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U.S. sulfur dioxide emission reductions: Shifting factors and a carbon dioxide penalty

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ABSTRACT

For more than 20 years, the large-scale application of flue gas desulfurization technology has been a dominant cause of SO_2 emission reductions. From 1994–2004, electricity generation from coal increased, but the shift to low-sulfur coal eclipsed this. From 2004–2014, electricity generation from coal decreased, but a shift to higher-sulfur subbituminous and lignite coal overshadowed this. The shift in coal quality has also created a CO_2 emissions penalty, representing 2% of the sector's total emissions in 2014.

1. Introduction

The power sector is responsible for 64% of the sulfur dioxide (SO_2) emitted in the United States, damaging human health, ecosystems, crop and timber production, and the built environment. The estimated cost of SO_2 pollution from power generation in the United States ranges from $71 to $223 billion per year (NRC, 2010; Muller et al., 2011; Muller and Mendelsohn, 2007; Jaramillo and Muller, 2016).

Over the last two decades, SO_2 emissions from the U.S. electric power sector have declined sharply, even as electricity generation has increased (Fig. 1). From 1994 to 2004, the focus of this analysis, SO_2 emissions decreased by 11.7 million tons/year (a 79% decline) (EPA, 2016; EIA, 2016a).

The factors contributing to these reductions have evolved over time, and the pace of emission reductions has been variable. Prior research has highlighted the impact of various shifts in market conditions and technologies, highlighting the role of an aging and inefficient coal fleet, the increasingly expensive cost of building new coal plants and rising coal prices, advancements in technology such as flue gas desulfurization (FGD) pollution controls, the low cost of natural gas and falling costs of renewables, and sluggish electricity demand growth, particularly after the economic downturn of 2008. Policies have also evolved, including the 1990 Clean Air Act Amendments that set limits on SO_2 and NO_x gases from power plants, renewable portfolio standards, federal energy efficiency standards on end-use equipment, and much more (e.g., Culver and Hong, 2016; Fleischman et al., 2013; Tierney, 2012; Chan et al., 2015).

In this article, we use decomposition analysis to estimate the impact of a range of engineering factors that influence SO_2 emissions from the electricity sector and that are driven by these market, policy, and technology shifts. Decomposition analysis has become a commonly accepted method of understanding the factors contributing to carbon emissions since it was first proposed by Kaya (1990) at a workshop of the Intergovernmental Panel on Climate Change (IPCC, 2001). The Kaya identity included three factors: energy intensity, GDP, and population growth. Decomposition analysis has also been used in two recent papers to examine air pollution from Chinese industry. Fujii et al. (2013) examined five indicators of air pollution from 10 industrial sectors, focusing on end-of-pipe treatment, coal pollution intensity, the energy mix, proactive efficiency, and production scale change. In turn, Yao et al. (2016), examined three factors impacting air pollution from Chinese industry: engineering emission reduction, structure emission reduction, and supervision emission reduction.

Our analysis is the first application of decomposition analysis to SO_2 emissions from the U.S. electricity industry. In particular, we evaluate five factors that have historically impacted SO_2 emissions from coal-fired power plants, examining their influence over the past two decades using decomposition analysis. These factors are the amount of electricity generated by coal plants, the sulfur and heat content of the coal burned, the heat rate of electricity generation from coal, and the use of FGD pollution controls. We

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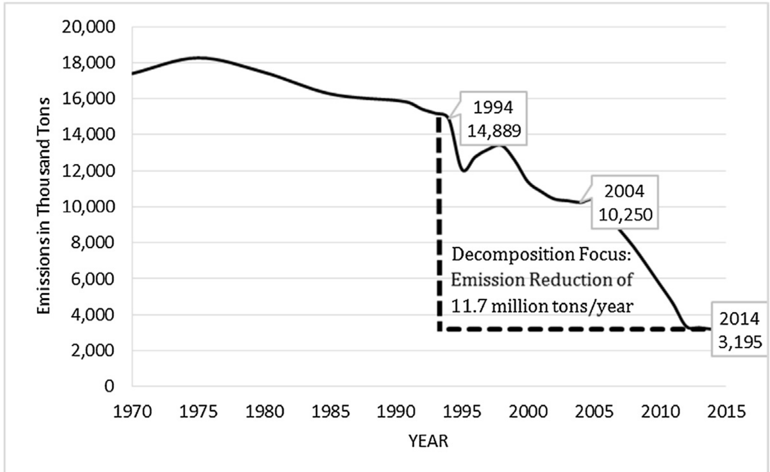

Fig. 1. 1970–2014 SO_2 emissions from electric utilities[1] (EIA, 2015a, 2015b).

focus on the 1994–2014 period (Fig. 1), and we uncover the dynamics across this period by examining each of the two decades separately.

