THE PLUME:

A VALUATION OF SULFUR DIOXIDE EMISSIONS FROM THE MARTIN DRAKE POWER PLANT

A Thesis

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THE PLUME:
A VALUATION OF SULFUR DIOXIDE EMISSIONS FROM THE MARTIN DRAKE POWER PLANT

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Mathematical Economics

Abstract:

This thesis examines sulfur dioxide (SO_2) emissions from the Martin Drake coal-fired power plant in downtown Colorado Springs and quantifies the resulting negative public health impact on local residents. This paper utilizes an ordinary least squares regression with White standard errors to model the impact of the plant's SO_2 emissions on ambient surface-level SO_2 concentrations using daily emissions, concentration and weather data from 2014 to 2017. The resulting public health response is estimated using established correlations of SO_2 concentration and all-cause mortality rate. The mortality rate impact is subsequently priced using the statistical value of a life, thus quantifying the negative externality of the plant's SO_2 emissions. This paper finds that accelerating decommissioning of the Drake plant by 10 years (to 2025 rather than 2035) would avoid 1.517 premature deaths and generate a net present value public health benefit of $9,183,312 from the SO_2 emission reduction alone.

KEYWORDS: (SO_2, Electricity, Coal, Air Quality, Pollution)

JEL CODES: D62, K32, L94, Q35, Q51, Q53

ON MY HONOR, I HAVE NEITHER GIVEN NOR RECEIVED ANY

UNAUTHORIZED AID ON THIS THESIS.

________John Higham___________

Signature

LIST OF UNITS AND ABBREVIATIONS

AMPD – EPA Air Markets Program Data
AQBAT – Air Quality Benefits Assessment Tool
CDPHE – Colorado Department of Public Health and Environment
CO – Carbon monoxide
CO_2 – Carbon dioxide
CSU – Colorado Springs Utilities
EIRP – Electric Integrated Resource Plan
FROI – Financial Return on Investment
Hg – Mercury
MMBtu – One million British thermal units, imperial unit of energy
MSA – Metropolitan Statistical Area
MW – Megawatt, SI unit of power
MWh – Megawatt hour, SI unit of energy
NAAQS – National Ambient Air Quality Standard
ng/m^3 – Nanograms per meter cubed, SI unit of concentration
NO – Nitric oxide
NO_2 – Nitrogen dioxide
NO_x – The combination of NO and NO_2
NPV – Net present value
O_3 – Ozone
OLS – Ordinary least squares
Pb – Lead
PM – Particulate matter, includes $PM_{2.5}$ and PM_{10}
$PM_{2.5}$ – Particulate matter with a diameter less than 2.5 µm
PM_{10} – Particulate matter with a diameter between 2.5 and 10 µm
ppb – parts per billion
SO_2 – Sulfur dioxide
SROI – Sustainable Return on Investment
µg/m^3 – Micrograms per meter cubed, unit of concentration
µm – Micrometer, one millionth of a meter
VIF – Variance Inflation Factor
VSL – Valuation of a statistical life

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Introduction

Colorado Springs Utilities (henceforth “CSU”) is a publicly owned utility company that serves the greater Pikes Peak region with electricity, gas, water, and wastewater service. Since 1962, CSU has owned and operated the Martin Drake power plant, a large coal-fired steam turbine power plant in downtown Colorado Springs. In recent years, the plant has generated controversy within the city due to its contribution to local air pollution. However, estimates of the actual economic impact of the plant’s air pollution vary greatly. Internal CSU reports and third party studies have investigated the plant’s emissions, but due to various methodological differences these reports have generated vastly different conclusions.

Due to these discrepancies and the perceived difficulties in accurately quantifying the public health impacts, the Colorado Springs City Council, in their acting role as the CSU Board of Directors, ordered CSU not to price public health impacts in their 2016 Electric Integrated Resource Plan (EIRP). While public health impacts were discussed qualitatively in the report, the actual extent of the health risks remains unknown. Without thorough analysis from CSU, the debate over the severity of the plant’s air pollution remains unsettled while the plant continues to operate and pollute. This paper improves upon the methodology of previous studies by calculating a conservative and economically sound approximation of the public health externalities of the Drake plant’s SO_2 emissions.

Background

CSU Generation Portfolio:

CSU's electricity division currently provides 4.58 million MWh to 221,796 active meters each year. With a generation portfolio comprised almost entirely of base-load resources[1] and a reserve margin[2] above 20%, CSU performs consistently as one of the most reliable electricity providers in the country, with power available over 99.99% of the year and the fastest median outage response time in the nation (Colorado Springs Utilities [CSU], n.d.). CSU's generating resources and power purchase contracts are listed below in Tables 1 and 2.

Table 1: CSU Generating Resources

Generation	Summer Capacity (MW)	Winter Capacity (MW)	Unit Type	Primary Fuel
Ruxton	1	0	Conventional Hydro	
Manitou 1	2.5	2.5	Conventional Hydro	
Manitou 2	2.5	2.5	Conventional Hydro	
Manitou 3	0.46	0.46	Conventional Hydro	
Tesla Hydro	28	28	Ponded Hydro	
Cascade	0.85	0.85	Conventional Hydro	
Birdsall 1	16	16	Steam Turbine	Natural Gas
Birdsall 2	16	16	Steam Turbine	Natural Gas
Birdsall 3	23	23	Steam Turbine	Natural Gas
Drake 5	46	46	Steam Turbine	Coal
Drake 6	77	77	Steam Turbine	Coal
Drake 7	131	131	Steam Turbine	Coal
Nixon 1	208	208	Steam Turbine	Coal
Nixon 2	30	32	Combustion Turbine	Natural Gas
Nixon 3	30	32	Combustion Turbine	Natural Gas
Front Range	460	480	Combined Cycle	Natural Gas
Total	1,026.31	1,049.31		

Source: (CSU, 2016). Note: The Drake 5 unit is listed in red because it was decommissioned in early 2017. Its capacity is excluded from totals.

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[1] Base-load resources, in contrast to variable resources, are able to generate power whenever needed, regardless of time of day or weather conditions.

[2] Reserve margin is defined as the difference between capacity and peak demand divided by peak demand. It is a commonly used measure of reliability.

Table 2: Power Purchase Agreement Contracts

Purchases	Summer Capacity (MW)	Winter Capacity (MW)	Commission Year
Wind - Western – LAP	61	57	
Wind - Western - SLCA/IP	15	60	
Solar – Air Force Academy	5.25	5.25	2011
Solar – CSG Pilot	2	2	2011, 2012, 2015
Solar – CSG Tariff	2	2	2015
Solar - Clear Springs Site	10	10	
Total Purchases	95.25	136.25	

Source: (CSU, 2016). Note: CSG = community solar garden.

It should be noted that the Drake 5 unit did not operate after March of 2016 and was permanently decommissioned in early 2017. The plant was decommissioned due to public opposition and the costly SO_2 pollution controls (scrubbers) that were mandated the Regional Haze State Implementation Plan as of January 1, 2018. The 2016 EIRP recommended that the plant be converted to a natural gas plant and used primarily as a peaking unit[3] beginning in 2018, thereby avoiding the scrubber installation (CSU, 2016). However, subsequent analysis demonstrated that the additional peaking capacity would not be needed for at least ten years and decommissioning early would generate net present value savings of $2 million. CSU has also since finalized a 10 MW power purchase agreement with a utility-scale solar array at their Clear Springs Ranch site and is moving forward with a plan to integrate 95 MW of solar generation by 2020.

Coal Pollution Overview:

There are a number of ways a coal-fired power plant can negatively impact public health through its emissions. Combustion of coal releases dozens of harmful pollutants[4]

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[3] Peaking units are utilized on an as-needed basis to meet short demand peaks, and are not designed to operate around the clock. These units are most commonly natural gas plants and storage systems such as pumped hydroelectric or batteries.

