FACILITATING GREATER PUBLIC USE OF THE EPA'S CLEAN AIR MARKET DIVISION POWER SECTOR ANALYSIS TOOLKIT

ANALYZING THE IMPACT OF NUCLEAR RETIREMENT ON CARBON EMISSIONS

by

Mengdi Wang, Qinling Li, Yaofeng Gu

Dr. Luana Marangon Lima, Advisor

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Executive Summary

The concentration of CO2 has been increasing since the pre-Industrial Revolution from 280 ppm to an astonishing 405 ppm. The carbon dioxide concentration has reached the highest point over the past 800,000 years, which is due to fossil fuels combustion. As fossil fuels are intensively used in the electric sector, more emphasis have been placed on the power generating facilities. Two major federal agencies in the US, Environmental Protection Agency (EPA) and Energy Information Administration (EIA), have accumulated the GHG related information of power plants and published multiple databases available for public usage.

Nuclear power has been considered as clean energy with zero-carbon emission from the process of nuclear fission. However, one third of U.S. nuclear power plants are facing early retirement mostly because they are less economically competitive with decreasing natural gas prices and favorable policy for renewables. This study focuses on nuclear retirement and applies different methods to understanding and estimating its impact on carbon emissions with multiple databases from EPA and EIA.

The first section of this report provides an overview of the current status of nuclear power, benefits of nuclear power, reasons for retiring nuclear power and impacts of nuclear retirement. It also reviews the concept of decommissioning and its process, as well as the implications of nuclear retirement.

The second section of this report describes the data used in this analysis. The research area of this study is continental United States. Nuclear retirement data is from EPA's dataset National Electric Energy Data System (NEEDS). As two methods were applied to this study, the Multivariate Linear Regression Model (MLR) and the Tools for Energy Modeling Optimization and Analysis (Temoa), data used is also separated into two parts. As for MLR, monthly carbon emission from the electric sector, the electricity demand, the electricity generation mix, and nuclear outage data are collected from EIA. For the purpose of consistency, monthly data from July 2015 to September 2018 is used in this analysis. As for the Temoa model, the database for the U.S. energy system is the main source of data and parameters including natural gas prices and nuclear capacity are modified based on data from EIA. The timeframe of the Temoa model is every five years from 2015 to 2040.

The third section of this report provides a detailed description of the methods used in this study. The MLR model incorporates the nuclear outage, the electricity demand, and the energy mix as predictors for the carbon emission from the electric sector. The coefficients of the regression are then extracted from the model result and used to predict the carbon emission from 2019 to 2022. The electricity demand and energy mix data used for prediction is from EIA's Annual Energy Outlook 2019. They are separated into 7 scenarios which are the reference scenario, high/low economic development, high/low oil prices, and high/low oil and gas technologies. The nuclear

outage data is projected with time series analysis models based on historical data. And the nuclear retirement data from NEEDS is incorporated as part of the nuclear outage predictor in the prediction. The Temoa model, an open-source model developed by North Carolina State University, is used to examine how nuclear retirement will influence the carbon emission from the electric sector from the perspective of capacity expansion. Assumptions are made on natural gas prices and early nuclear retirement rates and 12 scenarios are built and run by combining different natural gas prices and early retirement rates.

The fourth section depicts results from both the MLR model and the Temoa model in terms of the carbon emission projection and its relationship with nuclear retirement and other independent variables. The MLR model serves as a first order analysis of historical data and Temoa model incorporates more parameters for the future predictions. Results of Temoa model include not only electric sector emissions but future cumulative carbon emissions from the entire energy system, as well as the total system cost under assigned scenarios.

The fifth section discusses the model results, and the sixth section provides recommendations of how a low-carbon future can be realized and what policy efforts may lead the system to the cleaner end of projection. Having adequate knowledge of energy system transformation from fossil fuel dominating to renewable dominating will be the key to a sustainable grid in the future.

