

#### *Baseline 2015 scenario emission rates under MATS*

Further SO<sub>2</sub> 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<sub>2</sub> and 1.7 million tons of NO<sub>x</sub> (11). This represents a 32% reduction in SO<sub>2</sub> from our calculated 2012 coal and oil total, and a 5% increase in NO<sub>x</sub> emissions. We adjusted emissions of SO<sub>2</sub> and NO<sub>x</sub> equally for all coal and oil plants such that total emissions equaled the anticipated 2015 levels. Emissions of CH<sub>4</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub> 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<sub>4</sub> 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<sub>x</sub>, SO<sub>2</sub>, PM<sub>2.5</sub>, PM<sub>10</sub>) 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<sub>2</sub> emission rate was calculated by multiplying the heat rate by the carbon content of natural gas. To calculate emission rates of NO<sub>x</sub>, SO<sub>2</sub>, CH<sub>4</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub> 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.

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

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<sub>2.5</sub> and PM<sub>10</sub>) could be considered black carbon, and all SO<sub>2</sub> could be considered SO<sub>x</sub>. Additionally, we assumed NO<sub>x</sub> is made of 90% NO and 10% NO<sub>2</sub> 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<sup>2</sup> to between 8 and 9 W/m<sup>2</sup> 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<sub>2</sub> 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<sub>2</sub>, or CO<sub>2</sub>eq. CO<sub>2</sub>eq 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<sub>2</sub>, NO<sub>x</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub> 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<sub>x</sub>, SO<sub>2</sub>, PM<sub>2.5</sub>, PM<sub>10</sub>, volatile organic compounds (VOCs), and ammonia (NH<sub>3</sub>) from each county in the USA. We excluded damages due to VOC and NH<sub>3</sub> from our analysis due to uncertainty in the atmospheric science surrounding these pollutants, and the relatively small damages they cause compared to SO<sub>2</sub>, NO<sub>x</sub>, 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<sub>2.5</sub> caused by SO<sub>2</sub> and NO<sub>x</sub> is linear with reduced emissions, with no threshold (31). Major cohort studies have found PM<sub>2.5</sub> concentration-response functions and mortality are linear with no threshold (32 – 34). Since we find NO<sub>x</sub> made up only 8% of total health damages from the electricity sector in 2012, we ignore the known

second-order nonlinearities in PM<sub>2.5</sub> formation associated with NO<sub>x</sub> emissions due to decreasing SO<sub>2</sub> 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 <sub>2</sub>	NO <sub>x</sub>	SO <sub>2</sub>	CH <sub>4</sub>	PM <sub>2.5</sub>	PM <sub>10</sub>
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