[4] Carbon dioxide (CO2) is also released by coal combustion, but it is not included in this list because the EPA does not currently regulate it as a pollutant.

including sulfur dioxide (SO_2), nitrogen oxides (NO_x, or a combination of NO and NO_2), particulate matter (PM_{10} and $PM_{2.5}$ depending on particle size), mercury (Hg), lead (Pb), cadmium (Cd), carbon monoxide (CO), Arsenic (As), volatile organic compounds (VOC's), and other toxic heavy metals. All of these chemicals harm human health to varying degrees, and all are released by coal power plants in varying concentrations. $PM_{2.5}$ has many severe health implications because the small size of the particles allows the pollution to pass through the immune system's defenses and lodge deeply in the lower respiratory system. Among other serious illnesses, $PM_{2.5}$ has been linked to lung cancer, heart disease, heart attack, and decreased pulmonary function (Schwarze et al., 2016; Atkinson, Kang, Anderson, Mills, & Walton, 2014). SO_2 pollution has been shown to cause decreased lung function, difficulty breathing (Environmental Protection Agency [EPA], 2016a), increased blood pressure, and decreased heart rate (Campbell et al. 2007). NO_2 can cause decreased lung function, exacerbate asthma and other lung conditions, and increase the risk of pulmonary infection (EPA, 2016b). In addition to the health effects of gaseous SO_2 and NO_x, these compounds can also contribute to $PM_{2.5}$ pollution as they react with chemicals in the upper atmosphere and precipitate as sulfate and nitrate particles. SO_2, NO_2, and $PM_{2.5}$ have all been shown through epidemiological studies to contribute to all-cause mortality rates (Campbell et al. 2007).

Drake Pollution Overview:

As a coal-fired power plant, Martin Drake generates and emits all of the harmful pollutants described above, but the plant utilizes several pollution controls that reduce the degree of air pollution. Drake operates soot-removing baghouses that remove 99.8 percent of fly ash (removes nearly all PM_{10}, $PM_{2.5}$ and Hg from emissions) and overair fire ultra low NO_x burners that remove 83 percent of NO_x emissions (CSU, 2017). The plant is designated as a low mercury emitter due to its halogenated PAC sorbent injection mercury control units. As of 2016, the plant operates advanced dual alkali burner SO_2 scrubbers, which according to their now-defunct designer Neumann Systems, capture up to 99 percent of SO_2 emissions. The actual efficacy of the scrubbers is discussed at length in the Analysis section of this paper, but as it stands, the scrubbers have not yet performed consistently at those levels.

Literature Review

CSU Internal Analysis

2016 Electric Integrated Resource Plan. In order to qualify for federal hydroelectric power purchase agreements, CSU is required to prepare and publish a comprehensive Electric Integrated Resource Plan (EIRP) every five years. CSU's most recent EIRP, approved in 2016, synthesizes cost-benefit analysis with ratepayer preferences to provide a detailed path to reliably and safely meet future electricity demand. However, following direction from the Colorado Springs City Council, CSU did not quantify any public health impacts and instead considered them holistically as "intangible" consequences of electricity generation.

In the report, CSU analyzed nine potential resource portfolios under 85 probabilistically weighted scenarios to rank them according to three criteria: cost[5], financial risk, and intangible considerations. Cost summarized expected net present value (NPV) revenue requirements for a given scenario. Financial risk considered the 95th percentile NPV revenue requirements under the 85 different scenarios. The intangible considerations included categories such as consumer resource preference, dispatchability, and societal benefits. All public health impacts were relegated to a subset of the societal benefits category, which itself accounted for a total of 1.8% of the overall weighted decision matrix. As a result, the EIRP drastically undervalued the negative externalities of the Drake plant's air pollution.

Pricing air pollution is not required in an EIRP, and it is not even standard industry practice. But while it is understandable why private utility companies might forgo internal pricing of air pollution, it is curious why a municipal utility would do the same. For while

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[5] The cost consideration was divided into two categories, one under the impending regulations of the EPA's Clean Power Plan (CPP) and one assuming the CPP would not take effect. The CPP was later permanently canceled by the EPA under the Trump administration.

some externalities such as carbon dioxide distribute globally, air pollution primarily impacts the local area and its residents. Therefore, for a public utility, these externalities fall on the utility's owners (and the city council's constituents) and are therefore closer to internal costs than true externalities. For this reason, it is indeed in CSU's best interest to analyze the extent to which its power plants contribute to local air pollution.

Previous Analysis of Drake Public Health Impacts. In 2013, CSU commissioned a report from HDR Engineering on the environmental and public health impacts of the Drake plant as well as options for decommissioning timelines. The report (HDR Inc. & CSU, 2013) analyzed a broad assortment of impacts related to the operation of the plant, including criteria pollutant emissions, carbon emissions, water consumption, by-product landfilling, highway and rail traffic, and land degradation. Analysis of these external impacts combined with traditional financial considerations allowed the authors to calculate both sustainable return on investment (SROI) and financial return on investment (FROI) figures for different decommissioning scenarios. The report concluded that a 2019 decommissioning produced the highest SROI while a 2043 decommissioning yielded the highest FROI.

However, the pollution analysis relied on a questionable assumption that likely induced considerable bias to the findings. For all criteria pollutant emissions, the authors did not analyze impacts on ambient concentrations but instead applied generalized cost-per-ton values for pollutants emitted in an urban environment, as estimated by previous studies. While this approach greatly simplifies the analysis, it overlooks the factors of physical geography, weather patterns, and population density that determine the actual concentrations that a population will encounter. Since the exact sources of these approximations were not cited, it is difficult to know the types of urban environments the values refer to. Regardless, considering the relatively sparse population density[6] of Colorado Springs, it does not make sense to analyze it alongside cities with substantially more dense populations. By overlooking this discrepancy, the authors almost certainly overestimated the public health impact of the Drake plant's air pollution.

Those inflated air pollution costs, as well as the inclusion of a social cost of carbon, produced figures of Drake's annual health and environmental externalities in the hundreds of millions of dollars. According to Katie Hardman, principal engineer of energy resource planning at CSU and the project lead for the 2016 EIRP, these massive external cost estimates drew pushback from city council members, who at the time were largely skeptical of anthropogenic climate change and generally supportive of the Drake plant (Katie Hardman, personal communication, February 27, 2018). This reason is likely why the city council instructed Hardman and her team to forgo pricing of externalities in their report.

Sulfur Dioxide Compliance and Attainment

Regulatory Framework. The 1963 Clean Air Act designates six criteria pollutants (SO_2, NO_2, PM, O_3, CO, and Pb) which are regulated by the EPA through National Ambient Air Quality Standards (NAAQS). These standards mandate upper limits on the allowable surface level concentrations of each individual pollutant and prohibit large point-source polluters from contributing to ambient air concentrations that violate the limits. Colorado Springs is currently in attainment (i.e. not in violation) with all of the NAAQS other than SO_2, for which it maintains an "unclassifiable" designation. It is for this reason that the majority of the research on the Drake plant centers around its SO_2 emissions. The EPA's unclassifiable

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[6] For reference: In 2010, the Colorado Springs metropolitan statistical area (MSA) was the 656th most densely populated MSA in the United States, with a population density of 2,140.6 people per square mile. The top 21 most densely populated MSA's all had at least 5 times the density of Colorado Springs, and the top 174 most densely populated MSA's all had more than twice the population density of Colorado Springs (U.S. Census Bureau, 2010).

designation does not necessarily preclude that the area is in attainment, but merely that there has not been conclusive analysis of the SO_2 concentrations. The current standard for SO_2 is as follows: as of 2010, the yearly 99th percentile of daily maximum 1-hour SO_2 concentrations, averaged over 3 years, must not exceed 75 parts per billion (ppb)[7] (EPA 2016c).