The report includes multiple key findings and recommendations:

- The carbon emission from electric sector is projected to decrease over time by the MLR model.
- Natural gas prices, early retirement rates both have significant impacts on the carbon emission from the electric sector
- Nuclear capacities will be replaced by different fuel types based on the relative price of energy
- Not only electric sector but also residential and industrial sector should be taken into consideration in terms of the impact of natural gas price
- Nuclear retirement may not damage the reliability of the grid as the retirement happens gradually that allows the development of alternatives
- Developing the renewable plus energy storage can be crucial for future development

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INTRODUCTION

The greenhouse gas emissions have been long regarded as a major environmental crisis as the greenhouse gases (GHG) continue to trap heat in the atmosphere and warm up the planet. Among the category, carbon dioxide has the most significant influence on the global mean temperature due to its long lifetime and profound impact. The concentration of CO2 has increased from the pre-Industrial Revolution 280 ppm to an astonishing 405 ppm. The current carbon dioxide concentration has been the highest point over the past 800,000 years. Close to 40% of carbon dioxide emission in the US attributes to the electricity generation activity, and the industry has become the largest source of CO2 (Pétron et al., 2008). As a result, much of the emphasis has been placed on the power generating facilities. Two major federal agencies in the US have accumulated the GHG related information of power plants that provide electricity for resident, industrial and commercial uses: Environmental Protection Agency (EPA) and the U.S. Energy Information Administration (EIA).

Both federal agencies thrive to protect and promote the quality of nature and publishes multiple databases available for public uses. The main mission of EPA is to verify and ensure compliance of all kinds of activities with federal environmental legislation and rules. EIA is in charge of gathering, organizing and projecting energy statistics for the US. The 1990 Clean Air Act states that any U.S. fossil burning power plants with a nameplate capacity above the designated threshold has to report its hourly emission of CO_2, NO_X and SO_2 to the EPA Clean Air Markets Division (AMPD). In addition, EPA also publishes a comprehensive database with all statistics and information about the U.S. power generation, which is called the Emission and Generation Integrated Database (eGRID). The eGRID is published every two or three years, allowing sufficient time for data collection and compiling. Finally, the National Electric Energy Data System (NEEDS) of EPA offers a detailed description of all the power plants in the country from the unit level. NEEDS promotes the EPA power grid planning and serves as a basis for the projection to better integrate the inventory to capture the needs. All the three datasets establish a solid foundation for researches and analysis with the sufficiency of data in terms of comprehensiveness and temporal resolution.

Specifically, this study applies different methods to understanding and estimating the carbon emission increment after the nuclear retirements with multiple databases from EPA and EIA.

Power generation replies on multiple fuel types, including coal, natural gas, nuclear, wind, solar and other resources. This study focuses on nuclear plants and their future retirement impact on the emission of carbon dioxide. In addition, an energy system analysis model is used to estimate the increase in carbon emission under different scenarios in the future.

1. BACKGROUND

1.1 Current Status of Nuclear Power

Commercial nuclear reactors started to generate electricity since the late 1950s in the United States. As of February 2019, there are 98 operating nuclear reactors in the United States at 61 power plants in 30 states. Nuclear power plants have been contributing to 19% of U.S. electricity generation while nuclear capacity only accounted for about 9% in 2017. This indicates that nuclear plants are used more intensively than other generation resources. Compared with the other 30 countries in the world that use nuclear power to generate electricity, the United States has the highest nuclear capacity as well as the nuclear generation in 2015. The major proportion of uranium used at nuclear reactors in the U.S. is imported. In 2017, about 7% of uranium was produced in the U.S. while 93% came from overseas, of which about 35% came from Canada (U.S.EIA_Nuclear Power Plants, 2019).

In 2017, nuclear accounted for 19% of total electricity generation mix in the U.S. and EIA projected that in 2050, nuclear power would decrease to 12% of the energy mix. Some states such as California, New Jersey and Massachusetts are in favor of renewable energy and/or non-emitting power generation their respective Renewable Portfolio Standards (RPS). As a result, nuclear energy is likely to remain in the energy mix of those states. In addition, New Jersey also has supportive policies for the operation of existing nuclear reactors as governor signs nuclear power subsidy bill into law, which will slow down the retirement processes. However, given all those optimistic situations for nuclear, nuclear energy is still projected to decline from 2018 in the U.S. (U.S.EIA_Energy Outlook, 2019).