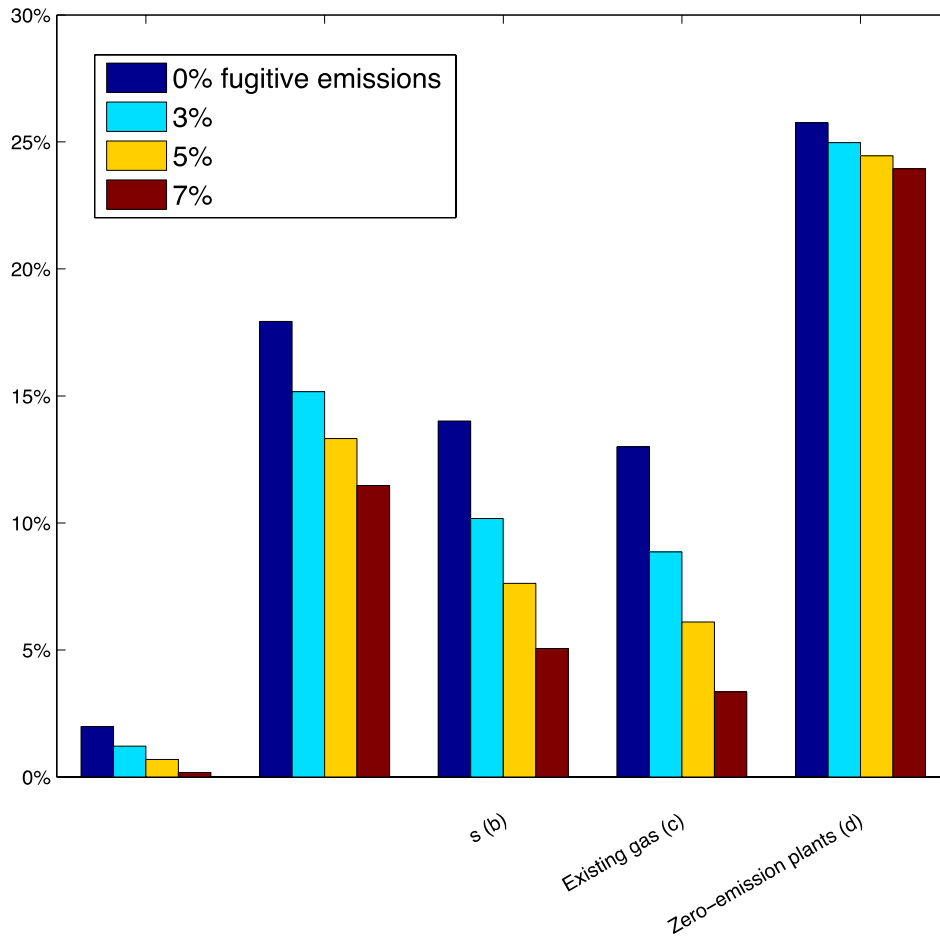
\* EPA anticipates 2015 NO<sub>x</sub> emissions will be 5% higher than 2012 levels (*12 Error! Bookmark not defined.*).

### *Effect on greenhouse gas emissions & atmospheric concentrations*

#### *Change in emissions*

In 2009, the carbon dioxide equivalent mass (CDE) of CO<sub>2</sub> and CH<sub>4</sub> (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<sub>4</sub> 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**