There are generally two ways in which attainment can be definitively demonstrated or refuted. The technique known as monitoring uses data from air quality probes to connect emission levels with actual concentrations at ground level. However since many pollutants disperse unevenly, this technique requires many different monitoring stations throughout an area, each constantly measuring air quality on 5-minute intervals. Monitoring was once the gold standard of compliance testing, but has fallen out of favor in recent years due to the prohibitive costs of operating sufficient monitoring stations. Modeling is a newer approach that uses computer software to simulate pollution dispersion using emissions, plant characteristics, meteorological data, and area geography. Because it is simulated, this technique does not guarantee completely accurate concentrations, but it describes far more detail about pollution dispersion than monitoring does.

The Colorado Department of Public Health and Environment (CDPHE) and the EPA both maintain that the Drake plant is the only significant point source of SO_2 emissions affecting the greater Colorado Springs area and therefore testing attainment status only requires modeling of Drake's SO_2 emissions and the underlying background concentration. The Nixon 1 plant also emits considerable amounts of SO_2, but due to its distance from the city, it does not significantly impact local air quality (Colorado Department of Public Health and Environment [CDPHE], 2017). For this reason, Nixon 1 emissions are not analyzed in this paper.

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[7] There also exists a secondary limit on maximum 3-hour average concentrations but since the secondary standard is far less stringent than the primary standard, it is not discussed in this paper.

Attainment Studies. Two recent studies published by the Sierra Club and CSU modeled the emissions of the Drake plant, but neither has definitively proven attainment or non-attainment. The Sierra Club's report (Sierra Club, Wingra Engineering, & Klafka, 2012) analyzed 2010 SO_2 output and five years of weather data from the Colorado Springs Airport. Their dispersion model predicted that nearly all of Colorado Springs was in violation of the NAAQS, with areas in the Broadmoor hills showing SO_2 concentrations of up to 18 times the NAAQS. In order to establish a more conservative argument, the Sierra Club report also modeled the dispersion of Drake emissions when operating at the EPA's maximum allowable emission rate of 428.1 lbs/hr. The resulting simulation indicated that even if Drake were to pollute below the allowable rate, it would still produce NAAQS violations in several areas west of town.

CSU officials along with the EPA and CDPHE rejected the Sierra Club report because the meteorological data was taken from the Colorado Springs Airport rather than on site (Anleu, 2016). This data was the most representative sample available at the time, but it was a large enough issue to invalidate the conclusions. In response to this concern, and the city's continued unclassifiable designation, the EPA ordered CSU to begin collecting on-site meteorological data so that more conclusive modeling could be performed.

A 2017 study published by CSU (Samani, Paine, Damiana, & AECOM Engineering, 2017) analyzed dispersion patterns using real on-site meteorological data collected from November 2015 to January 2017. This study analyzed a theoretical emissions limit based on new regulations of the Colorado Regional Haze State Implementation Plan. The new regulation, which went into effect January 1, 2018, requires that the plant's 30-day rolling average SO_2 emission rate not exceed 0.13 lb/MMBtu[8]. The resulting simulation showed the

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[8] For reference, the Drake plant's actual emission rate for February through October 2017 was 0.032 lbs/MMBtu (Energy Information Administration, 2018). Data for November and December 2017 is not yet available.

entire region in compliance with the NAAQS, with a maximum concentration of 36.66 ppb. Following this analysis, the CDPHE recommended that the EPA redesignate Colorado Springs as in attainment of the SO_2 NAAQS (CDPHE 2017). Regardless, though the exact reasons are unclear, the EPA declined to redesignate the area during its November 2017 hearing, and Colorado Springs maintains its unclassifiable designation (EPA 2018c).

Drake Mercury Emissions

Colorado College professor Lynne Gratz is currently conducting research into Drake's mercury emissions in collaboration with the CDPHE, and she graciously provided the author of this paper with a copy of the preliminary report (Gratz, Laufman, & Mattson, 2017). Because of the ongoing nature of this research, discussion of this work should not be interpreted as conclusive. The study used 8 weeks of privately collected 5-minute Hg and CO_2 concentration data and publicly reported 5-minute SO_2 and CO concentration data, all from the existing CDPHE Highway 24 monitoring site, to isolate the Drake plant's contributions to ambient surface level Hg concentrations. The observed Hg concentrations had a mean of 1.71 ng/m^3, not dissimilar from the northern hemisphere background Hg concentration range of 1.3 – 1.7 ng/m^3. The observed Hg concentrations do not correlate with the SO_2 concentrations as would be expected if the Drake plant (which is the largest SO_2 point source in the region) were the source of Hg concentration variance. Instead, the Hg concentrations appear to correlate with CO_2 concentrations, meteorological data, and local construction activities, indicating a possible link to soil evasion of legacy Hg. Though inconclusive at this time, the preliminary findings suggest that the Drake plant is not a significant contributor to ambient Hg concentrations in Colorado Springs. For this reason, and the unavailability of Hg concentration data, quantitative analysis of the Drake plant's mercury emissions is excluded from this paper.

Air Pollution Health Impact Evaluation:

Valuation of Health Outcomes. In order to price public health impacts, it is necessary to establish a clear and consistent mechanism of health outcome valuation. For non-fatal morbidity outcomes, these figures draw primarily from healthcare costs and willingness to pay studies. Healthcare costs reflect actual spending required to treat various medical outcomes while willingness-to-pay data approximates the negative value that individuals attribute to the suffering that accompanies those medical outcomes. Valuation of mortality depends on the value of a statistical life (VSL). The most common method of VSL calculation is the revealed preference wage hedonic approach that looks at the wage premium required for people to perform hazardous jobs. By connecting those wage premiums to the corresponding mortality risks, economists can calculate a population's revealed value of its own lives.

Mortality and morbidity valuation figures vary widely across studies, but in general, values for mortality dwarf those of any non-fatal outcomes. For this reason, this paper strictly analyzes the effects of SO_2 pollution on premature mortality. Excluding all other health outcomes simplifies the paper's analysis and contributes to a more conservative estimation of the externality. To value mortality outcomes, this paper uses the figure of $4.8 million (1990 dollars) that the EPA recommends. Adjusting for inflation, that figure translates to $8,989,845 (2017 dollars). In order to calculate NPV of future mortality, this paper utilizes a 3% discount rate as an approximation of the social rate of time preference, as recommended by the EPA (EPA, 2012).

Pollution Epidemiological Research. Because of the near ubiquity of air quality concerns in cities throughout the world, there exists an extensive body of epidemiological research on the public health impacts of criteria air pollutants. These studies use mathematical models to connect changes in different pollution concentrations with changes in health outcomes in a given area over time, thereby isolating the impacts of individual pollutants on various morbidity and mortality rates.

One such study (Burnett et al. 2004) performed a cross-sectional time series regression over 19 years in 12 major Canadian cities and found statistically significant correlations between non-accidental daily mortality and concentrations of SO_2, NO_2, CO, O_3, SO_4 and PM. The results of this study and several others (Burnett, Dales, Brook, Raizenne, & Krewski, 1997; Schwartz and Morris, 1995; Krupnick, Harrington, & Ostro, 1990; Abbey et al. 1995; Ostro, Lipsett, Wiener, & Selner, 1991; Burnett et al. 1995; Dockery et al. 1996; Stieb et al. 2000; Pope, Brook, Burnett, & Dockery, 2010) were subsequently used by Health Canada to construct a modeling software called the Air Quality Benefits Assessment Tool (AQBAT) (Judek, Stieb, & Jovic, 2006), designed to allow other Canadian cities to analyze public health impacts of variable air quality (Alrafea, Elkamel, & Abdul-Wahab, 2016). The AQBAT uses mortality risk coefficients of 0.046% per ppb for SO_2, 0.68% per $\mu g/m^3$ for $PM_{2.5}$, and 0.075% per ppb for NO_2 (Alrafea et al. 2016).

