CONVERSION FROM COAL TO NATURAL GAS AT WRIGHT-PATTERSON AIR FORCE BASE: AN ANALYSIS AND CASE STUDY

THESIS

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Abstract

Over the last 20 years, natural gas has replaced coal as the preferred fossil fuel for heat and power generation across the United States, due to its increased prevalence, lower cost, and reduced environmental impacts. While most conversion decisions are driven by cost savings, proponents of energy transitions often cite emissions reductions as a tangential benefit. Over the same time, climate change and its impact on the environment and society have come to the forefront of scientific inquiry. One example of the transition from coal to natural gas can be found in Dayton, Ohio. Wright Patterson Air Force Base (WPAFB) invested over $25M from 2014 to 2016, to retrofit two coal-fired steam-heat-generating plants to natural gas heating plants. A brief review of literature shows that natural gas has a number of environmental benefits as opposed to coal to include, reduced air emissions and water withdrawal, as well as the elimination of the hazardous solid wastes produced by coal combustion. Economic analyses used to inform these long-term infrastructure decisions rarely consider the uncertainty of climate change. In this study, a Monte Carlo simulation is performed to evaluate the sensitivity of cost savings from the switch while accounting future uncertainty of climatic changes in the region. Primary fuel consumption data for WPAFB was paired with historical data with climate forecasts to calibrate a model, connecting specific weather indicators to installation fuel demand. The sensitivity of each fuel demand to weather can be forecast using a range of expected outcomes for climate change across the region. Using this predictive model for fuel use, observations and comparisons are made for the range of possible outcomes of long-term

operating cost, environmental impacts, and how warming climate affects natural gas conversion return-on-investment. Finally, by analyzing geospatial data within the United States for coal and natural gas sources and infrastructure, as well as state power plant data, the Midwestern United States is found to be an extremely viable location for conversion projects similar to WPAFB. The results of this study help inform policy and aid in the long-term economic assessment of similar construction projects across the Department of Defense and Midwestern United States.

Acknowledgments

I would like to express my appreciation and thanks to my advisor, Dr. Chris Chini, for his patience and unwavering support throughout this research effort. I would also like to thank my wife for her continued support and understanding in the challenges of a military lifestyle.

Tyler Ferry

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I. Introduction

The projected impacts of climate change are forcing national policy makers to evaluate the future of our infrastructure and how they might best mitigate the effects of, and adapt to, a changing climate. Warming of our climate system is unequivocal and has shown observed increases in global average air and ocean temperatures (Gray 2007). The rising mean global temperature is primarily caused by the increase in atmospheric greenhouse gases (GHGs) from preindustrial times to present. The burning of fossil fuels in the transportation and energy sector contributes 80% of the global CO_2 emissions (Ramanathan & Feng 2008). These facts are leading to changing views in our industrial and commercial energy production sector, which have a strong impact on both our environmental landscape and our economic landscape. On military installations, operation and maintenance costs have been under scrutiny in recent years as ideas have been explored to optimize the Department of Defense (DoD) budget. The DoD is among the largest energy resource consumers in the world and the largest single consumer in the United States (Lengyel 2007). As a result, energy resources are an important and significant portion of the budget consisting of up to 3% of total defense spending (Demotakis 2006). Military installations worldwide have investigated opportunities to reduce their overall energy and resource demands as well as their environmental impact to drive a more sustainable enterprise into the future. In 2015 Wright-Patterson AFB converted its steam heat plants from coal to natural gas as the primary fuel.

Renewable energy sources are becoming widely popular; however, fossil fuels still remain the backbone of our national power generation strategy due to availability, efficiency, and reliability, producing 63% of United States electricity (Grubert 2020). In recent years, falling prices and increased abundance have made natural gas an attractive alternative to coal (Liang et al 2012). As a result of the United States shale gas revolution, natural gas prices are well below the price per unit of coal across most of the country (Carley 2018). Additionally, natural gas fired plants are more operationally flexible than similar coal plants which benefit energy grids as policies and economics evolve and change (Grubert et al. 2012). These facts have prompted retrofit projects for plant conversions from coal to natural gas as a primary fuel (Liang et al 2012). Natural gas is often thought of as a 'bridge' fuel by policy makers and a better alternative to coal until near-zero emission technologies become more feasible (Zhang et al 2014). In the meantime, national GHG emissions policy changes have been forcing modernization of energy production infrastructure (Gerrard 2012).

In April 2012, the United States Environmental Protection Agency (USEPA) anticipated the final publishing of the Boiler MACT regulations under the Clean Air Act. From that time, affected sources had three years to demonstrate compliance. Section 212 of the Clean Air Act maintains that the USEPA will regulate emissions of hazardous air pollutants (HAPs) from source categories including industrial, commercial, and institutional boilers that include the systems utilized at WPAFB. (Wright Patterson Air Force Base 2011). Prior to the EPA's regulations on boiler MACT, WPAFB was primarily heated by two coal fired steam heat plants which would require modernization to remain in compliance (Wright Patterson Air Force Base 2011). WPAFB funded an economic analysis of the available alternatives which included 1) upgrading the existing infrastructure to MACT compliance while maintaining coal as the primary fuel, 2) conversion of the central systems to 100% natural gas, or 3) decentralization of the primary facilities to provide individual facility systems that utilize natural gas heating. The considerations within the economic analysis included feasibility, environmental impacts, short term capital cost, and long-term fuel and maintenance costs (Wright Patterson Air Force Base 2011).

The environmental benefits of natural gas compared to coal have been well documented and as far as regional feasibility, Ohio had become a prime candidate for natural gas conversion. For the last decade, coal use had been declining and natural gas had been on the rise due to increased availability from hydraulic fracturing technology and infrastructure development (Capuano 2019). The Marcellus Shale formation located in New York, Pennsylvania, and Ohio became available as a result of hydraulic fracturing and is believed to hold a natural gas supply equivalent to 45 years of United States national consumption (Sovacool 2014). The economic analysis produced initial capital costs for all three alternatives with the lowest initial capital construction cost being option two; the conversion of primary facilities to natural gas. Despite the annual operating costs being slightly higher than decentralization, the 20-year net present value of option two was also the lowest at just over $388 million versus $420 million for option three, decentralization. Based on the findings of the economic analysis the government's decision was to pursue a conversion to 100% natural gas within the two primary heating facilities on WPAFB to maintain EPA compliance. The impetus for this major infrastructure upgrade was driven by environmental regulation, however, the decision to pursue natural gas was situated economically as gas is relatively cheap and natural gas fired plants are cheaper to construct and operate (EIA 2019).

Problem Statement

A simple life-cycle cost analysis of the alternatives, such as the one used by WPAFB in this case, might not be enough to capture the payback period of the retrofit. The primary weakness of using a simple lifecycle analysis is the improper treatment of uncertainty when there is sparse and imprecise information available (Lo et al. 2005). Lo et al. (2005) notes that using a Monte Carlo simulation reduces uncertainty and provides results that allow for a better-informed decision and a clearer comparison of alternatives. In the case of WPAFB's transition project, a changing climate was not considered, and it is likely to have effects on heating demand and fuel prices which may not be static in the future. In colder climates, models suggest a decrease in annual site energy demands with regards to heating (Wang and Chen 2014). Van Ruijven et al (2019) models climate change temperature projections in 2050 showing the highest decline to cold weather exposure in the mid-latitudes, which includes Ohio (2019). Additionally, global impacts of climate change could have significant effects on fossil fuel resource extraction and production resulting in uncertain fuel price trends going into the future (Parry et al 2007; Schaeffer et al 2012). This evidence taken into consideration could result in a longer payback period for this project or similar conversion projects elsewhere.

WPAFB is an ideal candidate for a case study on advancing economic analyses to include fluctuating long-term costs while considering climate change. Using a unique dataset of energy cost and consumption data specific to the installation's boilers, an investigation is performed on the fuel accounting data of the heating facilities three years before and after conversion. WPAFB’s decision to retrofit the heating plant was based on a cost-benefit analysis of the MACT. Additionally, the transition to natural gas at WPAFB was largely made feasible by improved technologies in natural gas extraction that were new to the industry around the time of the regulatory change (Zheng et al 2020). The purpose of this research is to:

1) Briefly summarize the environmental impacts and embedded resources of natural gas power/heat generation compared to coal.
2) Utilize a Monte Carlo simulation that accounts for fuel price variability and temperature change projections in analyzing the long-term payback period for a heating infrastructure project at Wright-Patterson Air Force Base in Ohio.
3) Geospatially analyze energy infrastructure to determine where these infrastructure locations might also make other transitions an attractive option.

II. Review and Analysis of Environmental and Embedded Resource Impacts of Coal and Natural Gas Energy Generation

As a primary fuel for commercial, industrial, and institutional heat and energy generation, natural gas has grown exponentially in popularity over the past 10 years (EIA 2020). Two motivators for this transition are natural gas's increased availability due to advancements in extraction technology enabling wider production and distribution, and the comparatively low cost of natural gas per unit of energy produced (Carley 2018; Gregory and Dzombak 2011; Grubert et al 2012). Additionally, natural gas power plants are operationally more flexible than coal plants while also being cheaper to maintain and operate (EIA 2019; Grubert et al 2012). U.S. Energy Information Administration projects coal production to decrease in the future due to retirement of coal fired plants, while natural gas production increases and prices remain low (Capuono 2019). Although the economic advantages of natural gas play a significant role in institutional decisions to transition fuels, the primary driver of natural gas's replacement of coal is its ability to meet stricter emissions standards enforced by the US Environmental Protection Agency (EPA). One example of this transition to natural gas is at Wright-Patterson AFB, where the installation invested $25M to demolish the aged coal handling equipment and install modern natural gas boilers (Wright-Patterson Air Force Base 2011).

With climate change becoming a priority and area of global concern, environmental considerations are an important driver for the movement away from coal generated power (Grubert 2012). Wright-Patterson AFB's transition to natural gas came as a result of an EPA rule change impacting institutional boiler emission standards. The option of transitioning to natural gas versus modernizing the existing coal infrastructure was chosen partially based on reduced emissions from natural gas which would help to avoid triggering compliance issues in the future (Wright-Patterson Air Force Base 2011). Renewable energy sources are becoming widely popular, however, fossil fuels still remain the backbone of our national power generation strategy due to availability, efficiency, and reliability, producing 63% of United States electricity (Grubert 2020). Natural gas is increasingly seen as a bridge fuel that can curb the impacts of global climate change until transitions to renewable or near-zero emission technology becomes more feasible (Moniz et al 2011; Paltsev et al 2011). More research is becoming available that explores the environmental impacts of natural gas from a lifecycle perspective as well as the direct and indirect impacts on embedded resources such as freshwater withdrawal and consumption. The goal of this research is to review available literature and summarize the lifecycle impacts of coal and natural gas as a fossil fuel energy source.

Environmental Impacts

An environmental lifecycle analysis of fuels would include extraction, production, distribution, consumption, and disposal. Predominantly, literature focuses on the consumption phase of energy producing fossil fuels and the emissions that coincide. As the natural gas industry continues to grow, more research is being done from a holistic approach that focuses on the entire lifecycle of the fuel from extraction to disposal to include resources that are embedded within the process such as water.

Air Emissions

Air emissions, greenhouse gases (GHGs) in particular, played a significant role in the EPA's Maximum Achievable Control Technology (MACT) rule that raised the standards on boiler air emissions controls (CEC 2020). Research has shown that natural gas has reduced air emissions when compared to coal. During combustion, natural gas emissions for CO_2, SO_2, and NOx are estimated at 1.2 lb/kWh, <0.001 lb/kWh, and <0.001 lb/kWh, respectively, compared to coal emissions that are estimated at 2.3 lb/kWh, 0.007 lb/kWh, and 0.02 lb/kWh, respectively. A great deal of concern exists regarding fugitive methane emissions due to leaks and other unintended releases for both coal and natural gas extraction and distribution with estimates varying and inconsistent (Kirchgessner 1997).