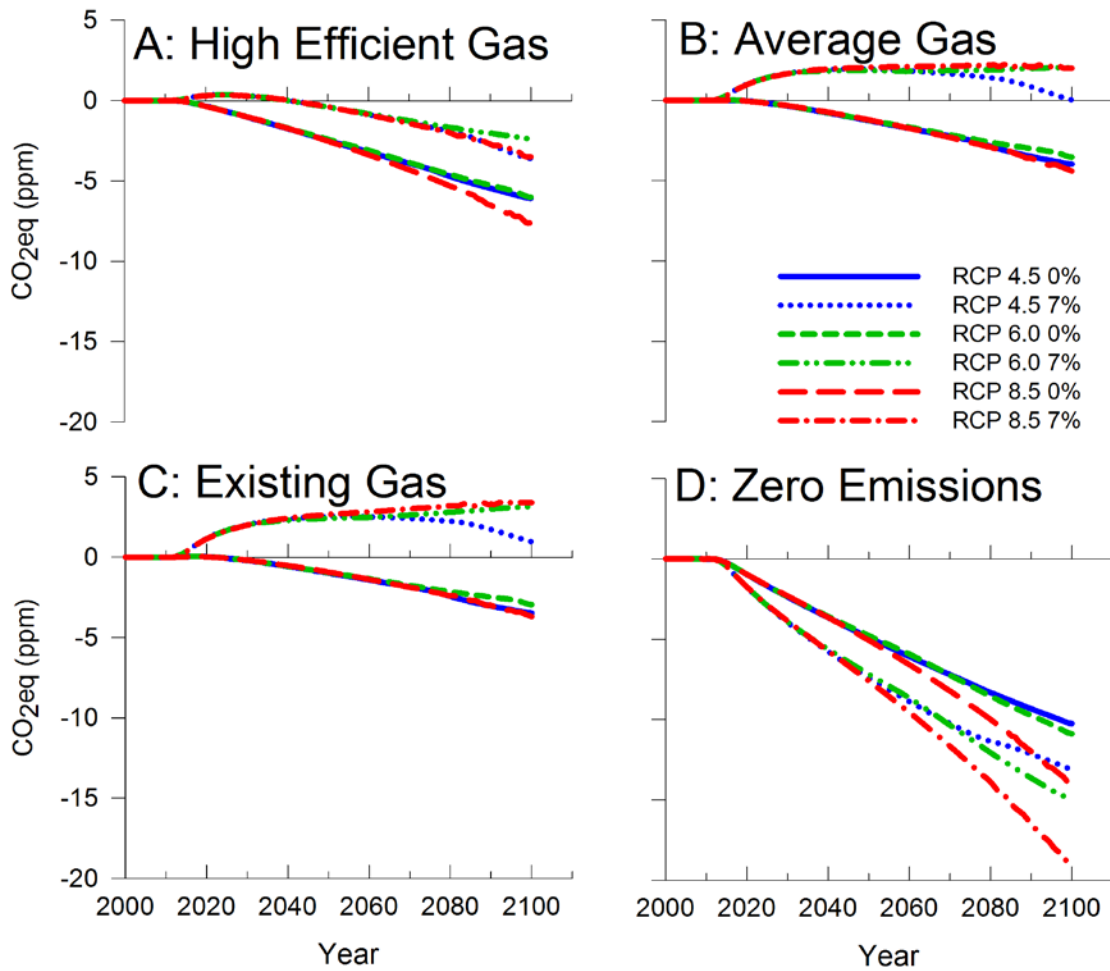
#### *Climate effects*

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<sub>2</sub>eq) in the short term due to reduction in aerosols and increased fugitive methane emissions, and decreases CO<sub>2</sub>eq by 2100 due to reduction in CO<sub>2</sub>. 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  $\pm 25\%$ .

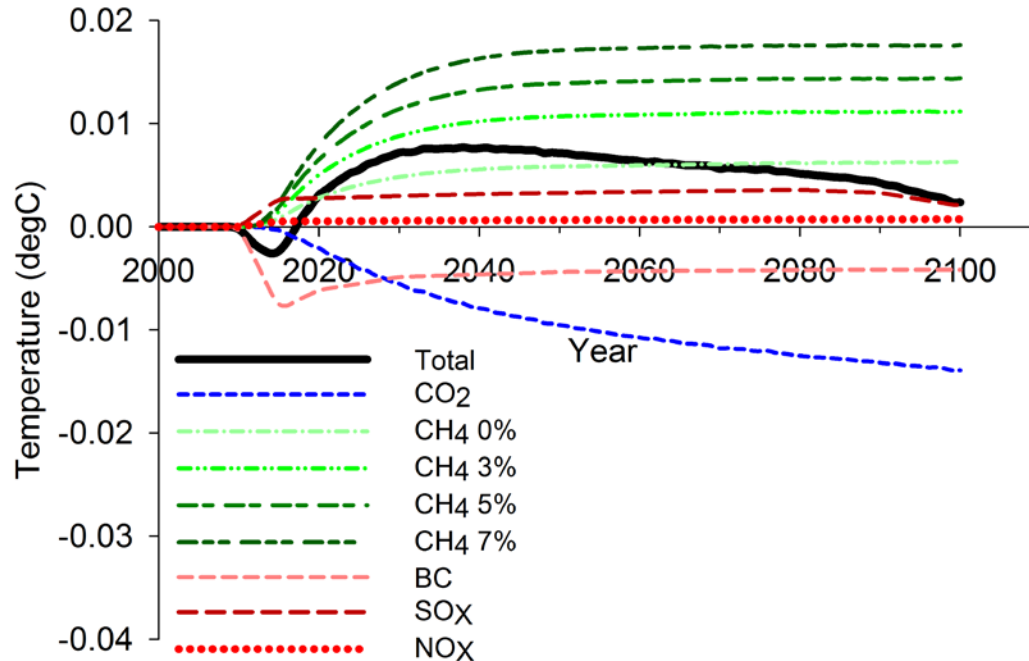
Figure 2 shows the change in CO<sub>2</sub>eq from business as usual for the USA policy for scenarios a) -d). All of the coal to natural gas scenarios and RCPs are similar; scenario a) is best at reducing CO<sub>2</sub>eq concentrations, while scenario c) is least effective. The zero emissions scenario d) is roughly 2-3 times more effective at reducing CO<sub>2</sub>eq as the gas scenarios. While a USA policy reduces the nation’s contribution of CO<sub>2</sub> and CH<sub>4</sub> from its 2010 CO<sub>2</sub>eq of 30 ppm by, in some cases, over 33%, the reduction values are small