A similar study (Katsouyanni et al. 1997) looked at the mortality impacts of SO_2 and PM_{10} in 12 European cities and found risk coefficients of 0.06% per $\mu g/m^3$ for SO_2 and 0.04% per $\mu g/m^3$ for PM_{10}. There is no direct conversion factor for $\mu g/m^3$ to ppb, but using the average ambient temperature and average barometric pressure of Colorado Springs, the author calculated a conversion ratio of 0.36062 ppb per $\mu g/m^3$ (see Appendix B for calculations). Applying this conversion ratio, the figure for SO_2 becomes 0.1664% per ppb.

There have been no similar epidemiological studies on SO_2 mortality impacts in the United States, but there have been two studies (Krewski et al. 2009; Lepeule, Laden, Dockery, & Schwartz, 2012) on $PM_{2.5}$ mortality. Krewski et al. and Lepeule et al. calculated $PM_{2.5}$ all-cause mortality risk coefficients of 0.5827% per $\mu g/m^3$ and 1.3103% per $\mu g/m^3$ respectively. These figures for United States $PM_{2.5}$ mortality are consistent with the corresponding figure for Canada (0.68% per $\mu g/m^3$) as estimated by the AQBAT. While acknowledging the potential estimation bias that it may cause, this paper uses that similarity between US and Canadian $PM_{2.5}$ concentration mortality response to support the use of the AQBAT SO_2 mortality coefficient in analyzing SO_2 concentration response in Colorado Springs. Without a comprehensive SO_2 mortality study in the United States, the AQBAT coefficient is the best available estimator for SO_2 mortality in this study.

Data

Colorado Springs has had 18 air quality monitors measuring various criteria pollution concentrations within the city over the last few decades, but most have since been shut down. Currently there are only two EPA certified monitoring stations operating in Colorado Springs. One site near Highway 24 measures SO_2 and CO concentrations, and another site on the Colorado College campus measures $PM_{2.5}$ and PM_{10} concentrations (see Figure 1 for map). The Highway 24 site measures pollution concentrations as well as wind direction, wind speed, outdoor temperature and relative humidity in 5-minute increments, dating back to August 2014[9]. The Colorado College site monitors 1-hour $PM_{2.5}$ concentrations every day and 24-hour PM_{10} concentrations every third day. It also collected ambient temperature and ambient pressure data every third day but only until June 2016. All of this data is reported to the EPA and published in the EPA's AirData database (EPA, 2018a). Comprehensive hourly reports of the Drake plant's operations, including SO_2 emissions, NO_x emissions, and gross load are available from the EPA Air Markets Program Data (AMPD) dating back to 1980 (EPA, 2018b). The U.S. Energy Information Administration (EIA) publishes EIA-923 forms that report monthly fuel consumption, power output, and fuel sulfur content for all conventional generating units in the United States (EIA, 2018).

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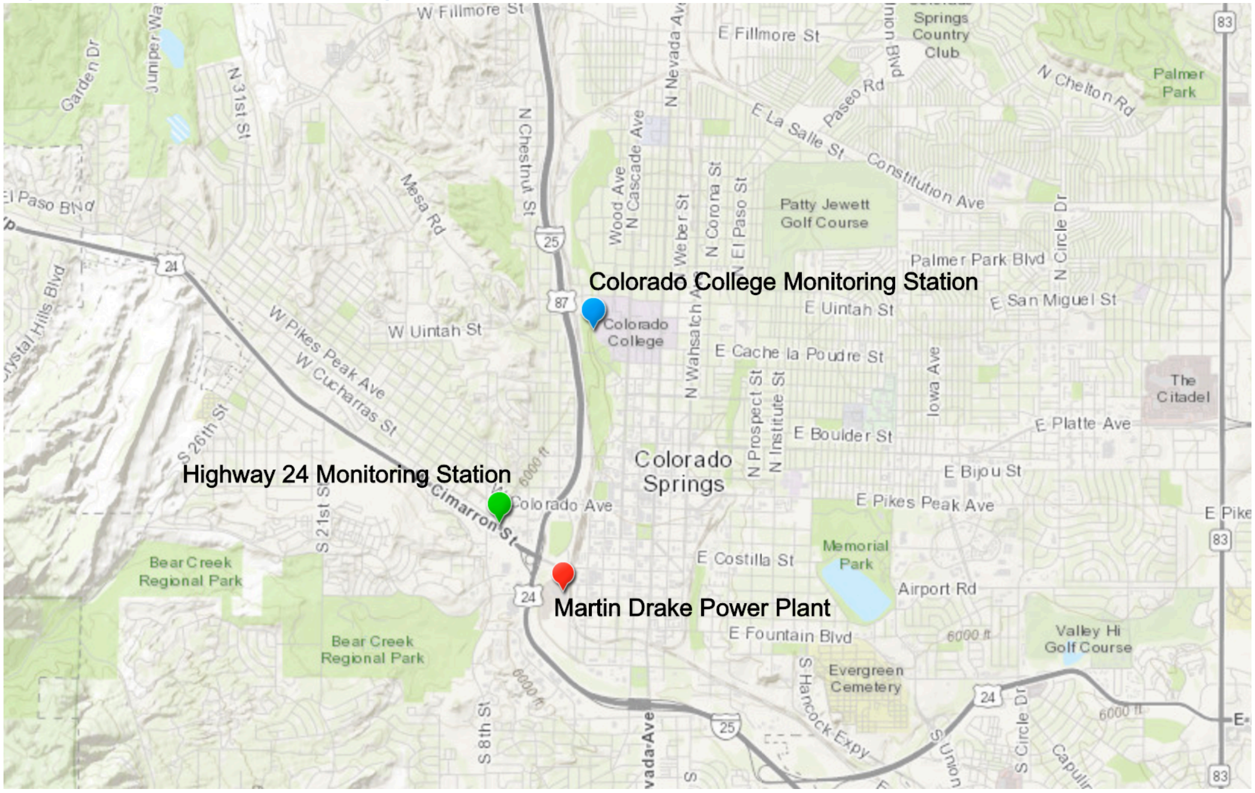
[9] The site began reporting SO_2 and CO data in 2013, but meteorological data reporting did not begin until August 13, 2014.

Figure 1: Location of Monitoring Stations and Drake Plant



Source: Primary, made with ESRI ArcGIS.

Methodology

This paper uses daily Drake SO_2 and NO_x output data and daily monitored pollution concentration data to establish a correlation between pollution output and ambient pollution concentrations, thereby allowing an estimation of the background concentrations that would persist if Drake were decommissioned. The regression model is as follows:

$$PC = \beta_1 P + \beta_2 WD + \beta_3 AT + \beta_4 AH + \beta_5 WS + \sum_{i=6}^{25} (\beta_i DV_i) + \alpha \qquad (5.1)$$

Where:

PC = Average daily ambient pollution concentration (ppb)

P = Daily pollutant emission from Drake plant (tons)

WD = Wind deviation (absolute value of difference in compass degrees between average wind direction and the compass direction of the Drake plant)

AT = Average temperature (degrees Fahrenheit)

AH = Average humidity (percent)

WS = Average resultant wind speed (knots)

DV_i = Binary dummy variables for year, month, and day of week

α = Constant

Once the regression equation is established, the potential change in ambient pollution concentration (ΔPC) is estimated by calculating the change in PC that occurs when P decreases to zero from a baseline output. The paper then uses mortality risk coefficients from the existing epidemiological literature to approximate the impact that the Drake plant has on all-cause mortality in Colorado Springs. The equation of this process is as follows:

$$N = MR * RC * \Delta PC * POP \quad (5.2)$$ [10]

Where:

N = Number of additional premature deaths

MR = Annual all-cause mortality rate

RC = Risk coefficient (percent change in MR per unit ΔPC)

ΔPC = Change in ambient pollution concentration

POP = Population

The resulting estimation of additional premature deaths is subsequently translated into dollar values using the EPA's recommended VSL. Discounting those approximated costs of future deaths using the EPA's recommended discount rate yields an estimate of the 2017 NPV of the Drake plant's air pollution externalities.