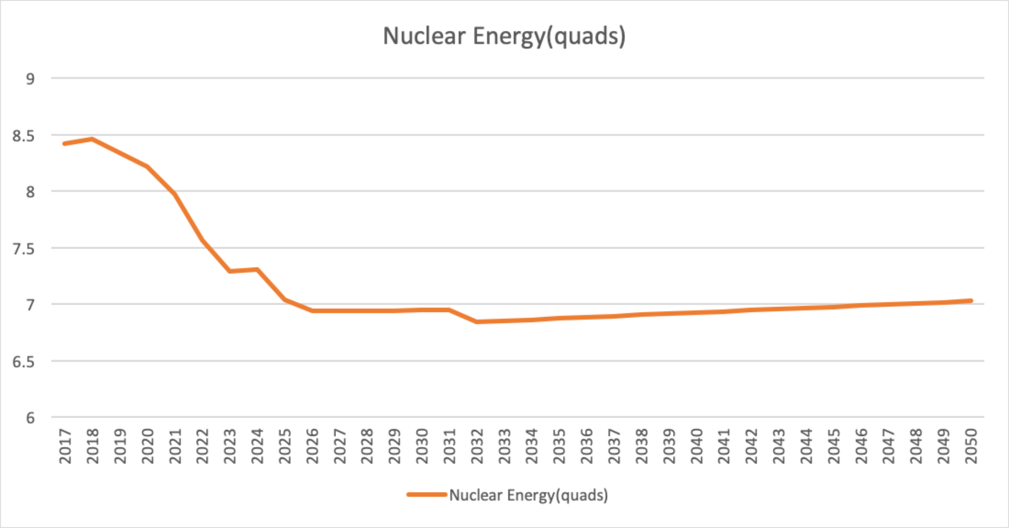

Figure 1: Nuclear Energy Projection (EIA, 2019)

1.2 The Benefits of Nuclear Power

For a long time, nuclear has been regarded as the key to the future. The energy density of uranium-235 is so gigantic that dwarfs those of coal and natural gas. With a complete fission process, one kilogram of uranium-235 releases around 24,000,000 kWh of power; while with a complete combustion process, one kilogram of coal generates 8 kWh and one kilogram of mineral oil produces 12 kWh. Although not all of those energy resources can be captured and turned into electric power, the generation efficiency is not considered as an issue since the total amount of energy released is enormous.

In addition, the fission process of uranium-235 itself does not generate CO_2 or any other greenhouse gases. In fact, aside from hydroelectric power, nuclear power accounts for almost all of the low-carbon generation in the U.S. (Roth and Jaramillo, 2017). Unlike coal-fired or natural gas plants, nuclear plants emit low carbon dioxide in their entire life-cycles. The energy production process does not emit CO_2, but construction, operation, maintenance and decommissioning all include some low amount of carbon emission. It is estimated that nuclear energy releases 90 to 140 grams of CO_2 from the production of one kWh of electricity. Even with all those emissions taken into consideration, the nuclear energy is still considered one of the best ways to mitigate the environmental crisis since one kWh of electricity production will produce 915 grams of CO_2 from coal-fired plants and 549 grams of CO_2 from a natural gas-based power plant (Proctor, 2019).

To meet the emission reduction goal in the power sector, preserving nuclear power can serve as a way of carbon-avoidance as nuclear is likely to be replaced by natural gas. Under different natural gas price scenarios, even the low natural gas price scenario, the multi-reactor plants perform well in terms of carbon avoidance costs. For single-reactor plants, the benefits of preserving nuclear plants are not obvious (Roth and Jaramillo, 2017).

1.3 Reasons for Retiring Nuclear Plants

Given all the advantages, the disadvantages of nuclear energy have slowly appeared in the production process and retirement is necessary due to many reasons as a consequence. Unlike wind or solar power, nuclear power is non-renewable as the production rate of raw uranium-235 material is much slower than the consumption rate. At the current rate of consumption (conversion) with conventional reactors, the world supply of viable uranium will only last for 80 years (Zyga, 2019). This renders nuclear power unsustainable from the perspective of power source regeneration. In addition to the unsustainability, the profitability of nuclear facilities has been greatly overwhelmed by the natural gas-based facilities due to the plunge in natural gas price with booming fracturing technologies. Moreover, the renewable energy industry is also undergoing great expansion with favorable policy and tax credits. Both fuel types pose huge challenge on the operation of nuclear plants. Currently, most existing US nuclear power plants have licenses that would allow them to operate until the 2030 to 2050 timeframe. However, the economic challenges including low natural gas prices, more affordable renewable technologies and increasing operational costs have led to some nuclear reactors being retired or slated for retirement (UCS_Nuclear Power & Global Warming, 2019). From the Union of Concerned Scientists' (UCS) analysis, more than one-third of existing plants, representing 22% of total US nuclear capacity, are unprofitable (UCS_The Nuclear Power Dilemma, 2018). At the same time, there still underlie uncertainties in electricity price among various forms of power market. As a result, for nuclear plants which have a large amount of upfront costs, the risk of recovering the costs will be higher. Although CO_2 emission reduction policies such as carbon tax and "cap-and-trade" program in some states reduce the cost-effectiveness of the carbon-emitting energy resources (Rothwell, 2000), the withdrawal from the Paris Agreement poses uncertainty on those emission reduction policies. In fact, out-of-the-market subsidies are desirable to maintain nuclear facilities with the zero-emission attribute and prevent rapid early shutdowns without carbon pricing. As suggested by Roth and Jaramillo (2017), a cost of between \$8 and \$44 per MWh is needed in order to fill the revenue gap under a low natural gas price scenario from the Energy Information Administration.