Freshwater Resources Impacts

Freshwater resources are an embedded resource that are often overlooked in a simple impact analysis of fuel consumption. Water is withdrawn and consumed in every stage of the fuels lifecycle and the United States is seeing greater water shortages each year (Heggie 2020). Water withdrawal for coal fired power plants is estimated throughout fuel extraction, processing and transportation as 3.29 m^3/MWh while estimates for water withdrawal during natural gas extraction, processing, and transportation are 1.8 m^3/MWh (Kondash et al 2019). For water consumption during combustion of coal and natural gas the water impacts are 1.893 m^3/MWh and 0.871 m^3/MWh respectively (Grubert et al 2012). The resulting estimates for water consumption rates for coal and natural gas lifecycles are 5.183 m^3/MWh and 2.671 m^3/MWh. From a lifecycle analysis of coal and natural gas water consumption rates, natural gas shows a nearly 50% decrease in water demand.

Coal Combustion Residue

Another environmental drawback of coal fired energy is the residue that is left behind. On average, 11% of coal by weight remains after combustion as coal combustion residual (CCR). CCR consists of fly ash, bottom ash, boiler slag, and flue gas desulfurization material (Stewart 1999). The remaining CCR that is left after coal combustion poses many environmental hazards and is heavily regulated through disposal. The environmental hazards consist of leaking contaminants into groundwater, blowing of contaminants into the air as dust, and the catastrophic failure of coal as surface impounds that could result in freshwater resource contamination (US EPA n.d.). Although in recent years 59% of CCR has been recycled into other products such as concrete, 41% still poses an environmental risk and adds additional demand on hazardous waste landfills (Adams 2020). CCR waste results in additional operation and maintenance costs to coal fired plants in the form of hazardous waste removal and disposal.

Conclusion

As aging power generation infrastructure is retired and modernizations or alternative fuels are considered, the environmental impacts should be considered along side the economic considerations. Literature shows that natural gas has a reduced water withdrawal demand throughout the lifecycle of the fuel when compared to coal and also shows reduced emissions at the point of combustion. Natural gas also has very little residue for disposal which is inferred by the lack of literature on the topic while coal produces a significant amount of combustion residue which poses serious environmental concerns and strains hazardous waste landfills.

III. Cost Uncertainty and Climate Change for Centralized Heating

Abstract

Over the last 20 years, natural gas has replaced coal as the preferred fossil fuel for heat and power generation across the United States, due to its increased prevalence, lower cost, and reduced environmental impacts. While most conversion decisions are driven by cost savings, proponents of cleaner energy production often cite emissions reductions as a tangential benefit. Over the same time, climate change and its impact on the environment and society have come to the forefront of scientific inquiry. One example of the transition from coal to natural gas can be found in Dayton, OH. Wright Patterson Air Force Base (WPAFB) invested over $25M from 2014 to 2016, to retrofit two coal-fired steam-heat-generating plants with natural gas equipment. Economic analyses used to inform these long-term infrastructure decisions rarely consider the uncertainty of climate change. In this study, a Monte Carlo simulation is performed to evaluate the sensitivity of cost savings from the switch while accounting future uncertainty of climatic changes in the region. Primary fuel consumption data for WPAFB is paired with historical data with climate forecasts to calibrate a model, connecting specific weather indicators to installation fuel demand. The sensitivity of each fuel demand to weather can be forecast using a range of expected outcomes for climate change across the region. Using this predictive model for fuel use, the range of possible outcomes can be observed and compared for long term operating cost, environmental impacts and how warming climate affects natural gas conversion return-on-investment. The results of this study help inform policy and aid in

the long-term economic assessment of similar construction projects across the Department of Defense and Midwestern United States.

Introduction

Between 2013 and 2016 WPAFB transitioned from primarily coal generated heat to natural gas burning centralized heating facilities. This decision was based on an Environmental Compliance Report that evaluated feasibility, environmental impacts, and short and long term economic costs (Wright Patterson Air Force Base 2011). The decision to pursue a \$25M transition project to natural gas was primarily based on long term economics when considering operations and maintenance costs of the alternatives. The DoD does not currently weigh the impacts of climate change into their long-term economic planning and infrastructure investment strategy. This research presents a Monte Carlo simulation that accounts for fuel price variability and temperature change projections in analyzing the long-term payback period for a heating infrastructure project at Wright-Patterson Air Force Base in Ohio.

A simple life-cycle cost analysis of the alternatives, such as the one used by WPAFB in this case, might not be enough to capture the payback period of the retrofit. The primary weakness of using a simple lifecycle analysis is the improper treatment of uncertainty when there is sparse and imprecise information available (Lo et al. 2005). Lo et al. (2005) notes that using a Monte Carlo simulation reduces uncertainty and provides results that allow for a better-informed decision and a clearer comparison of alternatives. In this case, a changing climate is not taken into account where it is likely to have effects on heating demand and fuel prices which may not be static in the future. In colder climates, models suggest a decrease in annual site energy demands with regards to heating (Wang and Chen 2014) and Van Ruijven et al (2019) models climate change temperature projections in 2050 showing the highest decline to cold weather exposure in the mid-latitudes, which includes Ohio. Additionally, global impacts of climate change could have significant effects on fossil fuel resource extraction and production resulting in uncertain fuel price trends going into the future (Parry et al 2007; Schaeffer et al 2012). This evidence taken into consideration could result in a longer payback period for this project or similar conversion projects elsewhere.

WPAFB is an ideal candidate for a case study on advancing economic analyses to include fluctuating long-term costs while considering climate change. Using a unique dataset of energy cost and consumption data specific to the installation's boilers, this research investigates the fuel accounting data of the heating facilities three years before and after conversion. WPAFB's decision to retrofit the heating plant was based on a cost-benefit analysis of the MACT. As a result, the first question this research aims to answer is: *how does the expected payback period of this retrofit change when including changing climatic conditions and non-static fuel prices?*

To answer this question, monthly data from October 2010 to September 2018 for the WPAFB boilers is available. This includes tons of coal, CCF of natural gas, and costs of materials. To determine climate uncertainty, historic temperature data will be modeled and compared to projections accounting for climate change. Using this data, a Monte Carlo simulation can be run to determine the expected payback period with different climate change scenarios.

Background and Case Study

Wright Patterson AFB, located in Southwestern Ohio, provides an interesting case study due to its size (8000 acres), population (>27,000 personnel), and geographic location (Wright Patterson Air Force Base 2019). Due to a large population, industrial economy, and wide seasonal temperature variations, Ohio is among the top ten states in total energy consumption. Ohio is also among the top ten coal consuming states, and while Ohio is the 15th largest coal producing state, more than three times as much coal is consumed as is produced there (EIA 2020). Due to advancements in natural gas extraction technology, Ohio's natural gas production was more than 30 times greater in 2019 than in 2012. Almost all of the state's natural gas comes from the Utica Shale wells where horizontal drilling and hydraulic fracturing are required to extract the gas (EIA 2020). Ohio's natural gas production surpassed consumption for the first time in 2015 and in 2018, the electric power sector became the state's largest natural gas consumer (EIA 2020). WPAFB and Dayton, Ohio falls within International Energy Conservation Code (IECC) climate zone 5 also known as the cold zone (U.S. Dept of Energy 2015). Within this zone heating costs are expected to be of higher demand than cooling and it is also expected that the effects of climate change will result in a significant reduction in heating demand projected into the future (Van Ruijven 2019).

Prior to 2015, Wright-Patterson Air Force Base (AFB) in Ohio utilized three primary hot water and steam heating plants to supply the base with both hot water and facility heating (Wright Patterson Air Force Base 2011). Additionally, the installation controlled two decentralized systems and several smaller systems to provide hot water and heat to the hospital and other remote or critical facilities. Among the three primary heat plants, two utilized coal-fired systems. WPAFB is divided into two independent locations known as Area A and Area B separated by State Route 444 (Wright Patterson Air Force Base 2019). Two separate facilities, one on each Area, utilized coal and natural gas to provide heat to approximately 245 buildings, making up over 86% of the installations heating demand (88th Civil Engineer Squadron 2011). While the heating plants both utilized natural gas throughout the year, coal was the primary fuel during peak heating season and provided over 60% of the annual heating demand to the service area. Due to the changes in boiler MACT regulations, an economic assessment was contracted by the installation to determine the most cost effective strategy to remain in compliance with the Clean Air Act. Converting the coal systems to natural gas was found to be the most economic long-term solution. In 2014, the heating facilities were converted to strictly natural gas boilers through a multi-year phased project. Within the installation's economic assessment, static fuel prices were used based on current unit prices and climate change affects were not considered (Wright Patterson Air Force Base 2011).

The data for this case study analysis came from the 88th Civil Engineer Squadron on WPAFB. Fuel accounting data was collected for both coal and natural gas from 2010 to 2018, before and after the conversion (See Figure 1). Due to the skewed fuel data during the construction period, the fuel accounting data was manipulated within MATLAB and categorized from Oct 2010 – May 2014 as pre-construction and Jul 2016 – Sep 2018 as post-construction data. The data from within the construction period was ignored due to the uncertainty and error introduced as the coal fired equipment was being phased out and natural gas equipment phased in. By analyzing the periods before and after the construction window, this research can develop projections of coal and natural gas consumption into the future.

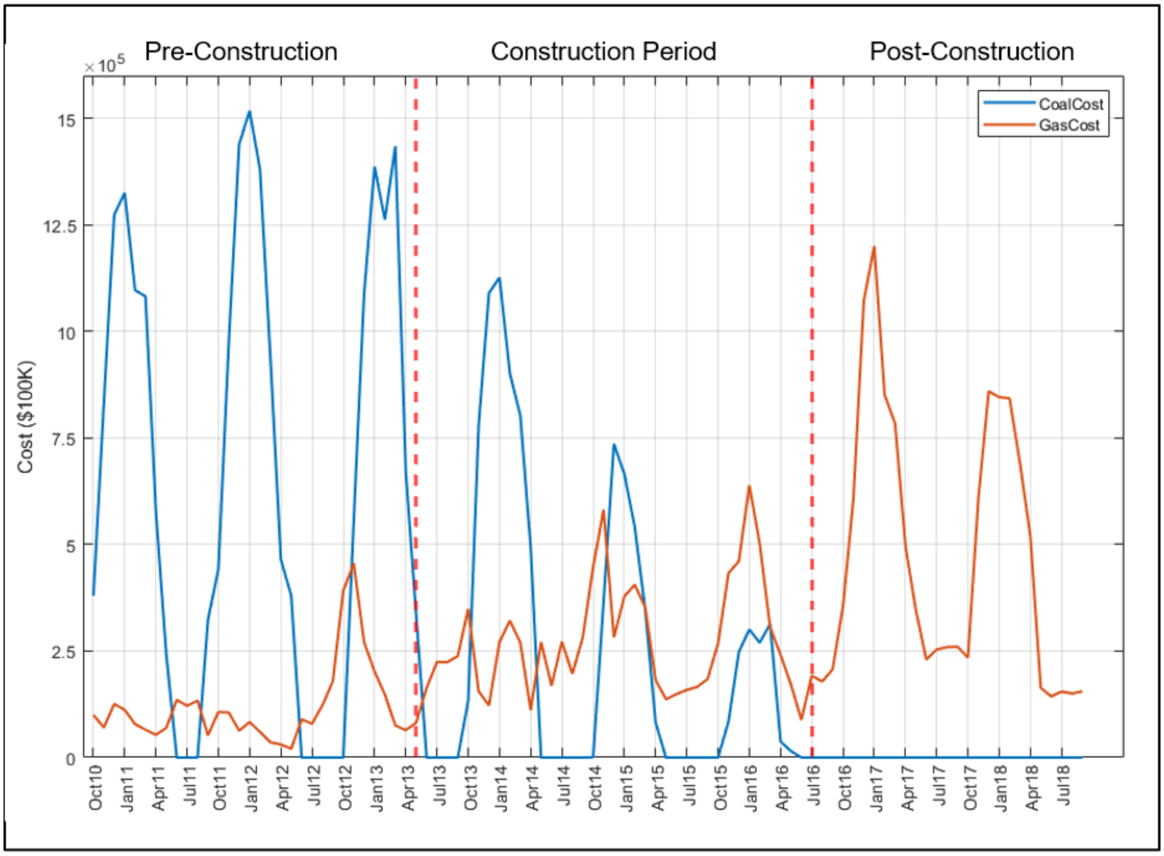


Figure 1. WPAFB fuel accounting data was filtered to only include fuel costs and quantities attributed to either of the two steam heat plants on WPAFB. Due to the skewed fuel data during the construction period, the fuel accounting data was manipulated within MATLAB and categorized from Oct 2010 – May 2014 as pre-construction and Jul 2016 – Sep 2018 as post-construction data

Methods

The methodology of this research consisted of two overarching categories; 1) data collection and analysis and 2) a Monte Carlo Simulation to determine the distribution of break-even years over 100,000 model simulations. Uncertainty was introduced into the model through variable coal and natural gas prices. Additionally, three future heating degree-day (HDD) scenarios were generated from historical data, Representative Concentration Pathway (RCP) 4.5 projections, and RCP 8.5 projections (Maurer et al 2007; Pierce et al 2014; Reclamation 2013; Reclamation 2014; Vano et al 2020). RCP projections were averaged over all models to create a synthetic scenario. Through analyzing and plotting historical prices for each fuel, appropriate distributions were assigned to both coal and natural gas from which to sample and introduce fuel price uncertainty. The distribution for coal prices assumed a uniform distribution. Natural gas price variations were assumed to follow a lognormal distribution (See Figure 2).