compared to global values (current anthropogenic CO<sub>2</sub> and CH<sub>4</sub> concentration is ~140 ppm CO<sub>2</sub>eq).



**Figure 2: Change in CO<sub>2</sub>eq 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<sub>2</sub>eq is defined as a concentration, and for our purposes includes CO<sub>2</sub> and CH<sub>4</sub> only.**



**Figure 3: Change from Business as usual for the USA Policy for Scenario b): Average Gas for RCP8.5 for temperature contribution ( $^{\circ}\text{C}$ ) 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<sub>2</sub>. Therefore, a shift from coal to gas would significantly reduce SO<sub>2</sub>, 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<sub>2</sub> emissions. Thus the avoided SO<sub>2</sub> 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.

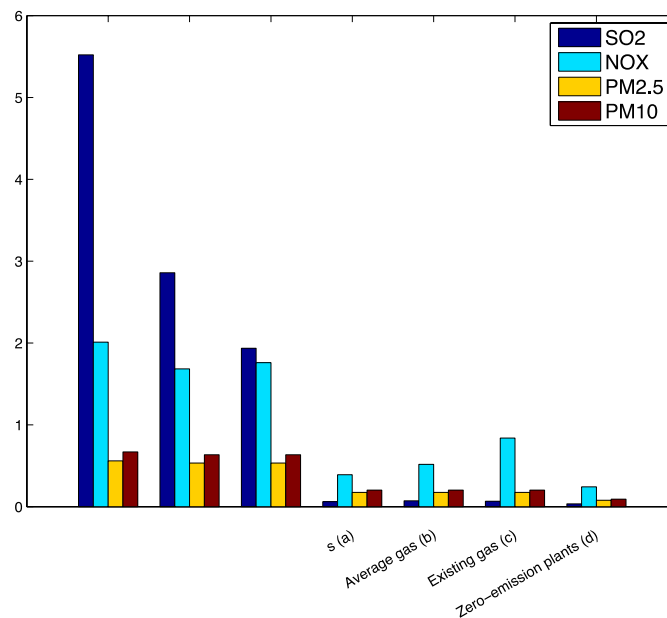
We note that MAGICC6's chemistry model has many interesting secondary effects we have not reported with these data, e.g., the lifetime of halogenated gases decreases as methane concentrations increase. As part of their work examining a coal to natural gas shift, Smith and Mizrahi calculate the change 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*