Besides lower natural gas prices and renewable energy costs, the slower growth in electricity demand and a lack of recognition of the value of zero-emission energy source in the power markets also make the economic situation of nuclear worse. In addition to the decreasing cost of other sources, the increasing cost of nuclear from additional safety costs after the Fukushima nuclear disaster adds to the challenge nuclear plants face (Vine, 2017).

Nuclear power also has safety and environmental risks related to nuclear waste. The problem of handling nuclear waste after production still remains an unsolved challenge and the proper nuclear waste disposal requires 10,000 years of careful monitoring in a safe geographical formation according to the EPA standard.[1] The nuclear waste can also be used to build nuclear weapons by the terrorists and the nuclear facilities are vulnerable targets for terrorist attack as well. Finally, in spite of an extremely low probability of accident under stringent security standard for every single reactor, the cumulative probability of a catastrophic failure is not negligible if more plants are built all over the world (Time for Change, 2007).

For example, in California, Pacific Gas & Electric (PG&E) developed a joint proposal in 2016 with organizations such as Friends of the Earth to retire PG&E's Diablo Canyon Power Plant's two reactors in 2024 and 2025. The proposal suggests that this nuclear plant will be replaced by energy efficiency measures as well as renewable energy. Due to California's progressive policies on generation reliability, the need for inflexible generation such as nuclear has decreased. Additionally, California's energy demand is projected to decrease because of aggressive energy efficiency policies. This will further reduce the need for nuclear power in California. Besides, California's renewable energy development has seen overgeneration. To meet the renewable energy target in California, it is necessary for a system operator to restructure the energy mix. Moreover, the environmental mitigation and compliance measures required for nuclear plants add burden to the existing plants and make the plant disadvantageous (MJB&A, 2016).

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[1] https://www.epa.gov/radiation/environmental-radiation-protection-standards-management-and-disposal-spent-nuclear-fuel

1.4 Decommissioning and its Process

Decommissioning refers to the process of safely closing a nuclear power plant (or another facility where nuclear materials are handled) to retire it from service after its useful life has ended. This process primarily involves decontaminating the facility to reduce residual radioactivity and then releasing the property for unrestricted or (under certain conditions) restricted use. This often includes dismantling the facility or dedicating it to other purposes. Decommissioning begins after the nuclear fuel, coolant, and radioactive waste are removed (U.S. NRC_Decommissioning, 2018).

There are 21 reactors in the U.S. undergoing decommissioning as of February 2019 and 7 reactors that have been decommissioned. And there are two reactors expressing their intent to permanently cease production (U.S.NRC_Status of the Decommissioning Program, 2017). The decommissioning process usually takes several decades to complete.

According to the Nuclear Regulatory Commission (NRC), when a power company decides to close a nuclear power plant permanently, the facility must be decommissioned by safely removing it from service and reducing residual radioactivity to a level that permits release of the property and termination of the operating license. The NRC has strict rules governing nuclear power plant decommissioning, involving cleanup of radioactively contaminated plant systems and structures, and removal of the radioactive fuel. These requirements protect workers and the public during the entire decommissioning process and the public after the license is terminated.

There are also multiple decommissioning strategies for the licensees to choose: DECON, SAFSTOR or ENTOMB. DECON stands for immediate dismantling, which refers to the situation where right after the shutdown of the nuclear plant, equipment, structures and parts of the facility with radioactive materials are removed or decontaminated to a designated level that allows the property to be of other uses. SAFSTOR means deferred dismantling, with which a nuclear plant is maintained and monitored so that the radioactive material can slowly decay in the facility. After all the material decays to the safety level, the plant will be dismantled, and the facility will be decontaminated afterwards. ENTOMB indicates that all the radioactive contaminants will be sealed permanently on site in structurally safe materials (i.e. concrete) and the entire structure is maintained and monitored until the radioactivity decreases to the safety level before the property is on restricted release. So far, no nuclear facilities licensed by the Nuclear Regulatory Commission has chosen this option yet.