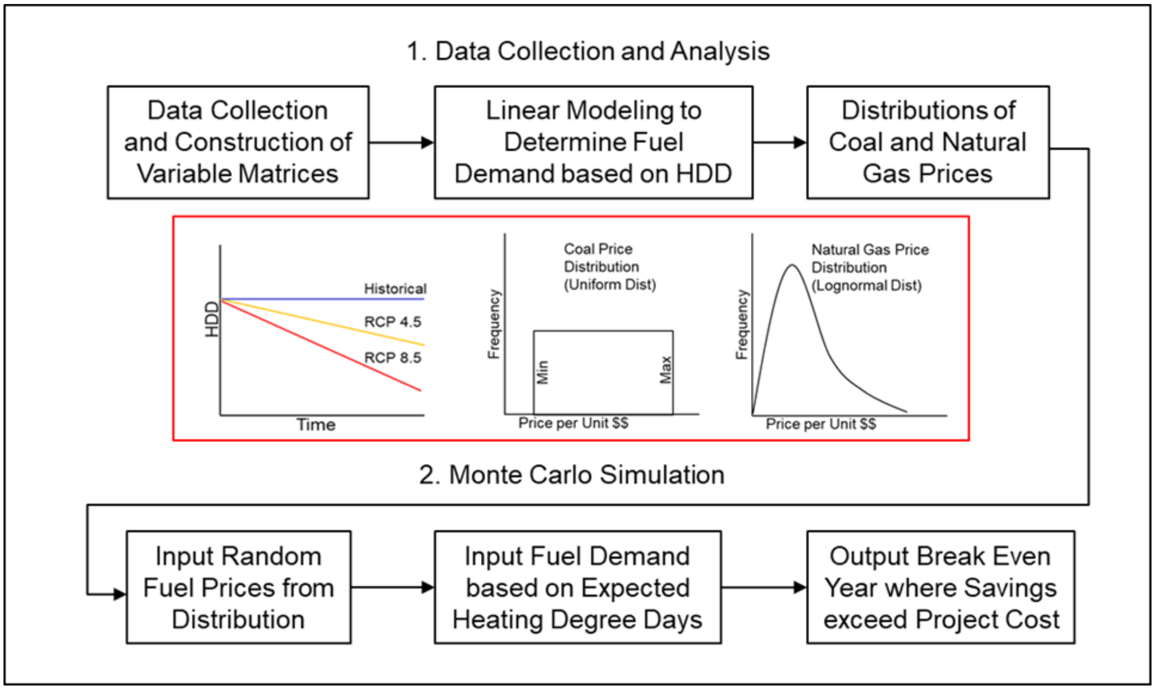


Figure 2. Fuel accounting data and conversion project data was collected from the 88th Civil Engineer Squadron on WPAFB. The accounting data for coal and natural gas was standardized by bringing all cost values to a 2010 present value and linear models were created based on historical relationships between fuel consumption and heating degree days. Distributions of fuel prices for both coal and natural gas were developed from historical pricing within the sample period (FY 2011-2018). From the data a Monte Carlo simulation was created to calculate the break-even year for the historical and RCP scenarios over 100,000 simulations.

Data Collection and Analysis

Data for this research came primarily from WPAFB accounting records containing monthly fuel cost and quantities for the period of October 2010 to September 2018 as well as monthly average temperature data for the same time period. Additionally, Coupled Model Intercomparison Project (CMIP) data was obtained for RCP models 4.5 & 8.5 for the time period ranging from January 2015 through December 2070 (56 years) (Maurer et al 2007; Pierce et al 2014; Reclamation 2013; Reclamation 2014; Vano et al 2020). The CMIP data contained 70 columns of RCP data values for each of the two projection where all models were averaged to produce a single projection for each. To produce a comparable projection that considers stationarity, the historical monthly temperature data from 2010 to 2018 were used to create monthly distributions, which were then sampled to produce a random monthly average temperature projection from 2015 to 2070 (See. Coal and natural gas quantities were presented in tons and CCF (hundred cubic feet), respectively, within the installation accounting datasheet. Fuel accounting data were further filtered to only include fuel costs and quantities attributed to either of the two steam heat plants on WPAFB.

Linear regression models were utilized to predict fuel usage. Of the various independent variables considered in this study (monthly extreme high and low temperatures, average high and low temperatures) heating degree days (HDD) were the best single predictor of fuel cost with an R-squared value of 0.81 for the entire period of performance. Utilizing the defined pre- and post- construction timelines, regression models for both fuel types were created using MATLAB software (See Figure 3). Pre-Construction natural gas vs HDD showed the poorest relationship which can be explained by the fact that during this time coal was the primary fuel for the base. Natural gas was used year-round for humidity control and to supplement coal shortages or temporary shutdowns due to environmental air permits. These variables caused natural gas to be used rather erratically pre-conversion. To keep the natural gas pre- and post-construction figures consistent, the pre-construction natural gas intercept was forced through the same intercept as post-construction at a baseline of 241,481 CCF per month. Due to a limited number of data points, there is significant uncertainty associated with the linear models. However, the uncertainty of these models are captured in the subsequent step, Monte Carlo simulations. Cost over quantity analysis was performed for both fuel types to determine a fuel cost distribution in order to simulate variable fuel prices over time. Coal costs followed a uniform distribution between approximately \$120 - \$166 / ton while natural gas prices followed a lognormal distribution with a mean of \$0.47 / CCF.

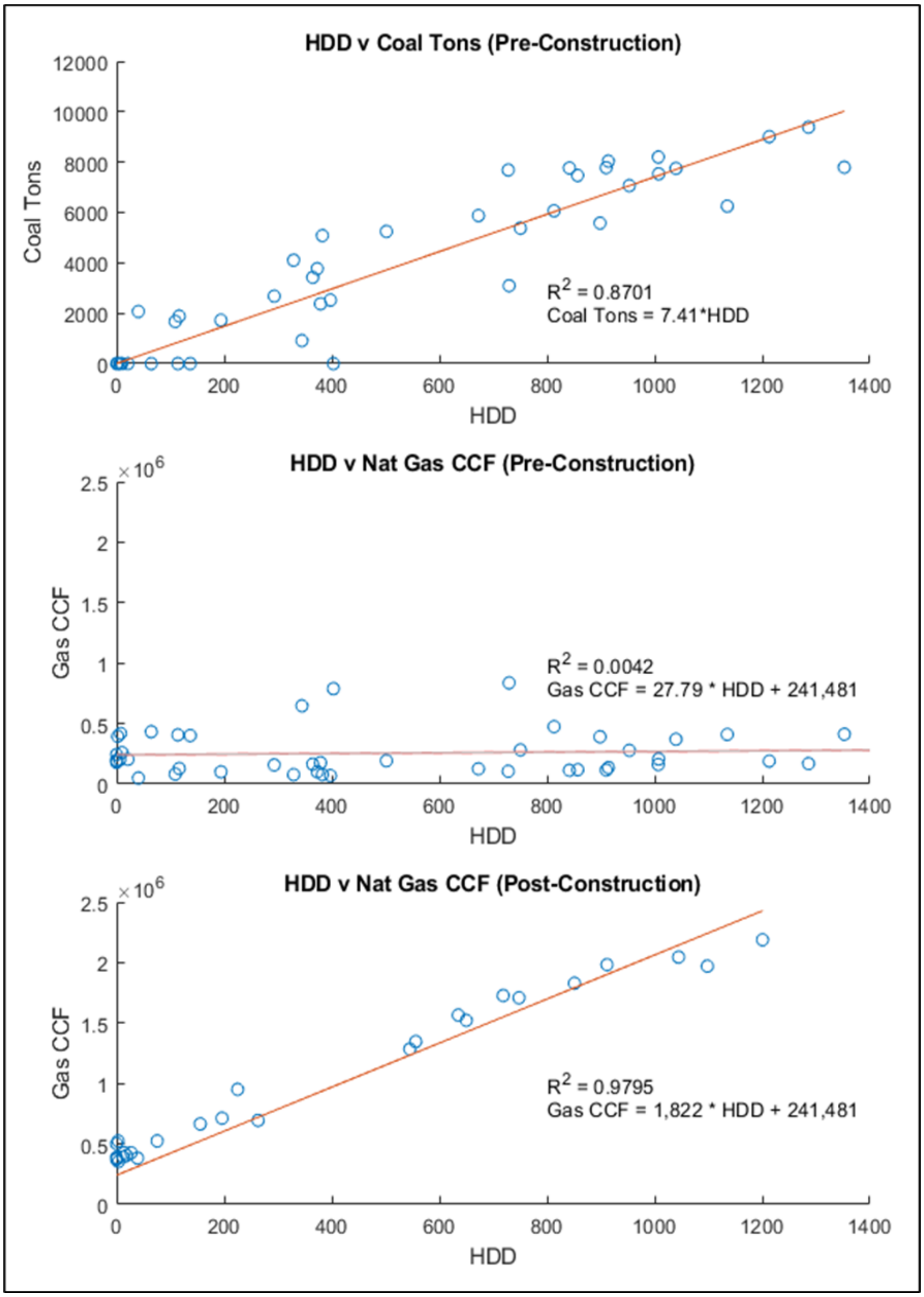


Figure 3. Linear plotting and regression was used to develop the relationship between fuel demand/consumption and HDD. A forced intercept was used to ensure pre-construction coal demand remained at zero as well as to ensure natural gas demand post construction maintained the same intercept as natural gas pre-construction.

Monte Carlo Simulation & Sensitivity Analysis

Once the data had been analyzed and prepped, three scenarios were built within MATLAB for a Monte Carlo simulation analysis. The three analyses would project historical weather data and two climate change projections (CMIP 4.5 & 8.5) beginning in 2015 and ending in 2070 (See Figure 4). The RCP 4.5 and 8.5 data sets consisted of 70 individual projections which were averaged to produce a single future climate projections for each scenario. It is for this reason that we see relatively smooth projections for RCP 4.5 and 8.5 in Figure 4, when compared to the projection based on historical data. Each individual simulation was set up to pull an average temperature for each month from 2015-2070 based on the projection. Additionally, the model would sample random coal and natural gas prices from the corresponding distributions and calculate a total fuel cost for each month within the time period based on the projected monthly HDD and respective linear regression equation. Within the model the fuel price distributions and the linear regression equations did not change. For pre-construction (coal as the primary fuel) the model included the sum of pre-construction coal demand and cost, as well as pre-construction natural gas demand and cost.