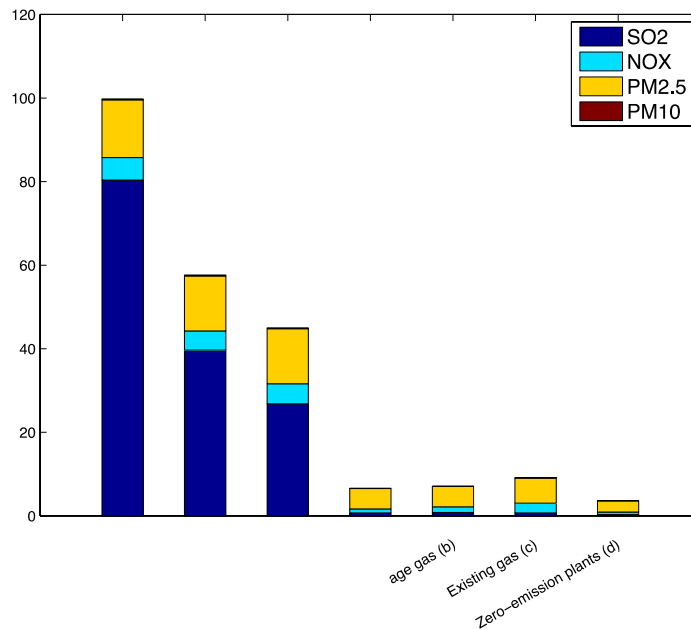
Figure 4 illustrates the changes in emissions of SO<sub>2</sub>, NO<sub>x</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub> that have occurred from 2009 to 2012, as well as anticipated 2015 levels under MATS and coal replacement scenarios. The significant reduction in SO<sub>2</sub> and NO<sub>x</sub> emissions 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<sub>2</sub> emission rates by 41% and NO<sub>x</sub> emission rates by 6%. Gas plants SO<sub>2</sub> rates fell 70% and NO<sub>x</sub> rates fell 22%, due to reduced co-firing with coal or oil. By 2015, total national emissions of SO<sub>2</sub> are anticipated to drop a further 32% to meet the MATS requirements; NO<sub>x</sub> emissions are anticipated to rise 5%. We likely overstate direct emissions of PM<sub>2.5</sub> and PM<sub>10</sub> 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<sub>2</sub> emissions by more than 95% when compared to the base 2015 MATS emission levels; NO<sub>x</sub> 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<sub>2</sub> emissions by more than 98% and NO<sub>x</sub> emissions by 86%.

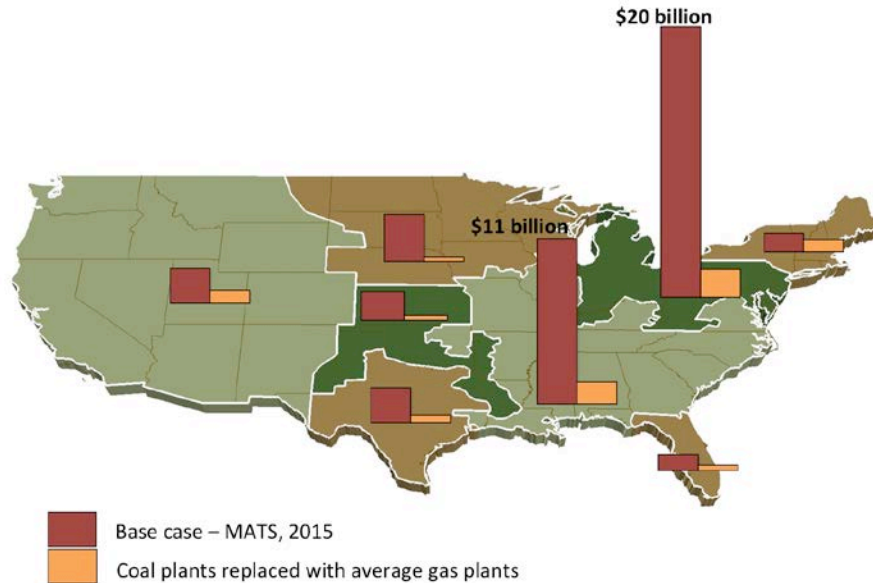


**Figure 4: Emissions of criteria pollutant emissions pollutants in 2009, 2012, anticipated 2015 levels under MATS, and levels under four coal replacement scenarios.**

The monetized annual health and environmental damages of emissions, via the APEEP model, are shown in Figure 5. Historically, SO<sub>2</sub> has been the predominant source of health damages from the electric power sector. Annual damages due to SO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> emissions. Flue gas desulfurization and direct sorbent injection are two emission control technologies (ECTs) used to mitigate SO<sub>2</sub> 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<sub>2</sub> 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 <sub>2</sub> control technology	Capital cost (\$/kW)	Fixed O&M (\$/MW-yr)	Variable O&M (\$/MWh)	Fuel cost (\$/MWh)	SO <sub>2</sub> 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<sub>2</sub>eq 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.