1.5 The Impacts of Nuclear Retirement

The potential environmental and economic consequences of nuclear retirement depend on the future energy mix. As estimated by Haratyk (2017), a 30 GW of nuclear retirement will increase around 5% carbon emissions if replaced by gas-fired units or will lead to a cost of subsidies more than $8 billion annually if replaced by renewable energy.

The nuclear retirement will potentially increase the amount of carbon dioxide emitted into the atmosphere. In the U.S., nuclear power provides half of carbon-free generation (Richards and Cole, 2017). Currently in the power market, nuclear energy serves the energy demand as baseload, which means that the output from nuclear energy will not vary significantly over the course of the day. This is due to the constant output and low marginal cost of electricity from nuclear energy. As nuclear power slowly retires over the next fifty years, other resource types will replace nuclear energy and possible alternatives include natural gas, solar power, wind power and other renewable energy. Among all these alternatives, natural gas is the most favorable one as it is of the least levelized cost and controllable in terms of power output. However, what people must be aware of is the huge emission difference between nuclear power and natural gas-based energy. If more natural gas is consumed in the future to generate power, then inevitably more carbon dioxide will be released into the atmosphere, given the same level of other technologies such as carbon capture and sequestration and no significant advancement of renewable energy. This causality directly leads to the objective of this study that uses different methods to estimate the impact of nuclear retirement on the carbon emission.

The Battle Group estimated that a 1,000 MW nuclear retirement would cause increased CO2 emissions in the range of 4.1 to 6.7 million tons per year, or 0.52 to 0.84 tons per MWh if replaced by coal and natural gas generation (The Brattle Group, 2016). This would increase climate change risk and greatly influence the transition to a low-carbon energy sector. Furthermore, it would make compliance with any future climate policy more difficult and more costly. In the analysis of impacts of Announced Nuclear Retirements in Ohio & Pennsylvania (4.7GW), it assumes 72% of the replacement would come from natural gas generation and 28% from coal. Under this scenario, these early retirements would increase 21 million tons of CO2 emissions per year and potential social costs of $921 million annually. In addition, the retirement of these plants would increase wholesale electricity prices, with roughly half the impact coming from the energy market and a half from the capacity market. This would lead to an increase of $400 million customers' annual gross electricity costs in Ohio, $285 million in Pennsylvania, and $1.5 billion in all PJM area. Also, this would cause a substantial reduction in state GDP and jobs in Ohio and Pennsylvania, as well as surrounding states (The Brattle Group, 2018). Richards and Cole (2017) also found that nuclear retirements would have implications on increased electricity prices, decreased energy security, and transmission congestion.

At the same time, there is also a chance where nuclear power is replaced by renewable energy. As mentioned before, the natural gas-fired plant is so far the most economically competitive fuel type. However, the federal and the state governments have adopted strong policies to slow down nuclear retirement and preserve the low-carbon generation capacity that nuclear energy has been providing. This creates a valuable buffer zone for renewable energy and other technologies to advance. Wind power, solar power, and/or energy storage may become the key to the successful replacement of nuclear plant and may even take the place of some contribution from natural gas. As we cannot foretell any technological breakthrough in the energy industry, we can only make reasonable assumptions about future scenarios and generate projections and analyses accordingly.

1.6 The Implications of Nuclear Retirement

As nuclear retirement is very likely to increase the anthropogenic carbon mission, it worsens the existing environmental crisis. Since the low-carbon emission attribute of nuclear plants is squeezed by the low production cost of natural gas plants, the nuclear capacity will continue to decline in the absence of carbon price and supportive policies. As the current emission finds its way in the higher end of emission scenarios in the Representative Concentration Pathways 8.5 (RCP 8.5) concluded in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5), the reduction in nuclear capacity will undoubtedly pose more burden on the atmosphere and the technology advancement. To make things worse, as the U.S. announced the withdrawal from the 2015 Paris Agreement on climate change mitigation, it remains unclear how the climate policy in the U.S. will change in the future (Eshraghi et al., 2018). How we handle the worrying concentration of greenhouse gas still remains the most overarching problem for us. Roth and Jaramillo (2017) conclude that the premature retirement of U.S. nuclear power plants could eliminate some of the benefits of proposed carbon regulations. Therefore, preserving America’s nuclear fleet is essential to satisfy the EPA’s Clean Power Plan (Brinton and Freed, 2015).