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[10] Model source: (Alrafea et al., 2016).

Results

Particulate Matter Modeling

Because of its advanced baghouse PM controls, the Drake plant emits minimal primary PM. However, since emissions of gaseous SO_2 and NO_x can contribute to $PM_{2.5}$, the author thoroughly investigated Drake's impact on ambient $PM_{2.5}$ concentrations. However, no significant correlation between Drake's emissions and local $PM_{2.5}$ concentrations could be established. For this reason, the details of this analysis are relegated to Appendix A.

SO_2 Modeling

In order to estimate the impact that Drake's SO_2 emissions have on ambient SO_2 concentration, the author performed an ordinary least squares (OLS) regression of the model described in equation (5.1) using daily values from the Highway 24 monitoring station from 2014 to 2017. This initial regression yielded significant results, but a subsequent Breusch-Pagan/Cook-Weisberg test indicated considerable heteroskedasticity. To correct for this, the author performed a second regression with White standard errors. The resulting regression output is reproduced below in Table 3.

Table 3: SO_2 Concentration Regression Output

RHS: Highway 24 Average Daily SO_2 Concentration (ppb)

Variable	Reg. Coef.	Value (t-value)	95% CI
Drake Total SO2 (P)	α_1	0.0850975 (4.07)	[0.044077326, 0.126117674]
Wind Deviation (WD)	α_2	-0.013374 (-7.48)	[-0.016880558, -0.009867442]
Average Temp. (AT)	α_3	0.0216155 (2.59)	[0.005225403, 0.038005597]
Average Hum. (AH)	α_4	-0.009245 (-1.94)	[-0.018574108, 8.41078E-05]
Wind Speed (WS)	α_5	0.0346287 (0.81)	[-0.049425486, 0.118682886]
Year 2014	α_6	1.318317 (3.98)	[0.668631011, 1.968002989]
Year 2015	α_7	1.073508 (4.25)	[0.577598662, 1.569417338]
Year 2016	α_8	1.201638 (8.38)	[0.920140786, 1.483135214]
January	α_9	0.1429833 (0.54)	[-0.379926848, 0.665893448]
February	α_{10}	-0.378059 (-1.51)	[-0.870179442, 0.114061442]
March	α_{11}	-0.4919435 (-1.93)	[-0.992428904, 0.008541904]
April	α_{12}	-1.120008 (-4.04)	[-1.663446776, -0.576569224]
May	α_{13}	-1.022135 (-3.37)	[-1.617245669, -0.427024331]
June	α_{14}	-1.163533 (-3.21)	[-1.875521411, -0.451544589]
July	α_{15}	-0.932682 (-2.05)	[-1.825263832, -0.040100168]
August	α_{16}	-1.266211 (-3.26)	[-2.027420912, -0.505001088]
September	α_{17}	-0.6364551 (-1.72)	[-1.361215606, 0.088305406]
October	α_{18}	-0.6068855 (-2.27)	[-1.132257027, -0.081513973]
November	α_{19}	-0.1974812 (-0.85)	[-0.652529681, 0.257567281]
Sunday	α_{20}	-0.1855762 (-0.9)	[-0.590342501, 0.219190101]
Monday	α_{21}	-0.1104388 (-0.57)	[-0.489040513, 0.268162913]
Tuesday	α_{22}	-0.0479355 (-0.25)	[-0.419692637, 0.323821637]
Wednesday	α_{23}	-0.0999401 (-0.57)	[-0.44604219, 0.24616199]
Thursday	α_{24}	-0.2462771 (-1.38)	[-0.596844205, 0.104290005]
Friday	α_{25}	0.0026078 (0.01)	[-0.392684399, 0.397899999]
Constant	β	2.040006 (3.55)	[0.911078792, 3.168933208]
R^2		0.2594	
F-statistic		25.52	

Source: Primary. Note: Number of observations = 1,170; CI = confidence interval; Reg. Coef. = regression coefficient.

This regression indicates statistically significant correlation for Drake total SO_2 (P), wind deviation (WD), and average temperature (AT). Any insignificant correlations for other continuous or binary variables do not harm further analysis because Drake total SO_2

(P) is the only variable required for subsequent calculations. To test for serial correlation, the author ran separate OLS regressions of the residuals with lagged residuals, offset by 1, 2, 3, 4, and 5 days. These regressions showed no statistically significant correlation with any of the lagged residuals, thus ruling out any problematic serial correlation. To investigate potential multicollinearity, the author generated a correlation matrix and variance inflation factor (VIF) list, reproduced in Appendix D. None of the resulting covariance or VIF values are particularly large or concerning. Average temperature and average humidity correlate negatively as meteorological intuition predicts. It is unclear what causes the slight correlation of Drake SO_2 with wind speed and average humidity, but it is likely due to seasonal trends in these three variables. Regardless, none of this minor multicollinearity harms the desired statistical significance.

To assess normality of the error term, the author performed a Jarque-Bera test of the regression residuals. The test returned a JB-stat of 3,850.154. Since the assumption of normality is rejected by any JB-stat above 5.99, the test indicates an irrefutably non-normal error term. The author attempted to correct this issue by transforming variables with natural logs, squared values, inverse values, etc. but none of the transformations produced a normally distributed error term. This non-normality presents significant problems for interpretation of the regression because the validity of the t-tests and F-tests depends on the assumption of a normal error term. The most viable solution to this problem is to build a much larger data set so that the t and F tests become valid through large asymptotic sample theory. The author attempted to create such a data set by contacting CDPHE and requesting hourly monitoring data[11] on numerous occasions, but CDPHE has yet to furnish the data. A subsequent draft of this paper will investigate this issue further, but at the present time, the regression results will be tentatively accepted in their current form.

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[11] Hourly data is collected, but only daily 1-hour maximums and 24-hour arithmetic means are reported publicly.

Analysis

The regression in the previous section yields a concentration impact coefficient of 0.0850975 ppb/ton, the incremental impact of Drake's daily SO_2 output on ambient SO_2 concentration. As described in equation (5.2), several more pieces of information need to be ascertained in order to connect this coefficient to the resultant public health impacts.