## 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, Jinhyok Heo, M. Granger Morgan, and David Luke Oates for helpful discussions.

## REFERENCES

- (1) U.S. Department of Energy. *Monthly Energy Review*; DOE/EIA-0035(2013/08); Energy Information Administration: Washington, DC, **2013**. <http://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf> (accessed Jan 8, 2014).
- (2) U.S. Executive Office of the President. *The President's Climate Action Plan*; Washington, DC, **2013**. <http://www.whitehouse.gov/sites/default/files/image/president27sclimateactionplan.pdf> (accessed Jan 8, 2014).
- (3) U.S. EPA. *eGRID2012 Version 1.0*; **2012**. <http://www.epa.gov/egrid> (accessed Jan 8, 2014).
- (4) Hayhoe, K.; Kheshgi, H.S.; Jain, A.K.; Wuebbles, D.J. Substitution of natural gas for coal: climatic effects of utility sector emissions. *Climatic Change*. **2002**, *54*(1-2), 107-139.
- (5) Jaramillo, P.; Griffin, W.M.; Matthews, H.S. Comparative life-cycle air emissions of coal, domestic natural gas, LNG, and SNG for electricity generation. *Environ. Sci. Technol.* **2007**, *41*(17), 6290-6296.
- (6) Wigley, T. M. Coal to gas: the influence of methane leakage. *Climatic change*. **2011**, *108*(3), 601-608.
- (7) Venkatesh, A.; Jaramillo, P.; Griffin, W.M.; Matthews, H.S. Implications of Near-Term Coal Power Plant Retirement for SO<sub>2</sub> and NO<sub>x</sub> and Life Cycle GHG Emissions. *Environ. Sci. Technol.* **2012**, *46*(18), 9838-9845.
- (8) Myhrvold, N.P.; Caldeira, K. Greenhouse gases, climate change and the transition from coal to low-carbon electricity. *Environmental Research Letters*. **2012**, *7*(1), 014019.
- (9) Weber, C.L.; Clavin, C. Life cycle carbon footprint of shale gas: Review of evidence and implications. *Environ. Sci. Technol.* **2012**, *46*(11), 5688-5695.
- (10) U.S. EPA. *Regulatory Impact Analysis for the Final Clean Air Interstate Rule*; Office of Air and Radiation: Washington, DC, **2005**.
- (11) U.S. EPA. *Regulatory Impact Analysis for the Final Mercury and Air Toxics Standard*; Office of Air Quality Planning and Standards: Washington, DC, **2011**.
- (12) PJM Interconnection. *Coal Capacity at Risk of Retirement in PJM: Potential Impacts of the Finalized EPA Cross State Air Pollution Rule and Proposed National Emissions Standards for Hazardous Air Pollutants*; Norristown, PA, **2011**. <http://pjm.com/~media/documents/reports/20110826-coal-capacity-at-risk-for-retirement.ashx> (accessed Jan 8, 2014).
- (13) Meinshausen, M.; Raper, S.C.B.; Wigley, T.M.L. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6—Part 1: Model description and calibration. *Atmospheric Chemistry and Physics*. **2011**, *11*(4), 1417-1456.
- (14) Muller, N.Z.; Mendelsohn, R. Measuring the damages of air pollution in the United States. *Journal of Environmental Economics and Management*. **2007**, *54*(1), 1-14.
- (15) U.S. EPA. *2005 National Emissions Inventory (Version 2)*; **2009**. <http://www.epa.gov/ttnchie1/net/2005inventory.html> (accessed Jan 8, 2014).
- (16) U.S. EPA. Air Markets Program Data. <http://ampd.epa.gov/ampd/> (accessed Jan 8, 2014).
- (17) Paul, A., Blair, B., Palmer, K. (2013). *Taxing Electricity Sector Carbon Emissions at Social Cost*; RFF DP 13-23; Resources For the Future: Washington, DC **2013**.
- (18) General Electric. *FlexEfficiency 60 Portfolio*; **2012**. [http://www.ge-flexibility.com/static/global-multimedia/flexibility/documents/FE60 Interactive pdf FINAL 9-25-12.pdf](http://www.ge-flexibility.com/static/global-multimedia/flexibility/documents/FE60%20Interactive%20pdf%20FINAL%209-25-12.pdf) (accessed Jan 8, 2014).
- (19) Siemens. *H-Class High Performance Siemens Gas Turbine SGT-8000H series*; **2011**. <http://www.energy.siemens.com/us/pool/hq/power-generation/gas-turbines/SGT5-8000H/downloads/H%20class%20high%20performance.pdf> (accessed Jan 8, 2014).
- (20) U.S. EPA. *National Electric Energy Data System Version 5.13*; **2013**. <http://www.epa.gov/airmarkets/progsregs/epa-ipm/BaseCasev513.html#needs> (accessed Jan 8, 2014).