The monthly savings were recalculated as a 2015 present value at a 2% discount rate per year. Finally, the break-even year was calculated by determining the year in which cumulative savings met or exceeded the project cost, which in this case a project cost of $25M was used. The simulation returned 100,000 results with each iteration recalculating random fuel prices from within the historical distributions. A histogram was produced for each of the three scenarios to visualize the distributions of expected break-even year and averages for each were calculated.

A sensitivity analysis was performed for four uncertain variables. The variables analyzed within the sensitivity analysis were coal price, natural gas price, project cost, and discount rate. These variables were chosen due to their inherent nature of uncertainty and each of the variables was adjusted by +/- 10%. The decision to adjust the variables by 10% each was due to that fact that there was no information available on likely degrees of uncertainty and therefore it was an effort to be as unbiased as possible in the sensitivity transformations. The simulations were re-performed for each adjustment to determine the average change in break-even year as produced by the model.

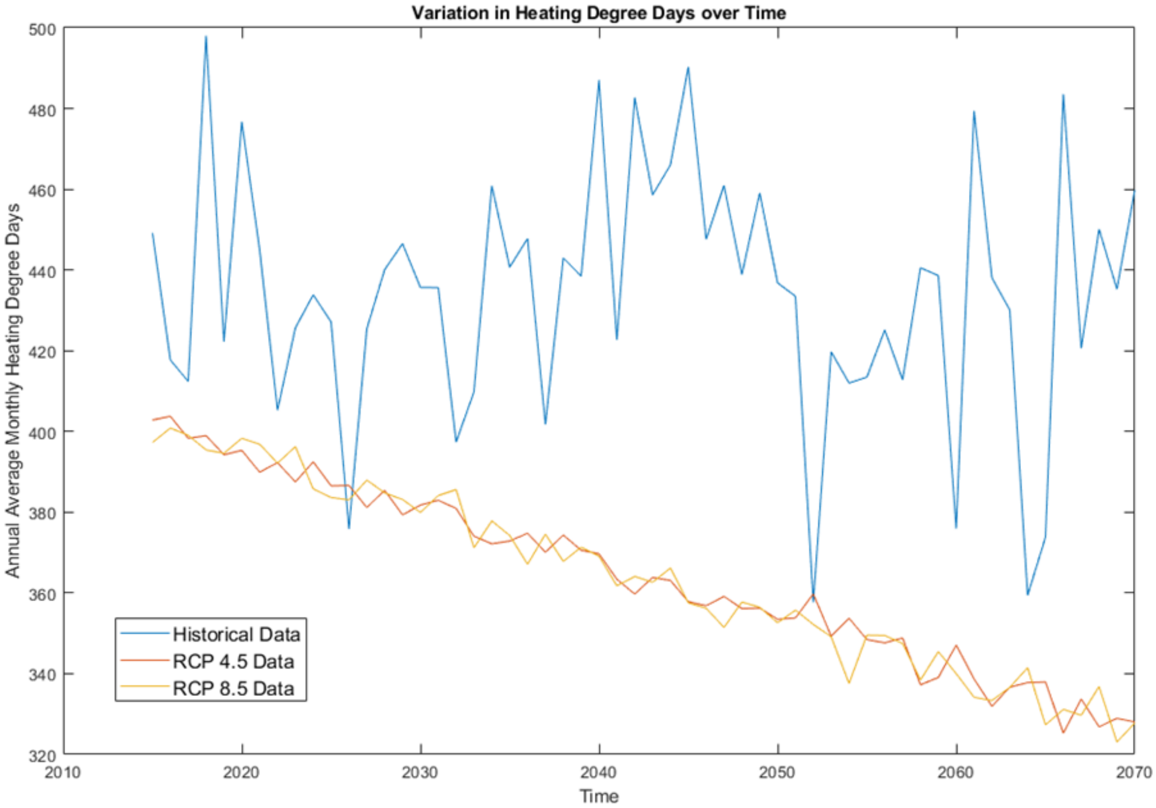


Figure 4. Heating degree days (HDD) over time for historical data, RCP 4.5 data, and RCP 8.5 data were used to introduce climate variability into the model. This figure averages monthly data for each year, however, HDD sampling within the Monte Carlo simulation pulled from average monthly temperatures. Historical weather data was constructed by sampling randomly from normal distributions of monthly HDD data for the time period of 2010 to 2018.

Results

The historical Heating Degree Day values that were calculated for the period from 2015 to 2070 resulted in a significant amount of ‘noise’ which can be seen in Figure 4. This noise is not unexpected, however, it stands in contrast to the much more linear appearance of the RCP 4.5 & 8.5 datasets. Each RCP data projection used in this analysis was produced from the mean values of 70 independent RCP projections which explains some of the linearity. The historical projection that does not account for climate change utilized only eight years (Fiscal years 2011 – 2018) of past temperature data to produce a weather projection.

Payback Period with Monte Carlo Simulation

The Monte Carlo Simulation results provided distributions for each of the three scenarios (See Figure 5): historical weather assuming no change in climate into the future, RCP 4.5 data being the more conservative climate change model, and RCP 8.5 data being the more extreme climate change model. Three distinct observations can be made from these results with the first being the change in mean between the historical weather data and the climate change models. The mean value for the historical data distribution returns 28.7 years while the RCP datasets return mean values of 34.7 years giving us a 20% positive shift in break-even year when considering climate change. A pair sample t-test was performed and confirm that the means were statistically different at a 99% level of significance. The second observation that can be made is the decrease in distribution kurtosis for the climate change models compared to the historical dataset. The standard deviation of the historical data break-even year distribution is 2.3 years as compared to 3.2

for both climate change models. The third observation that can be made from these results is the fact that very little, if any, divergence can be seen between the varied climate change datasets (not shown in figure). The RCP 8.5 data, based on the projection, was not provided enough forward time to create a discernible divergence from the more conservative RCP 4.5 model.

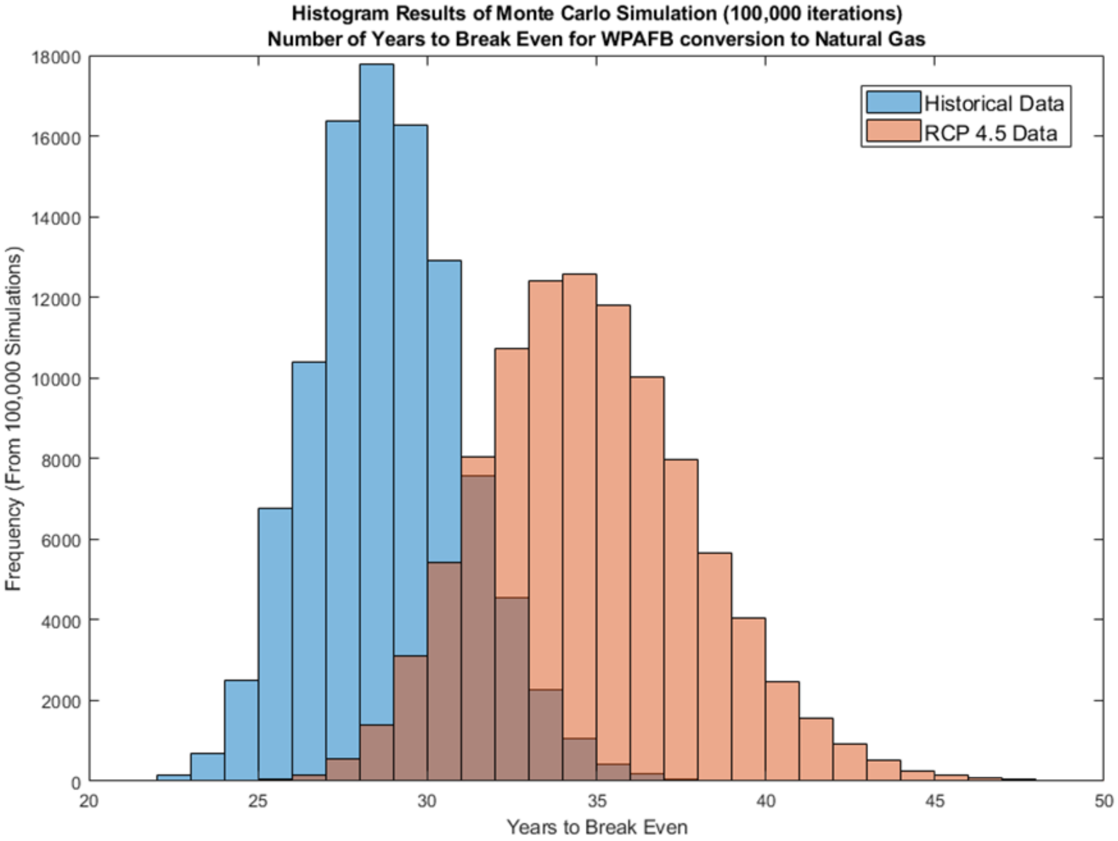


Figure 5. A histogram of the results of the Monte Carlo simulation showed a mean break even year of 28.7 for historical weather data while RCP 4.5 and RCP 8.5 data both resulted in a break even point of 34.7 years.

Sensitivity Analysis

The results of the sensitivity analysis for the four uncertain variables can be seen in Figure 6. The Monte Carlo simulation results for the RCP 4.5 and RCP 8.5 datasets were nearly identical under these conditions and within the model timeframe and therefore only the RCP 4.5 data was used for an analysis of sensitivity. The primary observation from this analysis is the model's high level of sensitivity to fuel price and comparatively low sensitivity to project cost and discount rate. For a 10% decrease in coal price under both scenarios a payback period increase upwards of 20-30% can be seen. Conversely, and logically, a 10% increase in natural gas price increases the payback period by between 21-22%. Additionally, there is an apparent a skewness to the figure, showing a tendency for the model to increase in payback period versus a reduction. The historical model shows a higher level of sensitivity and a higher degree of skewness when compared to the climate change model.

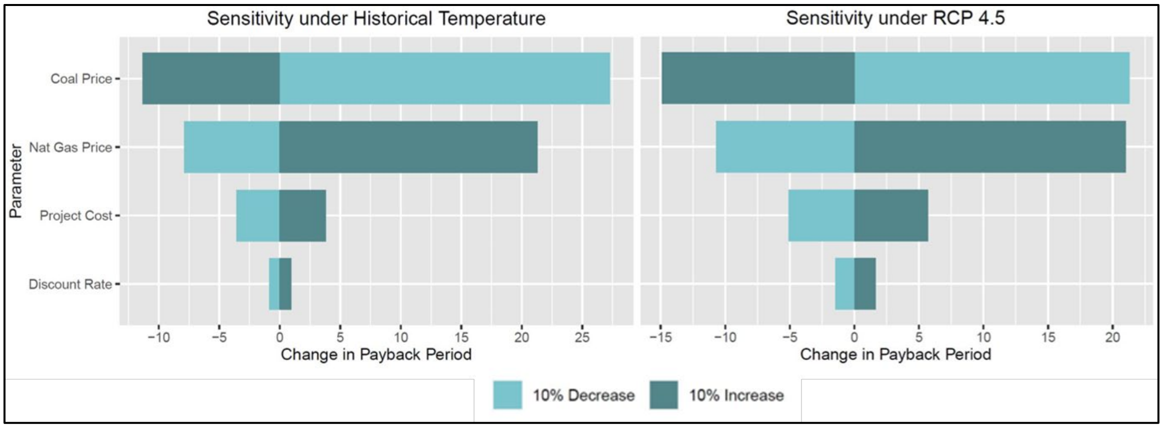


Figure 6. A sensitivity analysis for four uncertain variables within the model was performed for both the historical data and RCP 4.5 simulations. The variables were adjusted +/- 10% and the figures above show the resultant change in the break-even year outcome. Of the variables analyzed, coal and natural gas price showed the highest sensitivity. A 10% reduction in mean coal price or a 10% increase in natural gas price resulted in an additional 20+ years to achieve project payback.