Drake SO_2 Output Trend

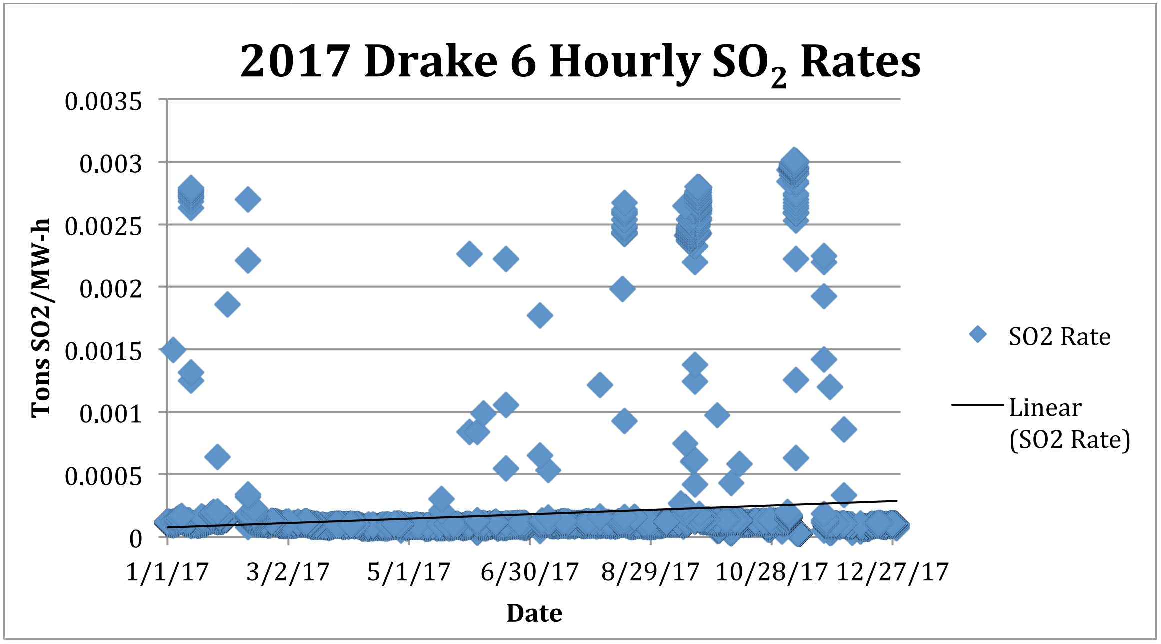
Estimating the marginal impact of the Drake plant on ambient SO_2 concentration first requires a reasonable approximation of the plant's average daily SO_2 emissions. The value of average daily SO_2 emissions is calculated by multiplying the plant's average post-scrubber SO_2 rate (tons SO_2/MWh) by the average daily gross output (MWh).

Post-Scrubber SO_2 Rates. Admittedly, there exists some uncertainty about how representative past SO_2 rates are of future SO_2 rates because all past data was collected prior to Drake's required compliance with the Regional Haze State Implementation Plan, which began January 1, 2018. The SO_2 scrubbers on Drake 6 and 7 were installed September 26, 2016 and February 8, 2016 respectively, but Drake operators have variable control over whether or not these scrubbers operate on any given day. In other words, the scrubbers having been installed does not automatically imply they were consistently being used to their fullest extent. However, Steve Duling, Principal Project Manager at CSU, asserts that both Drake scrubber units were being utilized fully throughout 2017 and that their performance in 2017 is indeed representative of future performance (Steve Duling, personal communication, February 21). With this in mind, this paper takes the average 2017 SO_2 rates as the expected SO_2 rates for future years.

Using 2017 emissions data from the EPA AMPD, average SO_2 rate was calculated by dividing yearly total SO_2 emissions by yearly total gross load for each unit. Drake 6 and 7 emitted SO_2 at rates of 0.00018184 tons/MWh and 0.00030959 tons/MWh respectively. It is worth noting that the SO_2 rates of these units fluctuate greatly. The standard deviations of hourly SO_2 rates for 6 and 7 are 0.000435038 tons/MWh and 0.00063932 tons/MWh respectively. There were many hours and full days during 2017 when the scrubbers appear to be offline entirely and the Drake plant continues to emit SO_2 at rates comparable to pre-scrubber years. The 2017 hourly SO_2 rates are graphed below in Figures 2 and 3. Note that a majority of the abnormally high values appear in distinct clusters. According to Steve Duling, these are likely periods of routine maintenance when the scrubbers were offline but the plant was still operating. These maintenance days will continue in future years as they are essential to the safe and reliable operation of the scrubbers.

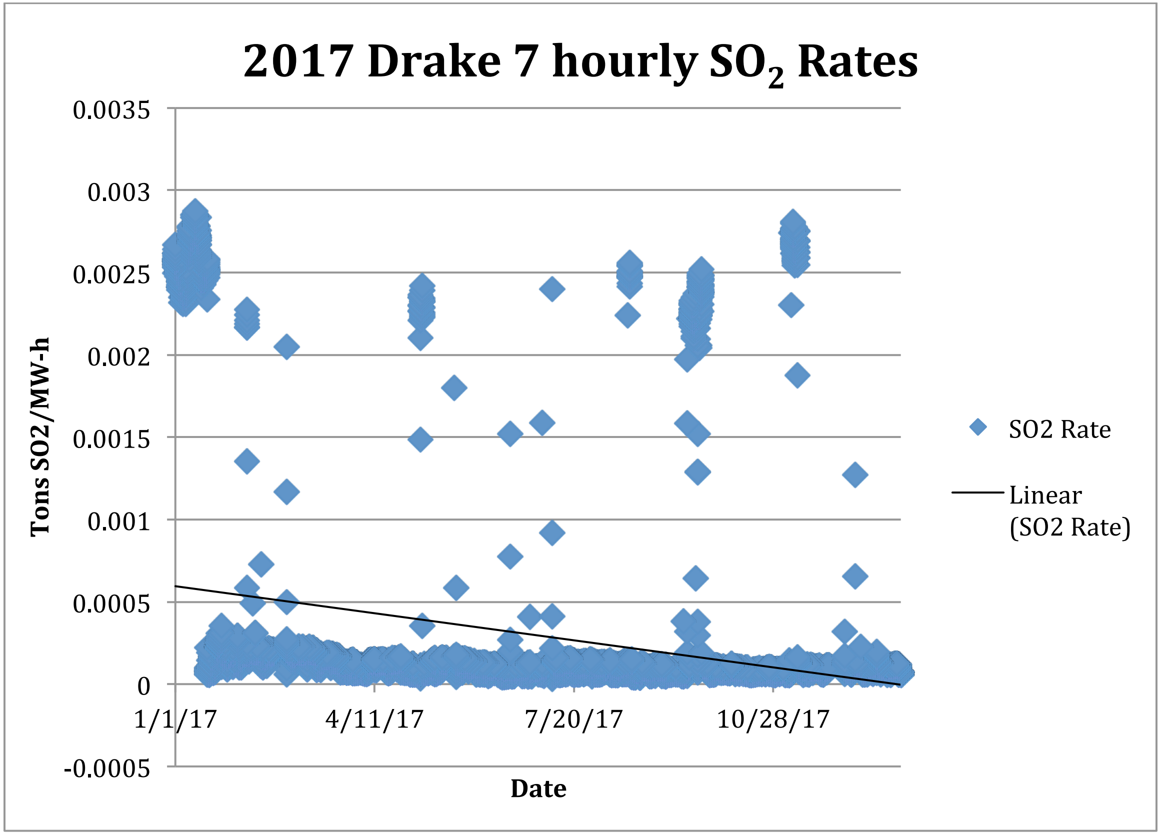
Despite the hugely variable SO_2 rates that contribute to a mean far higher than the median, this paper only considers the mean SO_2 rates in its analysis. This decision was made to fit with the linear damage functions from the literature. Since SO_2 exists in the local atmosphere on the order of hours, the outlier days only impact the ambient SO_2 concentrations on those specific days, but the linearity of the damage functions means that those short concentration spikes are exactly as harmful as their contribution to average daily concentrations.

Figure 2: Drake 6 Hourly SO_2 Rates



Source: Primary, Data Source: (EPA 2018b).