2. Methodology and data sources

The attribution of SO_2 emissions to different drivers can be evaluated by the following identity:

$$SO_2 = G * \left(\frac{SO_2}{S}\right) * \left[\left(\frac{S}{Coal}\right) / \left(\frac{E_{coal}}{Coal}\right)\right] * \left(\frac{E_{coal}}{G}\right) * (1 - FGD)$$

From this identity, the puzzle of SO_2 emissions reduction can be solved by illustrating the magnitude and direction of the change precipitated by each factor. Specifically, SO_2 emissions are decomposed using the following factors: total power generation (G), the sulfur content of coal (S/Coal), the heat content of coal (E_{coal}/Coal), the heat rate of coal (E_{coal}/G), and the fraction of emissions after FGD. The identity also includes a combustion factor for sulfur (SO_2/S). By assuming that all sulfur goes into sulfur emissions after combustion, the SO_2/S value is a constant, 1.998, defined by the ratio of the molecular weight of SO2 to the atomic weight of S.[2] For each of the factors, we use the natural log of the change in emissions over these two decades to simplify the analysis.[3]

These different components are described in greater detail in Table 1. This decomposition allows for attribution of the change in SO_2 emissions to each component driver and the factors contributing most to the decline in SO_2 emissions.

3. Contributing factors and trends over the past 20 years

The five factors can be grouped into three categories: plant performance (generation and heat rate), coal quality (sulfur content and heat content), and emission control (desulfurization technology). Each is described below.

3.1. Plant performance: electricity generation and heat rate

While total electricity generation has increased over the past two decades, the electricity generated by coal plants peaked in 2007, and then declined over the subsequent decade (Fig. 2). The overall reduction in coal generation over the two decades declined 7% from approximately 1700 million MWh in 1994–1580 million MWh in 2004.

From 1994 to 2014, total U.S. electricity generation increased while the percent of generation from coal declined slightly. Through 2004, coal accounted for about 50% of total U.S. electricity generation, but by 2014, the contribution of electricity generated from coal had declined to 40%. Over this last decade, natural gas and renewables became more prevalent, which has contributed to SO_2 emission reductions in the most recent decade.

The thermal efficiency of electricity generation is measured by the heat rate, or the amount of thermal energy used to generate one kilowatt-hour of electricity, measured in British thermal units per kilowatt-hour (Btu/kWh).[4] A generator with a lower heat rate can generate the same quantity of electricity while consuming less fuel, compared to a unit with higher heat rate (EIA, 2015a). Heat rates depend in part on the type of equipment installed at a generating plant and can vary substantially across fuel and technology types. For example, in 2012 generators primarily powered by coal-fired boilers had heat rates ranging from 8800 Btu/kWh to 25,000 Btu/kWh (EIA, 2015b). A typical heat rate for a coal-fired power plant is around 10,400 Btu/kWh. The average national heat rate of coal plants has increased by 1.8% over the past two decades, rising from 10.2 thousand Btu/kWh in 1994 to about 10.4 thousand Btu/kWh in 2014. Thus, coal plants are operating about 2% less efficiently today compared with 20 years ago, leading to a slight upward pressure on SO_2 emissions. This trend is reasonable considering the fact that electricity generation technologies used by coal plants are mature and stable. Other contributors are the implementation of environmental control equipment, existing power plants degradation with relatively few

[1] Prior to 1994, SO_2 emissions were estimated rather than aggregated from facility-level reporting. According to Title IV (Acid Deposition Control) of the Clean Air Act Amendments of 1990 (CAAA) published in January 1994, utility units are required to report SO_2 data to EPA. Beginning Jan. 1, 1995, all affected units were required to report heat input and SO_2 emissions. This change contributed to the "kink" in the curve between 1994 and 1995.

[2] SO_2/S is also called the sulfur retention ratio. It is a function of the fraction of sulfur in the coal that ends up in coal ash after combustion and the relative atomic weight of SO_2 to S. The former varies from 0% to about 10% resulting from the varying composition and quality of coal, along with the operational conditions of plants (Goodarzi, 2006; Sheng et al., 2000).

[3] For example, each factor's contribution over the two decades is calculated as: $\frac{\Delta S}{\ln(S_{2014}/S_{1994})}\ln\left(\frac{F_{2014}}{F_{1994}}\right) = emissionsreductionresultingfromachangeinfactorF\left\langle /en \right\rangle$

[4] The heat rate is inversely proportional to the thermal efficiency of electricity generation. To express the efficiency of a generator as a percentage, divide the Btu content of a kilowatt-hour of electricity (which is 3412 Btu) by the heat rate. For example, the thermal efficiency of generator with a heat rate of 10,400 Btu/kWh is equal to 3412/10,400 = 32.8%.