- (21) U.S. Department of Energy. *Annual Energy Outlook 2014 Early Release*; Energy Information Administration: Washington, DC, **2013**. <http://www.eia.gov/forecasts/aeo/er/index.cfm> (accessed Jan 8, 2014).
- (22) Meinshausen, M.; Smith, S.J.; Calvin, K.; Daniel, J.S.; Kainuma, M.L.T.; Lamarque, J.F.; Matsumoto, K.; Montzka, S.A.; Raper, S.C.B.; Riahi, K.; Thomson, A.; Velders, G.J.M.; van Vuuren, D.P.P. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change*. **2011**, *109*(1-2), 213-241.
- (23) Hanrahan, P. L. The plume volume molar ratio method for determining NO<sub>2</sub>/NO<sub>x</sub> ratios in modeling—Part I: Methodology. *Journal of the Air & Waste Management Association*. **1999**, *49*(11), 1324-1331.
- (24) Van Vuuren, D.P.; Edmonds, J.A.; Kainuma, M.; Riahi, K.; Weyant, J. A special issue on the RCPs. *Climatic Change*. **2011**, *109*(1), 1-4.
- (25) Van Vuuren, D.P.; Edmonds, J.; Kainuma, M.; Riahi, K.; Thomson, A.; Hibbard, K.; Hurtt, G.; Kram, T.; Krey, V.; Lamarque, J.; Masui, T.; Meinshausen, M.; Nakicenovic, N.; Smith, S.J.; Rose, S.K. The representative concentration pathways: an overview. *Climatic Change*. **2011**, *109*(1-2), 5-31.
- (26) Pinder, R.W.; Adams, P.J.; Pandis, S.N. Ammonia Emission Controls as a Cost-Effective Strategy for Reducing Atmospheric Particulate Matter in the Eastern United States. *Environ. Sci. Technol.* **2007**, *41*, 380–386.
- (27) Robinson, A. L.; Donahue, N.M.; Shrivastava, M.K.; Weitkamp, E.A.; Sage, A.M.; Grieshop, A.P.; Pandis, S.N. Rethinking Organic Aerosols: Semivolatile Emissions and Photochemical Aging. *Science*. **2007**, *315*(5816), 1259–1262.
- (28) National Research Council (US). Committee on Health, Environmental, and Other External Costs and Benefits of Energy Production and Consumption. *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use*. National Academies Press., **2010**.
- (29) Levy, J. I.; Baxter, L. K.; Schwartz, J. Uncertainty and Variability in Health- Related Damages from Coal- Fired Power Plants in the United States. *Risk Analysis*. **2009**, *29*(7), 1000-1014.
- (30) Fann, N.; Fulcher, C. M.; Hubbell, B. J. The influence of location, source, and emission type in estimates of the human health benefits of reducing a ton of air pollution. *Air Quality, Atmosphere & Health*. **2009**, *2*(3), 169-176.
- (31) Koo, B.; Wilson, G.; Morris, R.; Dunker, A.; Yarwood, G. Comparison of Source Apportionment and Sensitivity Analysis in a Particulate Matter Air Quality Model. *Environ. Sci. Technol.* **2009**, *43*, 6669-6675.
- (32) Krewski, D.; Jerrett, M.; Burnett, R. T.; Ma, R.; Hughes, E.; Shi, Y.; Turner, M.; Pope, C.A.; Thurston, G.; Calle, E.E.; Thun, M.J.; Beckerman, B.; DeLuca, P.; Finkelstein, N.; Ito, K.; Moore, D.K.; Newbold, K.B.; Ramsay, T.; Ross, Z.; Shin, H.; Tempalski, B. *Extended follow-up and spatial analysis of the American Cancer Society study linking particulate air pollution and mortality* (No.140). Boston, MA: Health Effects Institute, **2009**.