Discussion

In 2012, WPAFB was faced with changing environmental regulations that forced the government to significantly invest in their heat plant infrastructure in order to remain in USEPA compliance. Major power plant systems are extremely expensive and designed to last 30-40 years which drove the base to perform a long-term economic analysis (Carley 2018; Wright Patterson Air Force Base 2011). The two basic alternatives were to update the existing coal handling systems to modern emissions control technology or demo the coal systems altogether and retrofit the plants to utilize natural gas as the primary fuel for base heating (Barber 2013). The economic analysis considered, environmental impacts, regional feasibility, short term capital costs, and long term fuel and maintenance costs. (Wright Patterson Air Force Base 2011).

The environmental benefits of natural gas are well known and Ohio has become a prime candidate regionally for natural gas availability. The long term economic assessment utilized a simple economic analysis that relied on current fuel price rates did not consider any change in mean temperature over time. In this way the installation decision makers were given a poor view of the level of uncertainty contained within the assessment. As Lo et al (2005) establishes, a Monte Carlo simulation that introduces uncertainty can provide for a better informed decision based on clearer and more complete comparison of options. This research does not contend that WPAFB made a wrong or poor long-term decision, however, it does assert that similar conversion projects could benefit from a Monte Carlo analysis that considers uncertainty in climate change and fuel pricing through the lifetime of the infrastructure.

Monte Carlo Simulation and Sensitivity Analysis

The Monte Carlo simulation results can be seen as histogram figures of break-even-year frequency for both historical and climate change temperature projections (Figure 5). Due to the extremely similar nature of the RCP 4.5 and 8.5 results, only the RCP 4.5 results are shown for simplicity. The mean break-even-year of the conversion project under climate change weather conditions was 20% greater than the payback period under historical conditions. This information was not considered in WPAFB's economic analysis of alternatives. However, this might not have changed the decision based on maintenance and other operating costs and the benefits of natural gas under stricter environmental policies. The range of values for each climate projection scenario allow us to visualize some of the uncertainty that is inherent in long term infrastructure investments.

The sensitivity analysis that was shown in Figure 6 provides additional insight into the level of uncertainty that the model faces. The high sensitivity of fuel prices and their influence on the results tells us that these variables are extremely important to making an accurate long-term economic assessment. A 10% decrease in the mean coal price increases our payback period by over 20 years. In the small time period that coal data was available for WPAFB, the price distribution fluctuated +/-16% between \$120 and \$166 per ton. WPAFB utilized a static fuel price figure based on current fuel price data from the time of the economic assessment. What this type of simple analysis does not provide is the level of uncertainty within the underlying assumptions. This Monte Carlo simulation and sensitivity analysis provide a much clearer view of where and to what degree, uncertainty plays a role in our infrastructure decision making.

Limitations

There are a number of limitations to this research with the foremost being the limited dataset available for historic fuel prices at Wright Patterson Air Force Base. The fuel price distributions created using the available data were sampled from randomly within the Monte Carlo simulation which may create some results inconsistent with real world factors. For example, a long and short-term relationship likely exists between natural gas and coal prices that was not accounted for in this model. Additionally, any long-term economic projections for coal and natural gas availability and price was not taken into consideration. The fuel price data was based strictly on the eight years of available WPAFB accounting data. For sake of simplicity, the historical temperature data was used for the same time period from October 2010 to September 2018 which may or may not accurately reflect a true historical trend projected into the future to year 2070. This model and analysis only examines the payback period for the capital investment on the conversion project based on fuel price and climate projection uncertainty. Variation in other operations and maintenance costs such as equipment service life, recurring maintenance costs, and required manpower for operation were not considered in this model and would likely play a significant role in a full economic analysis of the alternatives. Due to the fact that operations and maintenance cost of natural gas plants are often much lower than that of coal fired plants, the inclusion of these variables would likely reduce the overall payback period of the infrastructure conversion (Grubert et al 2012).

Conclusion

In the existing body of literature, a great deal of research is available on the impacts of the commercial energy sector on climate change, however, very little research has been performed on the effects of climate change on commercial energy capital investment returns. This research provides valuable information to decision makers within municipalities and commercial energy providers nearing the end of their infrastructure service life. A simple deterministic economic analysis without considering fuel price and climate uncertainty may not provide an accurate projection of investment return. In this case study, a positive 20% shift in mean expected payback for WPAFB is seen when uncertainty is considered into the analysis. This positive 6-year shift in project payback is significant in that it could sway decision makers as they evaluate the economic viability of alternatives. Additionally, compared to a deterministic approach, a Monte Carlo analysis produces values of uncertainty for independent scenarios. This data would provide decision makers additional information and a clearer and more complete comparison of options to aid in significant long term economic assessments. Natural gas, as well as many forms of alternative and green energies, are becoming more available due to international concern over climate change, expanding infrastructure, and advancing technology. These conversions are extremely costly and have great environmental and economic implications. A broader view of uncertainty would benefit decision makers as these projects become more common due to environmental policy or as infrastructure nears the end of its service life. A Monte Carlo analysis provides the potential to account for uncertainty such as climate change to better inform decision makers within the DoD, local, State, and Federal systems.

III. Geospatial Analysis of U.S. Coal & Natural Gas Resources and Infrastructure

Over the last 20 years, natural gas has replaced coal as the preferred fossil fuel for heat and power generation across the United States, due to its lower cost, reduced environmental impacts, and increased availability due to advancements in extraction technology and transportation infrastructure. Wright Patterson Air Force Base (WPAFB) transitioned from coal to natural gas as its primary heating fuel to satisfy increasingly strict environmental air quality regulations and save long term operating costs. This transition was made possible by modern technological advances in natural gas extraction and transportation. Modern hydraulic fracturing and increasing pipeline infrastructure has greatly improved national access to natural gas resources. Transitions, such as the one at WPAFB, will likely increase in the future for both financial and environmental reasons but will be constrained by geospatial accessibility to natural gas resources and/or easier access to alternative energy resources. Data from the U.S. Energy Information Administration provides geospatial information on natural gas and coal resources, transportation infrastructure, and power plant consumption which was analyzed to determine what regions might have the highest potential for a similar transition away from coal to natural gas. By analyzing power plant data by primary fuel source across the United States against coal and natural gas infrastructure, this research shows that there is a higher density of natural gas capability in coal burning plants across the midwestern states. This information provides us with a geographic focus area for viability of future research into feasible coal to natural gas transitions.

Introduction

The WPAFB transition from coal to natural gas was a significant project taking multiple years to complete and costing upwards of $25M. The force behind the transition was a regulatory change made by the U.S. Environmental Protection Agency (EPA) in 2012 that affected air quality emissions standards for industrial, commercial, and institutional boilers (Wright Patterson Air Force Base 2011). For many facilities nationwide, including WPAFB, this would mean either a large-scale overhaul to modernize the existing coal fired boiler system, or a transition to an alternative fuel that could meet the same demand while maintaining increasingly strict emissions standards. Based on an economic analysis contracted by the Air Force Base, the decision was made to invest in a conversion to natural gas as the primary heating fuel. The economic analysis considered environmental impacts, short and long-term economics of alternatives, and regional feasibility. The environmental benefits of natural gas when compared to coal are well documented and the economic analysis resulted in a conversion to natural gas having a lower capital construction cost as well as reduced annual operations and maintenance costs. The EPA's rule change applied to over 1,700 existing boilers nationwide, however, many coal-fired plants are still in service today (CEC 2020). The transition to natural gas at WPAFB was largely made possible by improved technologies in natural gas extraction that were new to the industry around the time of the regulatory change (Zheng et al 2020). This drives the question*: if technologies have changed over time allowing WPAFB to transition to a cheaper and cleaner burning fuel, where else might a similar transition be viable?* The technology that has changed over time is largely in the natural gas extraction process and transportation infrastructure. To answer the previous question this research aims to geospatially analyze energy infrastructure data from EIA.gov and determine the infrastructure that has allowed WPAFB to transition from coal to natural gas and where these infrastructure changes might also make other transitions an attractive option for consumers and energy production industries.

Background

Wright Patterson AFB, located in Southwestern Ohio, provides an interesting case study due to its size (8000 acres), population (>27,000 personnel), and geographic location (Wright Patterson Air Force Base 2019). Due to a large population, industrial economy, and wide seasonal temperature variations, Ohio is among the top ten states in total energy consumption. Ohio is also among the top ten coal consuming states, and while Ohio is the 15th largest coal producing state, more than three times as much coal is consumed as is produced there (EIA 2020). Due to advancements in natural gas extraction technology, by 2019, Ohio's natural gas production grew to be more than 30 times greater than in 2012 (EIA 2020). Almost all of the state's natural gas comes from the Utica Shale wells where horizontal drilling and hydraulic fracturing are required to extract the gas (EIA 2020). Ohio's natural gas production surpassed consumption for the first time in 2015 and in 2018, the electric power sector became the state's largest natural gas consumer (EIA 2020). In 2019, natural gas provided more of Ohio's in-state electricity than coal for the first time (EIA 2020)

In 2015, WPAFB embarked on the process of switching their coal-fired boilers at two centralized heating plants to natural gas boilers, eliminating the need for coal at the installation. Natural gas is widely known as a cleaner and more environmentally friendly alternative to coal. Switching from coal to natural gas reduces SOx and NOx emissions and natural gas is often discussed as having a lower overall carbon footprint when compared to coal (Grubert et al. 2012). Additionally, the switch from coal to natural gas reduces water consumption upstream from the power plants in the fuel extraction and refinement practices. Using 2013-2016 data from the U.S. Energy Information Administration (EIA), Kondash et al. estimates direct and indirect water consumptions for fuel extraction, transportation, and refinement to be 0.60 m^3 per MWh for coal and only 0.18 m^3 for natural gas (2019).

While the environmental benefits are well documented, the driving force of this conversion is most likely situated economically as natural gas is relatively cheap and typical natural gas fired plants are cheaper and to construct and operate (EIA 2019). Additionally, natural gas fired plants are more flexible operationally than similar coal plants which may benefit energy grids as policies and economics evolve and change (Grubert et al. 2012). As time and money is applied to this area of research, this paper aims to analyze and discuss the United States geospatial energy usage by fuel type to determine which regions or states may find natural gas as an attractive option and where similar transitions might be viable.

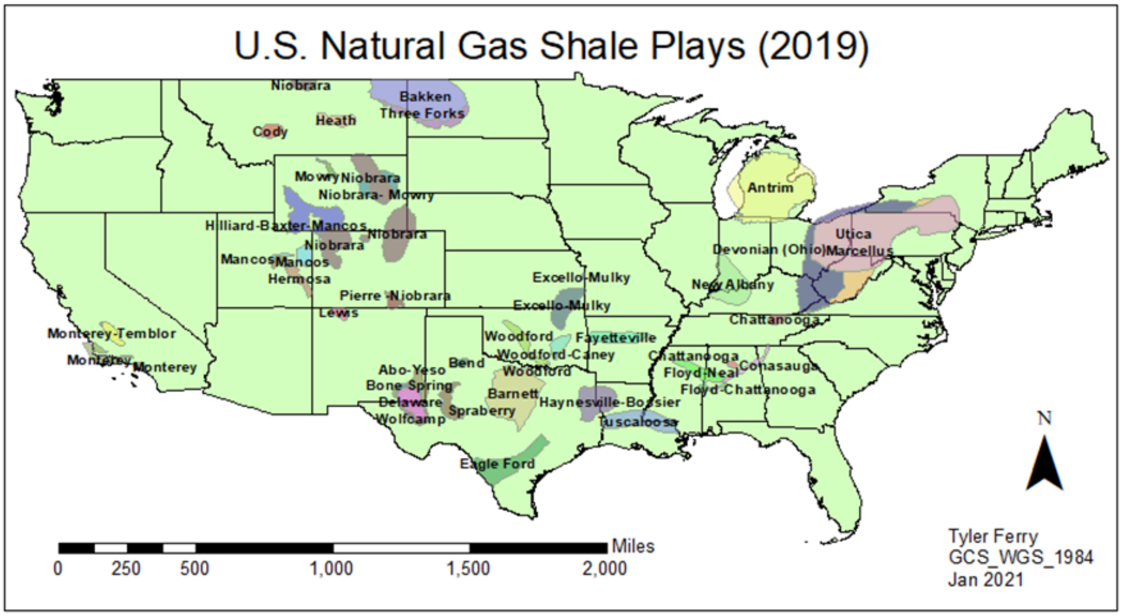


Figure 7. United States active natural gas shale plays as of 2019.