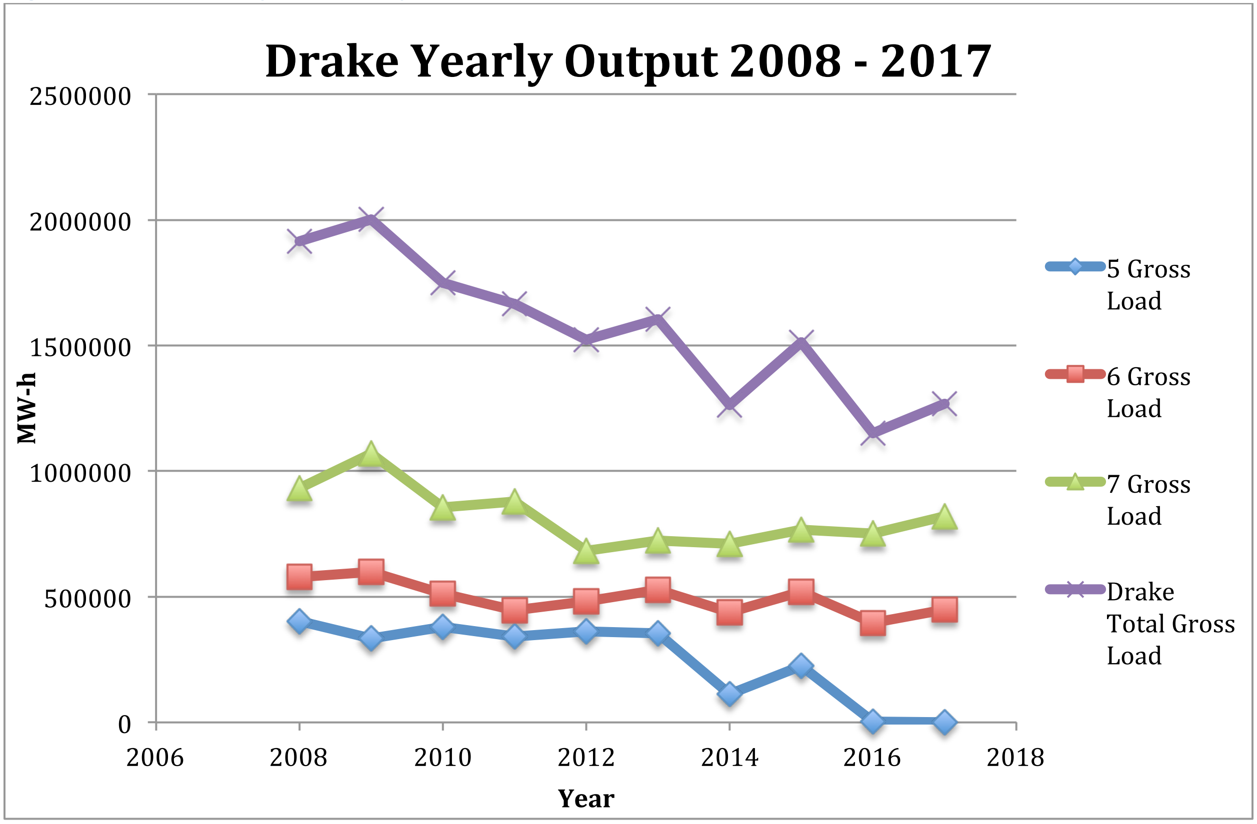
Figure 3: Drake 7 Hourly SO_2 Rates



Source: Primary, Data Source: (EPA, 2018b).

Drake Gross Load Trend. Approximating the utilization of the Drake plant in power generation is limited by a number of factors. CSU does not disclose the operating costs of the plant, so it is difficult to precisely predict the circumstances that lead to Drake being curtailed. CSU remains strongly committed to keeping Drake and Nixon 1 online at maximum capacity, but critics of the plant have argued that as the least efficient coal plant in Colorado, Martin Drake likely struggles to compete with the cheaper resources coming online. A November 2017 white paper published by the Applied Economics Clinic (Comings and Woods, 2017) cited the declining trend in annual Drake total output along with broader market trends to argue that Drake is being crowded out by CSU's other generating resources. But this analysis failed to account for two underlying factors that contributed heavily to that trend. A major fire in 2014 kept units 5, 6, and 7 offline for 45, 9, and 16 weeks respectively and caused a sizable drop in output during that year. Additionally, the decommissioning of Drake 5 in 2016 transformed Drake from a 254 MW plant to a 208 MW plant, greatly reducing the maximum output that the plant can achieve. However, if one observes the output trends of Drake 6 and 7 individually, this decline is much less obvious. Output trends of all three units and plant total are reproduced below in Figure 4.

Figure 4: Drake Yearly Gross Output 2008 - 2017



Source: Primary, Data Source: (EPA, 2018b).

This chart shows that outputs from both Drake 6 and 7 are down from their peaks in 2009, likely due to relatively flat demand growth and greater utilization of the Front Range natural gas plant. Regardless, output from Drake 6 and 7 has held relatively steady over the last 5-7 years. Because CSU is the only entity able to approve new resource integration, they have been prudent with resource decisions so as not to price Drake 6 and 7 out of the market. And while they are moving forward with deployment of 95 MW of utility-scale solar by the end of 2020 (Katie Hardman, personal communication, February 22, 2018), that level of variable generation is roughly equivalent to the 46 MW of firm output that Drake 5 formerly provided.

Considering CSU's efforts to keep its coal plants online at maximum capacity and the flat trend in Drake 6 and 7 output, this paper assumes that, excluding any major changes, the two units will continue to operate at the levels of the last 5 years, until 2035 or until CSU decides to decommission the plant, whichever comes first. The respective 5-year averages for Drake 6 and 7 are 465,949 and 754,738 MWh per year or 1,277 and 2,068 MWh per day. There is reason to suspect these figures represent a conservative prediction because of the major outages associated with the 2014 fire and the SO_2 scrubber installations. Since those outages need not be incurred again, these figures likely underestimate the true future output of the plant.

ΔPC Coefficient

The desired coefficient of change in pollution concentration that would result from decommissioning the Drake plant is calculated as follows:

$$\Delta PC = SO_2 rate * GL * CIC \tag{7.1}$$

Where:

SO_2rate = Average post-scrubber SO_2 rate

GL = Average daily gross load

CIC = Concentration impact coefficient (Drake Total SO_2 reg. coef.)

The values of these variables, restated from previous sections are summarized below in Table 4.

Table 4: Analysis Values

Metric	Drake 6	Drake 7
Average Post-Scrubber SO_2 Rate (tons/MWh)	0.00018184	0.00030959
Average Daily Output (MWh)	1276.571611	2067.776219
Ambient Concentration Impact Coefficient (ppb/ton)	0.0850975	0.0850975

Source: Primary

Using equation (7.1), the author calculated ΔPC coefficients for Drake 6 and 7 of 0.01975 and 0.05448 ppb respectively or 0.07423 ppb for the entire Drake plant. In other words, if the Drake plant were taken offline, average ambient SO_2 concentration at the Highway 24 monitoring site would decrease by 0.07423 ppb.

Extrapolation of the ΔPC Coefficient

Based on the analysis thus far, this paper can only speak definitively about the SO_2 concentrations at a single location within Colorado Springs. However, due the dearth of active monitoring stations, the Highway 24 monitoring site is the best available proxy for citywide ambient SO_2 concentrations. This limitation is far from ideal, as existing dispersion modeling depicts a thoroughly uneven distribution of Drake's SO_2. However in both of the dispersion modeling maps published by CSU (Samani et al., 2017) and the Sierra Club (Sierra Club et al., 2012), the Highway 24 monitoring site is far from the most severely impacted region in the city. The Sierra Club modeling predicts that roughly the entire city is as bad or worse than the Highway 24 site, with the areas in the Broadmoor hills many times worse off. The more conservative CSU report predicts that the most densely populated parts of downtown are impacted slightly more than the Highway 24 site with Manitou Springs and the surrounding suburbs to the north and east impacted slightly less than the Highway 24 site. These dispersion models coupled with the numerous conservative estimates utilized throughout the analysis allow this paper to tentatively extrapolate the analysis of the Highway 24 site to the greater Colorado Springs metropolitan area.