- (33) Lepeule, J.; Laden, F.; Dockery, D.; Schwartz, J. Chronic Exposure to Fine Particles and Mortality: An Extended Follow-up of the Harvard Six Cities Study from 1974 to 2009. *Environmental Health Perspectives*. **2012**, *120*(7), 965–970.
- (34) Correia, A. W.; Pope III, C. A.; Dockery, D. W.; Wang, Y.; Ezzati, M.; Dominici, F. Effect of air pollution control on life expectancy in the United States: an analysis of 545 US counties for the period from 2000 to 2007. *Epidemiology*. **2013**, *24*(1), 23-31.
- (35) Solomon, S.; Qin, D.; Manning, M.; Alley, R. B.; Berntsen, T.; Bindoff, N.L.; Chen, Z.; Chidthaisong, A.; Gregory, J.M.; Hegerl, G.C.; Heimann, M.; Hewitson, B.; Hoskins, B.J.; Joos, F.; Jouzel, J.; Kattsov, V.; Lohmann, U.; Matsuno, T.; Molina, M.; Nicholls, N.; Overpeck, J.; Raga, G.; Ramaswamy, V.; Ren, J.; Rusticucci, M.; Somerville, R.; Stocker, T.F.; Whetton, P.; Wood, R.A.; Wratt, D. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change - Technical Summary. In *Climate Change 2007: The Physical Science Basis*; Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M., Hiller, H.L., Eds.; Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, **2007**.
- (36) U.S. EPA. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2010*; EPA-430-R-12-001; Washington, DC., **2012**.
- (37) Bond, T. C.; Doherty, S. J.; Fahey, D. W.; Forster, P. M.; Berntsen, T.; DeAngelo, B. J.; Flanner, M. G.; Ghan, S.; Kärcher, B.; Koch, D.; Kinne, S.; Kondo, Y.; Quinn, P. K.; Sarofim, M. C.; Schultz, M. G.; Schulz, M.; Venkataraman, C.; Zhang, H.; Zhang, S.; Bellouin, N.; Guttikunda, S. K.; Hopke, P.



- K.; Jacobson, M. Z.; Kaiser, J. W.; Klimont, Z.; Lohmann, U.; Schwarz, J. P.; Shindell, D.; Storelvmo, T.; Warren, S. G.; Zender, C. S. Bounding the role of black carbon in the climate system: A scientific assessment. *J. Geophys. Res. Atmos.* **2013**, 118 (11), 2169-8996.
- (38) Smith, S. J.; Mizrahi, A. Near-term climate mitigation by short-lived forcers. *Proceedings of the National Academy of Sciences.* **2013**, 110(35), 14202-14206.
- (39) Lazard, Levelized Cost of Energy Analysis – Version 6.0 **2012**.
- (40) Spees, K.; Newell, S.; Carlton, R.; Zhou, B.; Pfeifenberger, J. *Cost of New Entry Estimates For Combustion Turbine and Combined-Cycle Plants in PJM*; Prepared for PJM Interconnection by the Brattle Group: Norristown, PA, **2011**. <http://www.pjm.com/~media/committees-groups/committees/mrc/20110818/20110818-brattle-report-on-cost-of-new-entry-estimates-for-ct-and-cc-plants-in-pjm.ashx> (accessed Jan 8, 2014).