Methods

The data for this research was found from EIA.gov (EIA n.d.) which consisted of geospatial data on power plants across the United States including total power output and output by fuel type. Additionally, coal and natural gas infrastructure data was available including tight shale plays for natural gas extraction (See Figure 7), active coal mines, natural gas pipelines, and railroads for coal transportation. The powerplants data was filtered to only include natural gas and coal fired plants by primary source, and later down to only power plants that list coal as a primary source. This data filtering was done by using ArcMap’s table to excel function to export data to an Excel pivot table. From this data, using graduated colors and symbols, the data could be visually analyzed based on fuel type used and total energy output. The original power plant data was then spatially joined to a basemap of United States states to analyze fuel usage trends across the nation. The

ArcMap buffer tool was then used to create buffers in distances of 1 mile, 5 miles, and 10 miles around plants that primarily utilize coal as their fuel source. From these buffers, and utilizing natural gas pipeline data, powerplants could be filtered to determine which plants were within a set distance from natural gas infrastructure. Finally, the most relevant data to this research came from filtering power plants that listed coal as their primary source but also had existing access to natural gas. These plants were determined through either a direct intersection with a natural gas pipeline or through filtering the data for primarily coal plants that also listed a supplementary output of natural gas energy.

Results & Discussion

From the initial geospatial analysis it can be seen in Figure 8 that power plants listing coal and natural gas are widely spread across the United States. There appears to be a larger count for plants listing natural gas as their primary source when compared to coal but it is important to note that this map does not consider total generation of the plant. The regions where coal fired plants become more common are in the rocky mountain states such as Colorado, Utah, Wyoming, and Montana, as well as North Dakota. The midwestern states such as Ohio, West Virginia, Kentucky, Indiana, Illinois, Iowa, Nebraska, Minnesota, Wisconsin, and Michigan all show a higher density of coal fired plants than does much of the rest of the country. The midwestern states also show a high density of natural gas fired plants as well. This preliminary data analysis provides us a focus area for the rest of the analysis as to where one might expect to see a viability for a transition from coal where natural gas is also available.

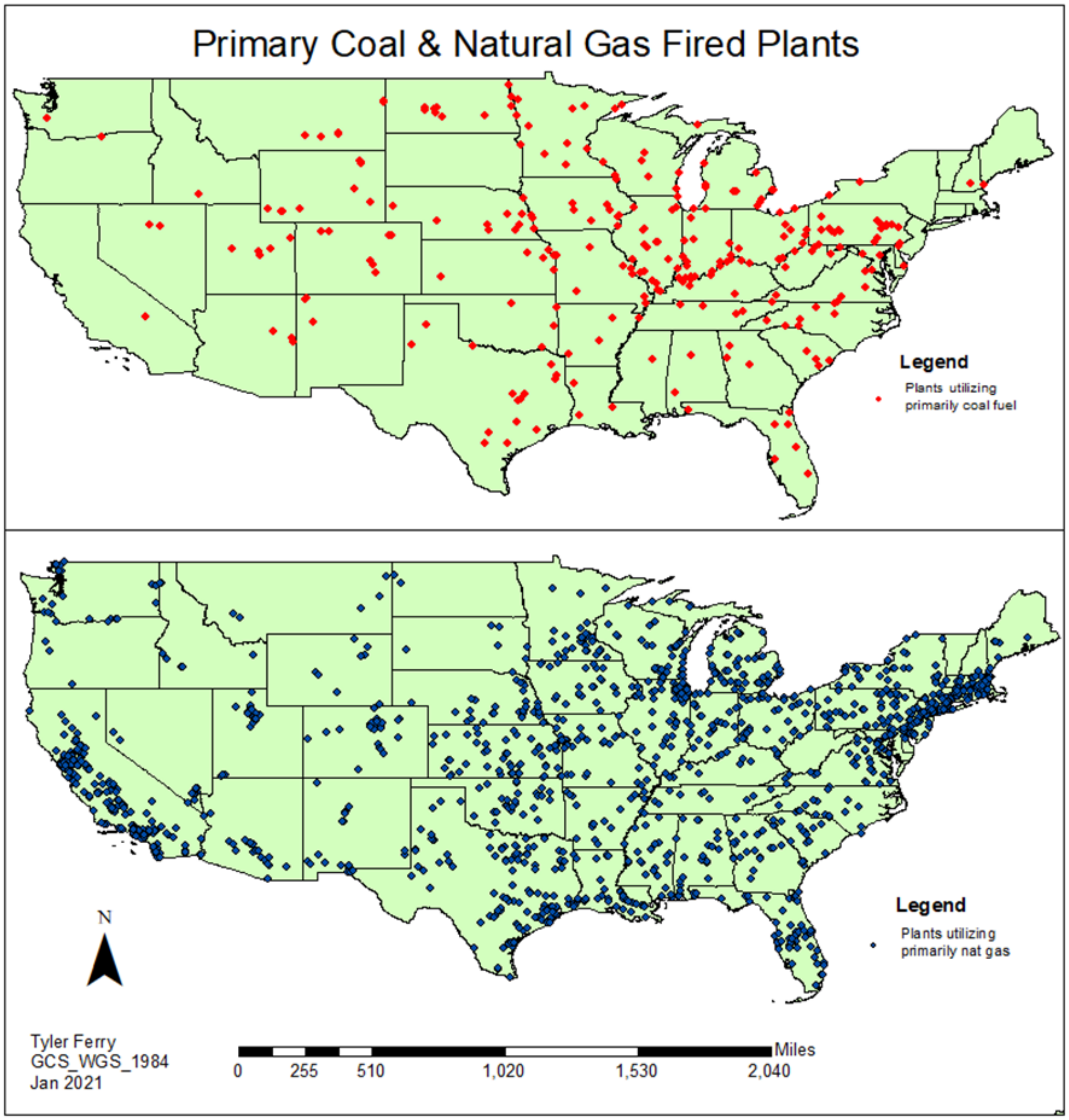


Figure 8. Primary coal and primary natural gas fired plants within the United States

Another important analysis that was performed as part of this research was to build an energy profile of the United States based on primary energy generation by fuel type. Figure 9 shows five maps of the United States for natural gas, coal, hydroelectric, nuclear, and wind & solar. These maps compare the energy produced across the state by a specific fuel as a percentage of total energy output from within that state. Starting with wind &

solar, the map shows a band of higher than average wind and solar output across the central United States stretching from Texas to North Dakota. A higher density of wind and solar generated power can also be seen in some western states such as California, Oregon, and Idaho. These states likely have better access to these resources based on terrain, annual climate, and especially space. Wind and solar power infrastructure can require a large amount of land area which could be partly responsible as to why there appears to be a very low density of wind and solar assets east of the Mississippi river.

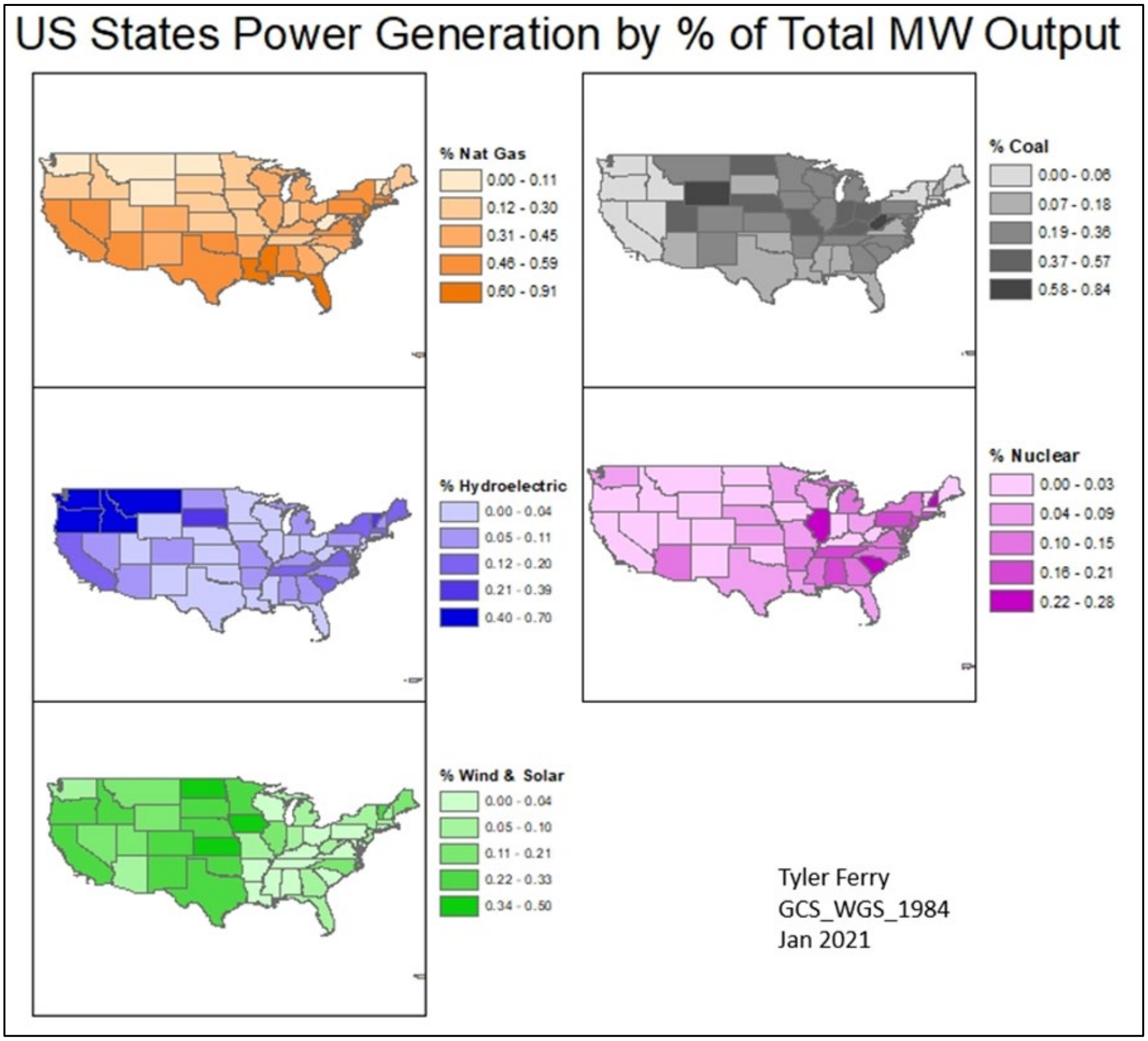


Figure 9. United States trends in power generation shown by fuel type as a percentage of total state energy production.

Hydroelectric power appears to show a much higher usage in the pacific northwest states of Washington, Oregon, Idaho, Montana, and into South Dakota. The Columbia and Missouri river basins have provided these states with a significant supply of hydroelectric power. Nuclear power is becoming more widely used but appears to be more utilized on the east coast with some frequency in the southern states. It is important to pay particular attention to the scales here which are not standardized across all maps and the highest percentage of output by state for nuclear power is ~30%. The most recent data that was acquired through EIA was from 2004 so there is a high likelihood that this information has changed greatly in terms of nuclear power usage across the United States

Natural gas usage appears to be a significant percentage of the total energy output for most of the gulf coast states as well as California and Nevada, and some of the Midwest and New England states. The higher percentage in the Gulf Coast states is due to the high availability of natural gas in that region. Coal appears to be widely used across the United States with the exception of the pacific coast, Gulf Coast, and far northeastern states. Looking specifically at the maps for natural gas and coal, it can be inferred that one of the regions where both fuels are common is across the midwestern states.