The implication of nuclear retirement on environmental policy is also uncertain. The potential environmental and economic impact of nuclear retirement has created a lot of discussion among researchers and policymakers across the U.S. For instance, Pennsylvania's Nuclear Energy Caucus releases a report detailing impacts of losing the state's nuclear industry. It notes that nuclear makes up 42 percent of the state's total electricity and 93 percent of its zero-carbon electricity. Lawmakers also argued that keeping nuclear plants open is essential to the state's environmental goals as well as its grid resilience (Merchant, 2018).

2.Data

Our research area is the Continental United States. The time period of data varies based on the availability of the data. For the purpose of consistency, we use monthly data from July 2015 to September 2018. In this analysis, we used the multivariate linear regression model and Tools for Energy Model Optimization and Analysis (Temoa) to project carbon emissions in the future. As for the linear regression model, we used historical data to generate a regression model and changed the value of independent variables to predict carbon emission. With Temoa, we wanted to explore carbon emissions from the perspective of capacity expansion in the future.

2.1 Emission from the Electric System

Emission data is published and available on the U.S. Energy Information Administration website (https://www.eia.gov/totalenergy/data/browser/?tbl=T12.01), spanning from Jan 1973 to Sept 2018. The emission data is divided into multiple categories by source, and we used the sum of emissions from coal and natural gas as both are the dominant source of emission from power plants. It is true that the oil and diesel may contribute to an extremely small portion of power plant emission, but that portion would appear minuscule compared to the emission from coal and natural gas-based facilities.

2.2 Electricity Demand

We obtained monthly U.S. electricity demand data from the U.S. Energy Information Administration (EIA, https://www.eia.gov/realtime_grid/?src=data#/status?end=20190223T08).

EIA's U.S. Electric System Operating Data tool provides real-time demand data, plus analysis and visualizations of hourly, daily, weekly, and monthly electricity demand on a national and regional level. The available data spans from July 2015 to present.

2.3 Nuclear Outage

As there are only 7 nuclear reactors that have been decommissioned, data points are insufficient to develop a time series model. We then approached the emission impact of nuclear retirement with nuclear outage data (https://www.eia.gov/nuclear/outages/) as they may have similar impacts on emissions. Nuclear power is scheduled for inspection, maintenance, or refueling usually in spring and fall when the load is relatively low compared with summer and winter times. There is also forced outage due to emergency reasons (U.S.NRC_Outage, 2018). By analyzing the relationship between outage data and corresponding carbon emission, we can have a basic understanding of how the two variables are interrelated. The outage data on EIA's website is daily nuclear outage in MWs from January 1st, 2007 to present. We converted data to monthly by summing daily outage data with R because emission data is on a monthly basis.

2.4 Energy mix

The generation mix also plays a part in nuclear retirement's impact on emissions. We obtained generation mix data in the U.S. on EIA Electricity Data Browser (EIA, https://www.eia.gov/electricity/data/browser/). EIA provides annual, quarterly and monthly generation data by fuel type including nuclear, coal, natural gas, solar and wind, etc. To incorporate the generation mix in our model, we converted generation from different fuel types into percentages. As nuclear power is likely to be replaced by natural gas and renewables after retirement, we include the percentage of generation from natural gas, renewables, and nuclear in our model. And because coal still makes up of a large trunk of total generation mix and is a major source of carbon emissions, we include coal in our model as well. As of September 2018, coal makes up of about 27% of the total generation mix, natural gas makes up of 39%, nuclear makes up of 18%, and renewables make up of about 9%. The available data spans from January 2001 to November 2018.

2.5 Nuclear retirement

We obtained the capacity of nuclear retirement from the National Electric Energy Data System (NEEDS) provided by the United States Environmental Protection Agency (EPA). NEEDS database contains the generation unit records to construct the plant model representative of existing and planned units in EPA modeling application. This dataset serves as a description of all the power plants in the country at the unit level, including basic geographic, operating, air emissions, and other data on these generating units. In addition, NEEDS v6 also includes a list of nuclear generators that will retire through the year 2021.