Population and Mortality Rate

In order to approximate the impact of SO_2 from the Drake plant on public health, this analysis will use the population of the Colorado Springs Metropolitan Statistical Area (MSA). The population of the Colorado Springs MSA as of 2016 was 712,327 (Bureau of Economic Analysis, 2017). Since the analysis in this paper aims to approximate the public health impacts between now and 2035, this 2016 figure represents a markedly conservative lower bound approximation.

The mortality rate required for this analysis is the annual all-cause mortality rate. Because mortality data is only compiled at the county level, this paper uses the mortality rate of El Paso County as an estimator of the Colorado Springs MSA mortality rate. Considering the vast majority of the population of El Paso County resides in the MSA, there is little reason to doubt the accuracy of this estimator. The Center for Disease Control's CDC WONDER mortality database reports an annual all-cause mortality rate of 623.7 per 100,000 for the years 2011-2016 (Center for Disease Control, 2018). The CDPHE reports a similar but slightly larger value of 741 per 100,000 for the years 2011-2015 (CDPHE, 2016). The CDPHE report also indicates that the mortality rate has risen slightly each year since 2011, with the figure for 2015 at 777 per 100,000. With this trend in mind, it is certainly likely that between now and 2035, the mortality rate will continue to rise. However in the continued interest of conservative estimation, this paper uses the CDC figure of 623.7 per 100,000.

Impact Analysis and NPV Valuation

Applying the values of mortality rate, risk coefficient, change in pollution concentration, and population to equation (5.2) yields the following calculation:

$$N = MR * RC * \Delta PC * POP \tag{5.2}$$

N = (623.7 deaths/100,000 people) * (0.046%/ppb) * (0.07423 ppb) * (712,327 people)

N = <u>0.1517 additional deaths per year</u>

Because the current debate centers around whether to close the plant in 2035 or as early as 2025, this paper considers the public health benefit of closing the plant 10 years earlier than currently planned. The EPA's valuation of mortality ($8,989,845 in 2017 dollars) was adjusted to account for lagged premature mortality occurring in the years 2026-2035. See Appendix C for calculations. The net present value (NPV) of the additional deaths during that 10-year period comes out to $9,183,312 in 2017 dollars. Therefore by closing the plant in 2025 instead of 2035, CSU would generate public health benefits of at least $9 million from the SO_2 reduction alone.

Conclusion

This paper finds that decommissioning Martin Drake in 2025 instead of 2035 would generate NPV public health benefits of over $9 million from SO_2-driven premature mortality alone. CSU's most recent financial analysis estimates the cost of a 2025-decommissioning scenario at $126 million (2017 NPV) above the baseline 2035 scenario (Colorado Springs Utilities Board, 2017). On its own, this paper's estimation of the cost of the plant's SO_2 emissions does not present a convincing financial argument for a 2025 decommissioning. However, this estimate represents a conservative lower-bound approximation of limited scope, analyzing only the impact of SO_2 emissions on premature mortality while overlooking all of Drake's other harmful pollution.

CSU is currently in the preliminary stages of conducting its 2020 EIRP, and it has not yet been decided if its authors will price externalities (Katie Hardman, personal communication, February 27, 2018). While it is unclear at this time whether the public health externalities of the Drake plant outweigh the costs of an earlier decommissioning, the fact remains that these externalities are substantial and uncertain. Considering the grave nature of these externalities, it is imperative that CSU conduct further analysis to adequately inform its resource planning decisions and value the health of its ratepayers.

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Appendix A: Investigation of Drake's Impacts on Ambient $PM_{2.5}$ Concentration

Since Colorado Springs does not have any active sulfate or nitrate monitors, the closest proxy to sulfate and nitrate pollution is the $PM_{2.5}$ monitor on the Colorado College campus. Using equation (5.1), the author performed regressions of $PM_{2.5}$ concentrations with Drake SO_2 and NO_x emissions, weather data, and dummy variables for year, month, and day of week. In order to investigate potential lag in conversion of SO_2 and NO_x to sulfate and nitrate, additional regressions were performed with time lags of 0, 3, 6, and 9 days. However, none of these regressions produced any significant correlation for Drake's SO_2 and NO_x emissions with $PM_{2.5}$ concentrations. This is not to say that Drake contributes nothing to local $PM_{2.5}$ concentrations, just that it does not directly cause significant deviations from the background $PM_{2.5}$ concentrations caused by vehicle emissions and other nearby point sources.

Appendix B: Conversion Ratio of μg/m³ to ppb

Converting μg/m³ to ppb uses the following relationship to determine the density of air in a particular location. $\rho = \frac{P}{T * 287.05 J/(kg * K)}$ (B.1)

Where: ρ = density of dry air in kg/m³

P = atmospheric pressure in Pascalls

T = ambient temperature in Kelvin

Using Colorado Springs' average barometric pressure (1996-2011) of 101,693.25 Pa (Desert Research Institute, n.d.) and average temperature (1981-2010) of 282.57 K (US Climate Data, 2018), the equation yields a density value of 1.2537 kg/m³. Using dry air's average molar mass of 28.9647 g/mol, this figure produces a value of 43.2837 mol air/m³. Then multiplying 1 μg SO_2/m³ by SO_2's molar mass of 64.066 g/mol yields a value of 1.56089×10^{-8} mol SO_2/m³. Finally, dividing the value of 1.56089×10^{-8} mol SO_2/m³ by 43.2837 mol air/m³ shows the relationship of 0.36062 ppb per μg/m³. Calculating the specific conversion ratio for Colorado Springs allows for more accurate calculations than a generalized value.

Appendix C: Discounting Future Mortality Impacts

Table B: 2017 NPV Calculations of Avoided Mortality, 2026-2035

Year	Lag (year minus 2017)	NPV of death in each year 3% DR	NPV of 0.1517 deaths in each year 3% DR
2026	9	6889967.629	1045208.089
2027	10	6689288.96	1014765.135
2028	11	6494455.301	985208.8692
2029	12	6305296.409	956513.4653
2030	13	6121646.999	928653.8498
2031	14	5943346.601	901605.6794
2032	15	5770239.418	875345.3198
2033	16	5602174.193	849849.825
2034	17	5439004.071	825096.9175
2035	18	5280586.476	801064.9685
Total 2016-2035			9183312.119

Source: Primary. Note: DR = discount rate

Appendix D: Correlation Matrix and VIF Output

Table C1: Correlation Matrix

	Drake Total SO_2	Wind Deviation	Average Temperature	Average Humidity	Wind Speed
Drake Total SO_2	1				
Wind Deviation	-0.0378	1			
Average Temperature	-0.0686	-0.1033	1		
Average Humidity	0.2484	-0.1685	-0.3765	1	
Wind Speed	-0.2601	0.0136	-0.0082	-0.1007	1

Source: Primary

Table C2: VIF Values

Variable	VIF	1/VIF
Drake Total SO_2	3.8	0.263157895
Wind Deviation	1.13	0.884955752
Average Temperature	7.04	0.142045455
Average Humidity	2.13	0.469483568
Wind Speed	1.21	0.826446281
2014	3.26	0.306748466
2015	4.42	0.226244344
2016	1.88	0.531914894
January	2.14	0.46728972
February	2.01	0.497512438
March	2.24	0.446428571
April	2.51	0.398406375
May	3.16	0.316455696
June	4.56	0.219298246
July	5.13	0.194931774
August	5.18	0.193050193
September	4.58	0.218340611
October	3.28	0.304878049
November	2.17	0.460829493
Sunday	1.72	0.581395349
Monday	1.73	0.578034682
Tuesday	1.75	0.571428571
Wednesday	1.74	0.574712644
Thursday	1.74	0.574712644
Friday	1.73	0.578034682
Mean VIF	2.89	

Source: Primary