Energy 109 (2016) 1160–1166

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

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

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ARTICLE INFO

Article history:
Received 4 November 2015
Accepted 16 March 2016

Keywords:
Natural gas
Coal
Climate change
Criteria pollutants
Human health

ABSTRACT

Abundant natural gas at low prices has prompted industry and politicians to welcome gas as a 'bridge fuel' between today's coal-intensive electric power generation and a future low-carbon grid. We used existing national datasets and publicly available models to investigate the upper limit to the emission benefits of natural gas in the USA power sector. As a limiting case, we analyzed a switch of all USA coal plants to natural gas plants, occurring in 2016. The human health benefits of such a switch are substantial: SO_2 emissions are reduced from the baseline (MATS (Mercury and Air Toxics Standard) retrofits by 2016) by more than 90%, and NO_X emissions by more than 60%, reducing total national annual health damages by \$20 – \$50 billion annually. While the effect on global temperatures is small out to 2040, the USA power plant fleet's contribution could be changed by as much as −50% to +5% depending on the rate of fugitive CH_4 emissions and efficiency of replacement gas plants.

1. Introduction

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

Recently, a growing body of research has questioned the ability of domestic natural gas to substantially reduce USA GHG (greenhouse gas) emissions. Natural gas power plants typically emit 50%–60% less carbon dioxide (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 sulfur dioxide (SO_2) and nitrogen oxides (NO_x), precursors of particulate matter. Natural gas also has lower primary emissions of particulate matter up to 2.5 μm in size ($PM_{2.5}$) and particulate matter up to 10 μm in size (PM_{10}) than coal. Exposure to $PM_{2.5}$ has been linked to human mortality and morbidity [10–14]. EPA regulations, including the CAIR (Clean Air Interstate Rule), the CSAPR (Cross-State Air Pollution Rule), and MATS (Mercury and Air Toxics Standard), are designed to reduce these emissions [14–16]. These regulations have been one cause of a switch from coal to natural gas plants [17,1].

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

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

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http://dx.doi.org/10.1016/j.energy.2016.03.078

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

We used U.S. DOE (Department of Energy) forecasts of emissions and generation as the baseline for our analysis. These forecasts include a significant reduction in SO_2 and NO_X emissions from existing coal plants from 2016 onward due to retrofits to comply with MATS. From this baseline, we replaced all coal plants with natural gas plants, starting in 2016. We then used two publicly available models to compute the health benefits of such a switch: the APEEP (Air Pollution Emission Experiments and Policy) model [20] and the EASIUR (Estimating Air pollution Social Impact Using Regression) model [21,22]. Using the GTP (Global Temperature Potential), we estimated how switching from coal to gas would affect the power plant fleet's contribution to global temperature until 2040, the last year for which EIA (Energy Information Agency) forecasts emissions and generation. We varied the fugitive methane emission rate from 0% to 7%, a range that includes estimates from existing literature [9].

2. Materials and methods

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

2.1. Calculation of baseline emissions

We developed baseline emission scenarios for 2016–2040 based on the forecasts from the DOE's EIA (Energy Information Agency) [23]. EIA forecasts installed capacity by plant type, electricity generation by fuel type, and total NO_X and SO_2 emissions from the electric power sector. These forecasts include the effects of existing policies, including CSAPR and MATS. We used the EIA's Reference scenario as our analysis baseline; we also consider the EIA's Low Oil and Gas Resource and High Oil and Gas Resource. Descriptions of each scenario are in Appendix C in the Supplementary material. We assumed that any switching from coal to gas not forecast by the EIA would be due to future policies, not market forces.

2.1.1. Baseline NO_X and SO_2 emissions

EIA forecasts total electric power NO_X and SO_2 emissions to 2040. It does not forecast emissions by fuel type. We therefore separated out the NO_X and SO_2 emissions associated with coal, oil, and gas plants. We first calculated NO_X and SO_2 emissions from oil and gas plants. We used plant-level emission data from the EPA AMPD (Air Market Program Database) to identify 2012 capacity-weighted average emission rates for oil and gas plants in 27 eastern states regulated by the EPA CAIR (Clean Air Interstate Rule) [24].

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

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

EIA does not forecast direct emissions of $PM_{2.5}$ and PM_{10} from power plants. We assumed that coal and oil plants emit 0.14 kg/MWh of $PM_{2.5}$ and PM_{10}, the limit imposed by the EPA's MATS [15]. Gas plants are not regulated by MATS, and therefore we used data from the 2005 NEI (National Emissions Inventory) [25] and eGRID 2005 [3] to identify gas plant $PM_{2.5}$ and PM_{10} combustion emissions rates. We found the capacity-weighted average emission rate of gas plants in the NEI database to be 0.06 kg/MWh for $PM_{2.5}$ and 0.07 kg/MWh for PM_{10}. For coal, oil and gas plants, we multiplied the assumed emission rates by EIA's forecast of annual electricity generation by each fuel.

2.1.3. Baseline greenhouse gas emissions

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

We calculated CH_4 emissions as the sum of combustion emissions and fugitive emissions from CH_4 production and transportation. Combustion CH_4 emissions for each fuel type are the capacity-weighted average CH_4 emission rates of plants in the EPA's eGRID (Emissions & Generation Resource Integrated Database), 2009. We parameterized the rate of fugitive CH_4 emissions in a range of 0–7%, covering estimates from existing literature [9]. We multiplied the fugitive rate by forecasts of total gas to calculate total fugitive CH_4 emissions. Total gas consumed was found by multiplying EIA's forecast of natural gas generation [23] by the capacity-weighted heat rate of existing gas plants in 2012 [3]. Other fugitive emissions (greenhouse gases, NO_x, SO_2, $PM_{2.5}$, PM_{10}) from the production and transportation of coal and natural gas did not qualitatively change our results and were excluded from the analysis. We did not include the coal life cycle emissions because the upstream emissions are only 5% of total GHG emissions of 96 g CO_2e/MJ, four times less than the overall uncertainty of the mean value [6].

2.2. Calculation of replacement plant emission rates

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

Scenario a) retired all coal plants and built new, high-efficiency NGCC (natural gas combined cycle) plants. New NGCC plants were assumed to have a heat rate of 5700 Btu/MWh achieved by state-of-the-art GE Flex-60 and Siemens Frame-H [26,27]. The CO_2 emission rate was calculated by multiplying the heat rate by the carbon content of natural gas. Other emission rates were assumed to be the load-weighted average emission rates of 450 existing NGCC plants, as identified by the EPA's National Electric Energy Data System [28]. This assumption somewhat overstates emission rates, as emission rates of new, high-efficiency NGCC will likely be lower than the existing NGCC fleet average. NO_X and SO_2 emission rates were based on 2012 emission rates (AMPD); CH_4 emission rates were from eGRID 2009; $PM_{2.5}$ and PM_{10} emission rates were based on NEI 2005.

Scenario b) retired all coal plants and built new natural gas plants with same heat rate and emission rates as the existing gas fleet's load-weighted average, considering both NGCC and combustion turbine plants. Heat rates, CO_2, NO_X and SO_2 emission rates were based on 2012 data (AMPD); CH_4 emission rates were from eGRID 2009; $PM_{2.5}$ and PM_{10} emission rates were based on NEI 2005. This scenario isolates the benefits of fuel switching from the benefits of switching to high-efficiency plants (scenario a). Load-weighted emission rates and load weighted heat rates were calculated as described in the Supplemental material.

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