2.6 U.S. National Energy System Database

Along with the model attaches the U.S. national energy system database on the website of the Temoa model. The current database compiled by the developer of Temoa model will serve as a great starting point. Further revise and modifications were made in the database to specify the nuclear capacity. In addition to nuclear facility specification, multiple scenarios of fuel sources were also added to form different conditions. By altering different parameters in the datasets are we able to simulate different future scenarios.

2.7 Natural Gas Price Projection

Natural gas price, as one of the parameters in Temoa, will impact future energy mix of the electric system, and thus be likely to influence carbon emissions of the electric system. EIA's Annual Energy Outlook 2019 provides annual natural gas price data by sector from 2017 to 2050 (https://www.eia.gov/outlooks/aeo/data/browser/#/?id=3-AEO2019&cases=ref2019&sourcekey=0). We treated EIA's natural gas price forecast as the base case and made assumptions on high natural gas price scenarios and low natural gas price scenarios.

3. Method

3.1 Linear Regression Model

3.1.1 Data processing

This part of analysis includes data of emission, electricity demand, nuclear outage and energy mix (i.e. percentages of coal, natural gas, nuclear and renewable in the entire fuel portfolio). As all raw data includes trends and seasonality, the first-order analyses are to standardize the data and to remove the trends and seasonality to obtain the intrinsic variations among all the variables. Since coal, natural gas, nuclear power and renewable do not take up the entire 100% of the energy mix, it is plausible to use all the four as independent variables without introducing the problem of high correlation between independent variables.

3.1.2 Model Description

We conducted a multivariate linear regression model to predict emission in 2019, 2020, 2021 and 2022 as we obtained nuclear retirement information in NEEDS through the year 2021. At first, due to our interest in exploring how nuclear retirement might impact carbon emission, we conducted a simple linear regression on emission with nuclear outage as the predictor. The p-value of this model is 0.3536, which indicates this model is not significant. We then incorporated the demand and energy mix into our model and the regression output is statistically significant with a p-value infinitely close to zero. The data here is the deseasoned, detrended, and standardized data.

$$\begin{aligned}\text{Emission} = \beta_0 + \beta_1 * Nuclear\ Outage + \beta_2 * Demand + \beta_3 * Coal \\ + \beta_4 * Natural\ Gas + \beta_5 * Nuclear + \beta_6 * Renewables\end{aligned}$$

3.1.3 Model Evaluation

We built the linear regression model to forecast emission with independent variables of electricity demand, nuclear outage and energy mix. To evaluate the model’s accuracy, firstly, we conducted the analysis by using standardized detrended and de-seasonal monthly emissions, electricity demand, nuclear outage and energy mix data from July 2015 to September 2017 to locate the relationship between emissions and other variables. Secondly, we used standardized detrended and de-seasonal monthly electricity demand, nuclear outage and energy mix data from October 2017 to September 2018 as inputs to forecast emissions of the same time period based on its relationship. Thirdly, we added back the value of mean and standard deviation, as well as the seasonality and trend to the forecasting result, and then compared it with real historical emissions data and generated an error report.

3.1.4 Model Prediction

To predict carbon emissions in 2019, 2020, 2021 and 2022 with the regression coefficients we got from the multivariate regression model, we assumed 7 scenarios considering oil and gas technologies, oil prices and economic development status. They are the reference scenario, high oil and gas technologies, low oil and gas technologies, high oil prices, low oil prices, high economic development, and low economic development. The reference scenario we used in our model is in accordance with EIA's projections in its annual energy outlook report (U.S.EIA_Annual Energy Outlook, 2019). And the rest of the scenarios are also extracted from EIA, and under different scenarios, electricity demand and energy mix are different. We used these demand and energy mix data to project carbon emissions using our regression model.

Table 1. Reference Scenario for the Prediction Model (EIA, 2019)

	2018	**2019**	**2020**	**2021**	**2022**
Demand (billion kWh)	3795.87	3775.57	3831.85	3863.16	3890.00
Coal (%)	28.96%	27.76%	25.89%	24.83%	24.47%
Natural Gas (%)	33.44%	34.18%	35.37%	35.73%	36.47%
Nuclear (%)	20.41%	20.27%	19.66%	18.96%	17.88%
Renewables (%)	17.36%	17.89%	19.49%	21.21%	22.09%

For the demand and energy mix, the data we used in our regression model is monthly data. To predict monthly emissions, we will use annual growth rates of the variables calculated from EIA's projections as the year-on-year ratio. For instance, we can calculate the electricity demand of April 2020 with that of April 2019 and the annual growth rate between 2019 and 2020. With the same method, we generate time series for monthly demand and energy mix in 2019, 2020, 2021, and 2022.