In Figure 10 the EIA data was analyzed to spatially view extraction and infrastructure data for coal and natural gas. This figure is two part, with the top map showing active coal mines and railroad infrastructure for transporting coal, and the bottom map showing tight shale plays within the United States and natural gas pipeline infrastructure. The active coal mines are plotted using symbols of graduating size based on the total coal output in short tons. Although the rail system is extremely prolific, coal extraction is relatively isolated to a few regions across the United States. Kentucky, Ohio, West Virginia, and Pennsylvania show a high density of mines, but we see higher output from individual mines in Wyoming and Montana. Interestingly, looking at the tight shale plays for natural gas it is apparent that they occur in many of the same locations and regions as active coal mines. The natural gas pipeline infrastructure is extremely dense near the gulf coast where gas can be obtained in high quantities from offshore drilling. A higher density of natural gas pipeline infrastructure can be seen in the midwestern states which further supports the hypothesis that both natural gas and coal is widely accessible in the Midwest.

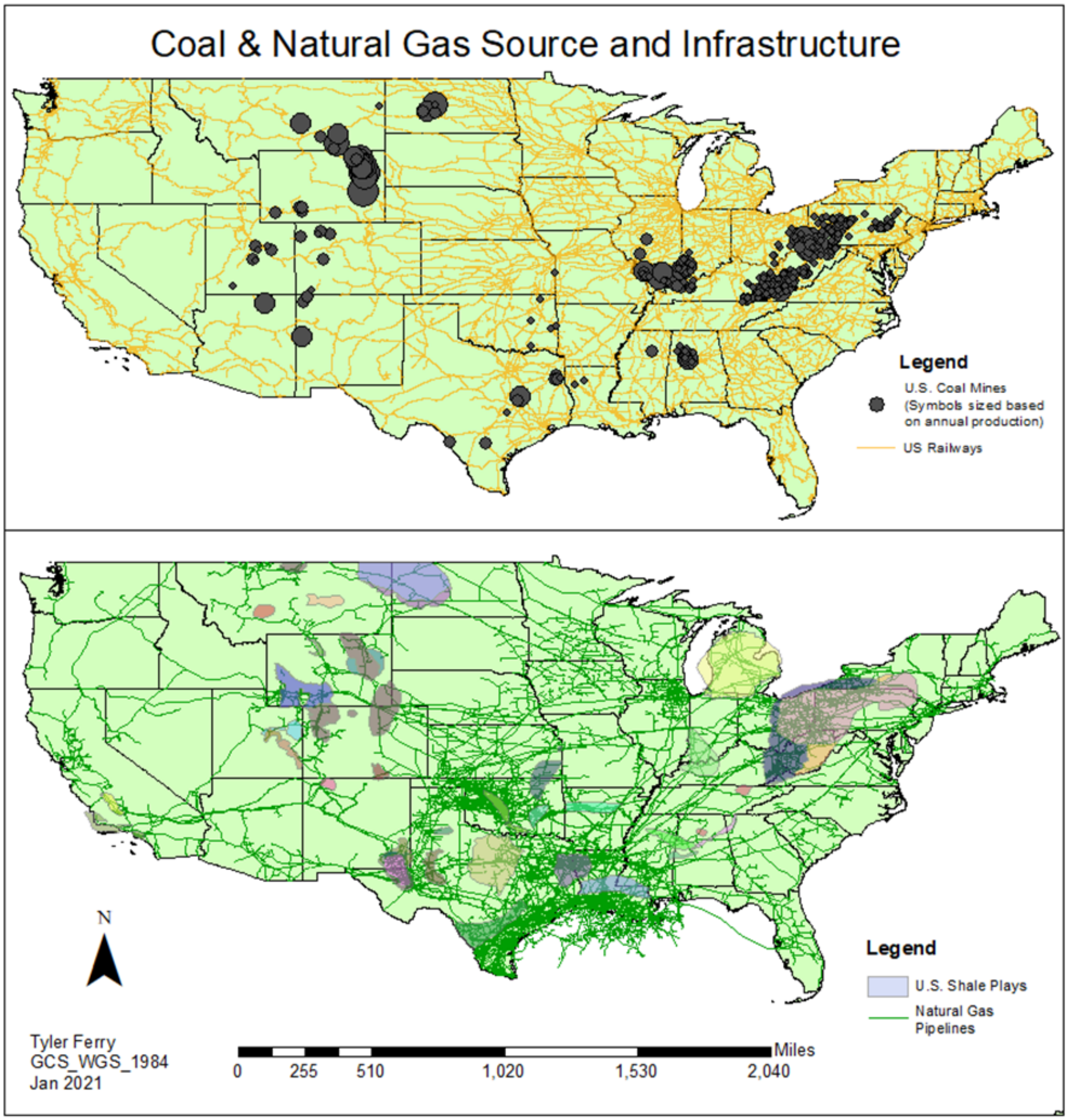


Figure 10. Active United States Coal mines and major shale plays coupled with transportation infrastructure.

From the powerplant data and natural gas pipeline data a proximity analysis was performed for coal fired plants nearest to natural gas pipelines. Figure 11 shows a map of all United States powerplants that list coal as their primary fuel source. The different colored symbols for some plants indicate the distance from the nearest natural gas pipeline. This map shows us an apparent density within the midwestern states but when it is cleaned up in Figure 12 a clear focus on the Midwest can be seen. Figure 12 shows United States power plants listing coal as a primary fuel source but also utilizing natural gas as a supplementary source. These plants have access to natural gas delivery, however, like WPAFB prior to 2015, they likely do not have the plant infrastructure to use natural gas as their primary fuel. The table in Figure 12 shows the tabulated data on these plants with facility names, utility owner, and the city and county of the facility.

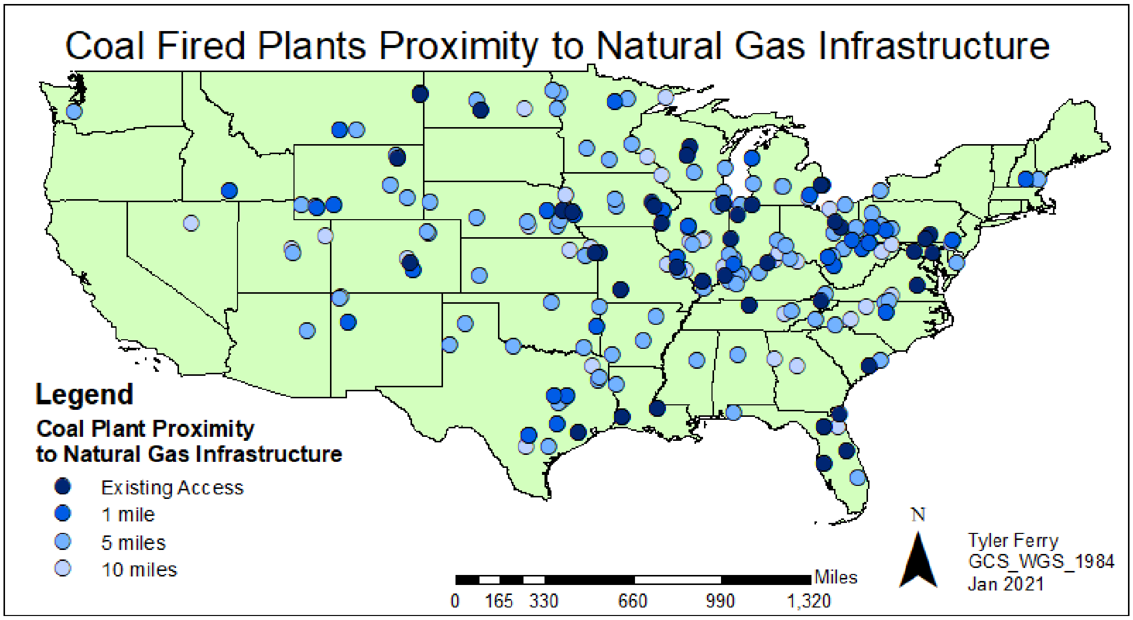
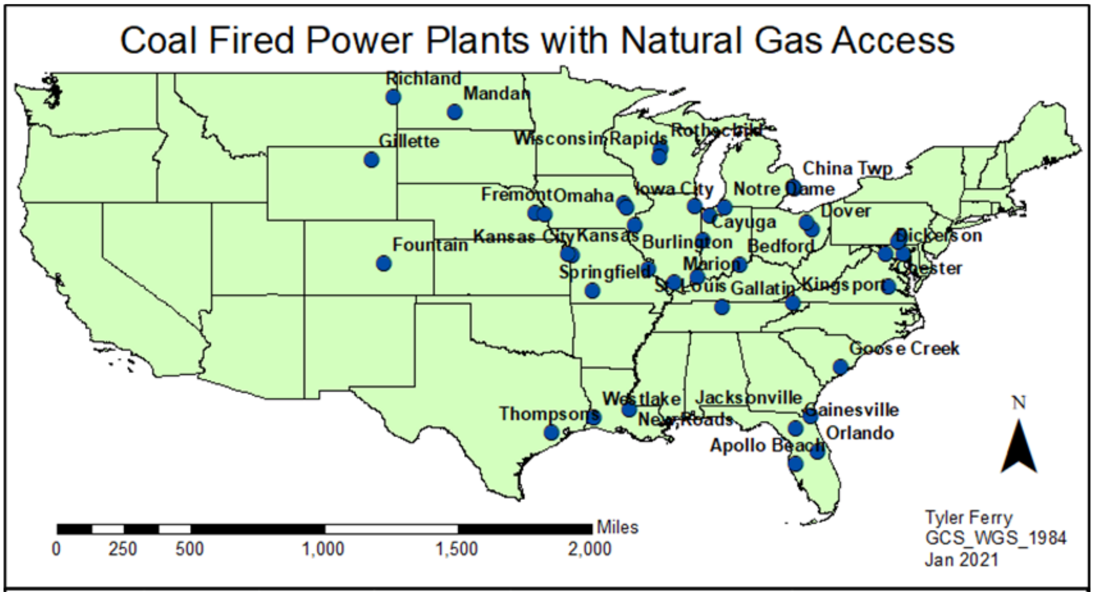
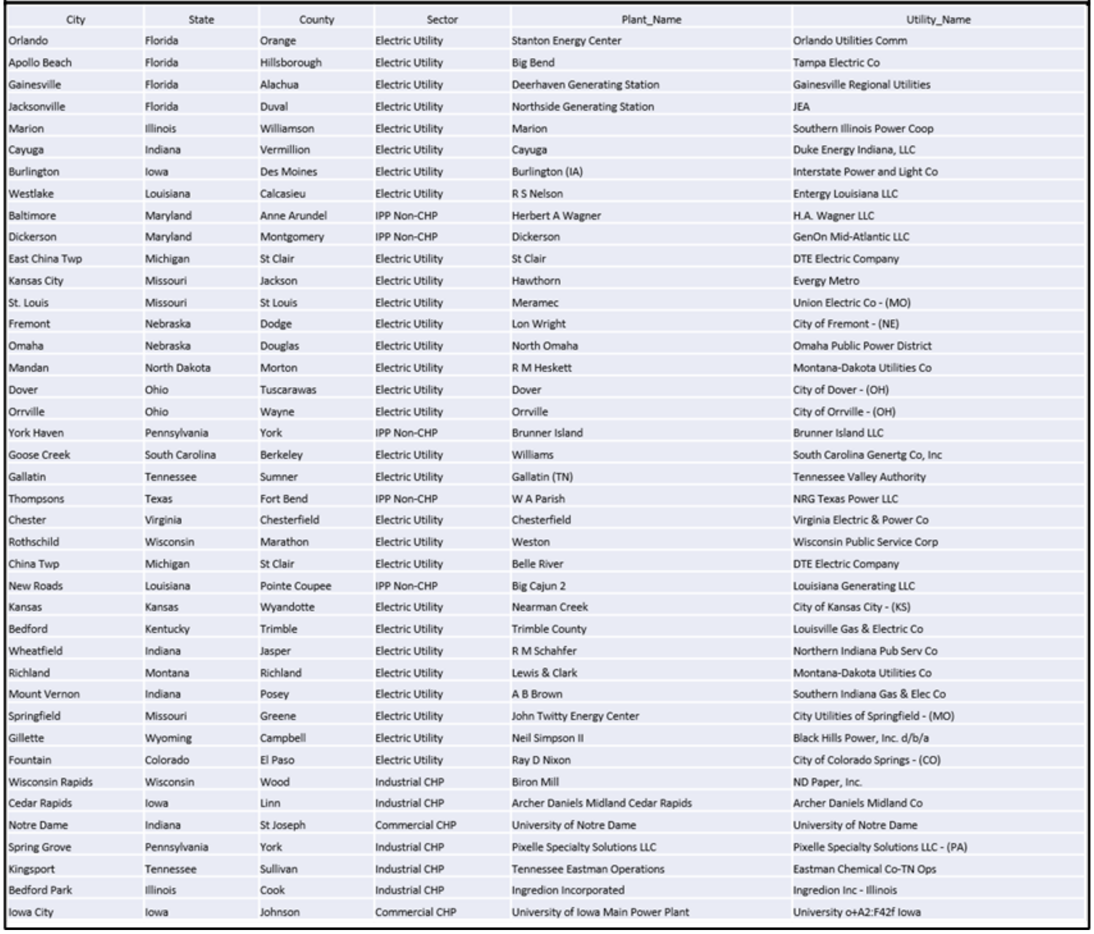


Figure 11. Proximity to natural gas infrastructure (pipelines) for active United States coal fired plants. Existing access is defined as plants that already have and use natural gas as a secondary fuel.



Coal Fired Power Plants with Natural Gas Access

Tyler Ferry
GCS_WGS_1984
Jan 2021



City	State	County	Sector	Plant_Name	Utility_Name
Orlando	Florida	Orange	Electric Utility	Stanton Energy Center	Orlando Utilities Comm
Apollo Beach	Florida	Hillsborough	Electric Utility	Big Bend	Tampa Electric Co
Gainesville	Florida	Alachua	Electric Utility	Deerhaven Generating Station	Gainesville Regional Utilities
Jacksonville	Florida	Duval	Electric Utility	Northside Generating Station	JEA
Marion	Illinois	Williamson	Electric Utility	Marion	Southern Illinois Power Coop
Cayuga	Indiana	Vermillion	Electric Utility	Cayuga	Duke Energy Indiana, LLC
Burlington	Iowa	Des Moines	Electric Utility	Burlington (IA)	Interstate Power and Light Co
Westlake	Louisiana	Calcasieu	Electric Utility	R S Nelson	Entergy Louisiana LLC
Baltimore	Maryland	Anne Arundel	IPP Non-CHP	Herbert A Wagner	H.A. Wagner LLC
Dickerson	Maryland	Montgomery	IPP Non-CHP	Dickerson	GenOn Mid-Atlantic LLC
East China Twp	Michigan	St Clair	Electric Utility	St Clair	DTE Electric Company
Kansas City	Missouri	Jackson	Electric Utility	Hawthorn	Evergy Metro
St. Louis	Missouri	St Louis	Electric Utility	Meramec	Union Electric Co - (MO)
Fremont	Nebraska	Dodge	Electric Utility	Lon Wright	City of Fremont - (NE)
Omaha	Nebraska	Douglas	Electric Utility	North Omaha	Omaha Public Power District
Mandan	North Dakota	Morton	Electric Utility	R M Heskett	Montana-Dakota Utilities Co
Dover	Ohio	Tuscarawas	Electric Utility	Dover	City of Dover - (OH)
Orrville	Ohio	Wayne	Electric Utility	Orrville	City of Orrville - (OH)
York Haven	Pennsylvania	York	IPP Non-CHP	Brunner Island	Brunner Island LLC
Goose Creek	South Carolina	Berkeley	Electric Utility	Williams	South Carolina Genertg Co, Inc
Gallatin	Tennessee	Sumner	Electric Utility	Gallatin (TN)	Tennessee Valley Authority
Thompsons	Texas	Fort Bend	IPP Non-CHP	W A Parish	NRG Texas Power LLC
Chester	Virginia	Chesterfield	Electric Utility	Chesterfield	Virginia Electric & Power Co
Rothschild	Wisconsin	Marathon	Electric Utility	Weston	Wisconsin Public Service Corp
China Twp	Michigan	St Clair	Electric Utility	Belle River	DTE Electric Company
New Roads	Louisiana	Pointe Coupee	IPP Non-CHP	Big Cajun 2	Louisiana Generating LLC
Kansas	Kansas	Wyandotte	Electric Utility	Nearman Creek	City of Kansas City - (KS)
Bedford	Kentucky	Trimble	Electric Utility	Trimble County	Louisville Gas & Electric Co
Wheatfield	Indiana	Jasper	Electric Utility	R M Schahfer	Northern Indiana Pub Serv Co
Richland	Montana	Richland	Electric Utility	Lewis & Clark	Montana-Dakota Utilities Co
Mount Vernon	Indiana	Posey	Electric Utility	A B Brown	Southern Indiana Gas & Elec Co
Springfield	Missouri	Greene	Electric Utility	John Twitty Energy Center	City Utilities of Springfield - (MO)
Gillette	Wyoming	Campbell	Electric Utility	Neil Simpson II	Black Hills Power, Inc. d/b/a
Fountain	Colorado	El Paso	Electric Utility	Ray D Nixon	City of Colorado Springs - (CO)
Wisconsin Rapids	Wisconsin	Wood	Industrial CHP	Biron Mill	ND Paper, Inc.
Cedar Rapids	Iowa	Linn	Industrial CHP	Archer Daniels Midland Cedar Rapids	Archer Daniels Midland Co
Notre Dame	Indiana	St Joseph	Commercial CHP	University of Notre Dame	University of Notre Dame
Spring Grove	Pennsylvania	York	Industrial CHP	Pixelle Specialty Solutions LLC	Pixelle Specialty Solutions LLC - (PA)
Kingsport	Tennessee	Sullivan	Industrial CHP	Tennessee Eastman Operations	Eastman Chemical Co-TN Ops
Bedford Park	Illinois	Cook	Industrial CHP	Ingredion Incorporated	Ingredion Inc - Illinois
Iowa City	Iowa	Johnson	Commercial CHP	University of Iowa Main Power Plant	University o+A2:F42f Iowa

Figure 12. United States power plants with existing natural gas access.

Conclusion

Natural gas is widely known as a cheaper and cleaner alternative to coal for heat and electricity production. Historically, due to extraction technology and infrastructure availability, natural gas was limited regionally. Advancements in hydraulic fracturing and pipeline infrastructure are rapidly expanding the availability of natural gas as a primary fuel and many communities and municipal power plants are considering a similar transition as WPAFB. From this analysis it can be seen that the midwestern states, where both coal and natural gas is widely available, are strong candidates for similar transitions. In advocating for natural gas as a more economic and environmentally beneficial fuel compared to coal, the midwestern states would be a focus area with the 41 plants listed in Figure 12 as the highest priority.

V. Conclusions and Recommendations

Centralized power and heating facility transitions away from coal have become increasingly common as environmental and societal concerns over climate change gain global attention. This research presents an objective analysis of United States coal to natural gas transitions centering on a case study of the fuel transition that took place at Wright-Patterson AFB between 2013 and 2016. This research focuses on three key areas which include the environmental impacts and embedded resources for coal and natural gas, consideration of climate change and non-static fuel prices in infrastructure economic analysis, and geospatial analysis of United States coal and natural gas infrastructure.

The environmental benefits of natural gas when compared to coal is well documented in published literature. Carbon Dioxide emissions of natural gas are nearly 50% lower than coal during combustion while freshwater withdrawal for natural gas for the lifecycle of the fuel is nearly 60% lower than that for coal. Additionally, the combustion of natural gas leaves virtually no solid waste while coal produces significant quantities of combustion residue presenting additional environmental risks and demands on hazardous waste disposal. When considering climate change in an economic analysis for infrastructure modernization investments, this research shows an increased capital payback period of greater than 20% for the WPAFB case study. This positive 6-year shift in project payback is significant in that it could sway decision makers as they evaluate the economic viability of alternatives. The use of a Monte Carlo simulation allows for the consideration of uncertainty while also providing model parameter sensitivity values that show fuel price having the highest impact on predicted payback period. A geospatial analysis of United States coal and natural gas infrastructure shows the lowest use of green energy production, including hydroelectric, in the Midwest and East Coast of the United States Natural Gas and Coal use overlap heavily in the Midwest while many coal-fired plants within this region already have access to natural gas making them viable for future transitions.

This research provides institutional and government decision makers with the benefits and regional viability of coal to natural gas transitions for centralized heat and power production. Additionally, this study demonstrates a clear need to consider climate change in long term economic analyses for heat and power infrastructure investments. A Monte Carlo analysis of the capital payback period for Wright Patterson AFB when considering climate change shows a clear shift in the positive direction. This data was not available to the installation and could not have been seen in the simple economic analysis contracted and utilized by the base in their analysis. A Monte Carlo analysis provides additional information and a more holistic picture due to the ability to consider uncertainty and express sensitivity of results. Climate change will have undeniable effects on the future of our infrastructure and should be considered in long term planning. This research provides evidence of one method in which climate change impacts could be modeled through a Monte Carlo simulation for long term infrastructure economic assessments.

Future research on this specific case study could benefit from extending the data before and after the transition project at WPAFB. In doing so, the historical weather data projection could be smoothed and error reduced. Additionally, much research is being performed on lifecycle air emissions for natural gas, specifically quantifying the effects that fugitive emissions might have and how they may be eroding the climate change benefits of natural gas over coal. As this research evolves, it may provide an opportunity to expand on the case study of WPAFB’s fuel transition.

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14. ABSTRACT

Over the last 20 years, natural gas has replaced coal as the preferred fossil fuel for heat and power generation across the United States, due to its increased prevalence, lower cost, and reduced environmental impacts. While most conversion decisions are driven by cost savings, proponents of energy transitions often cite emissions reductions as a tangential benefit. Over the same time, climate change and its impact on the environment and society have come to the forefront of scientific inquiry. One example of the transition from coal to natural gas can be found in Dayton, Ohio. Wright Patterson Air Force Base (WPAFB) invested over $25M from 2014 to 2016, to retrofit two coal-fired steam-heat-generating plants to natural gas heating plants. A brief review of literature shows that natural gas has a number of environmental benefits as opposed to coal to include, reduced air emissions and water withdrawal, as well as the elimination of the hazardous solid wastes produced by coal combustion. Economic analyses used to inform these long-term infrastructure decisions rarely consider the uncertainty of climate change. In this study, a Monte Carlo simulation is performed to evaluate the sensitivity of cost savings from the switch while accounting future uncertainty of climatic changes in the region. Primary fuel consumption data for WPAFB was paired with historical data with climate forecasts to calibrate a model, connecting specific weather indicators to installation fuel demand. The sensitivity of each fuel demand to weather can be forecast using a range of expected outcomes for climate change across the region. Using this predictive model for fuel use, observations and comparisons are made for the range of possible outcomes of long-term operating cost, environmental impacts, and how warming climate affects natural gas conversion return-on-investment. Finally, by analyzing geospatial data within the United States for coal and natural gas sources and infrastructure, as well as state power plant data, the Midwestern United States is found to be an extremely viable location for conversion projects similar to WPAFB. The results of this study help inform policy and aid in the long-term economic assessment of similar construction projects across the Department of Defense and Midwestern United States.

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