Table 2. Growth Rates of Demand and Energy Mix for the Reference Scenario (Calculated from Electricity supply, disposition, prices, and emissions table. Energy consumption by sector and source table)

	2019	2020	2021	2022
Demand	-0.59%	1.49%	0.82%	0.69%
Coal	-4.15%	-6.75%	-4.10%	-1.45%
Natural Gas	2.19%	3.50%	1.02%	2.07%
Nuclear	-0.70%	-2.99%	-3.60%	-5.70%
Renewables	3.01%	8.96%	8.80%	4.19%

For nuclear outage, there is no public data available for future outage capacity and we applied the prediction model, including non-seasonal autoregressive integrated moving average (ARIMA), seasonal ARIMA, exponential smooth and state space model in R, to forecast nuclear outage through the year 2022. To identify the best model that fits the nuclear outage trend well, we used the nuclear outage data from January 2007 to December 2017 as input and utilized different prediction models to forecast the outage in the year 2018. And then we compared our results with historical outage data in the year 2018 (Figure 2), and generated an error report (Table 3, more statistic explanation of these errors can be found in Appendix 1), from which we found that the seasonal ARIMA leads to the better forecast.

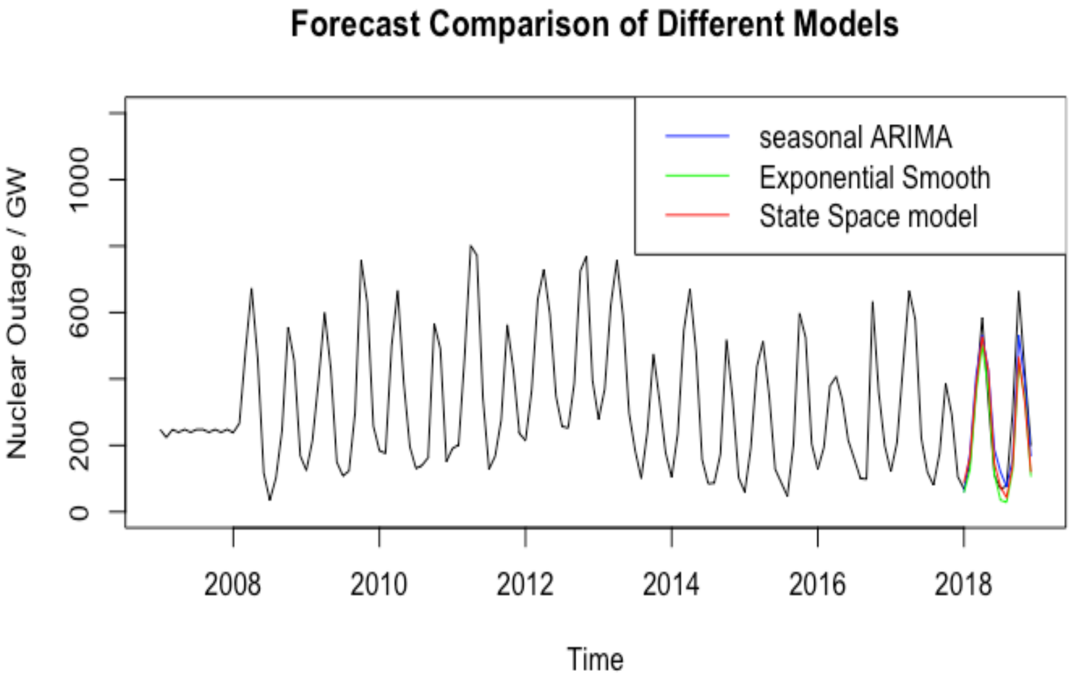

Figure 2: Nuclear Outage Forecast Comparison of Different Models

Table 3: Error Report of Forecast from Different Models

	MAE	**MSE**	**MAPE**
Seasonal ARIMA	57.37	5110.35	26.67
Exponential Smooth	67.32	8646.37	27.39
State Space Model	66.67	7815.53	25.98

Therefore, we predicted monthly nuclear outage capacity through the year 2021 by the seasonal ARIMA model.

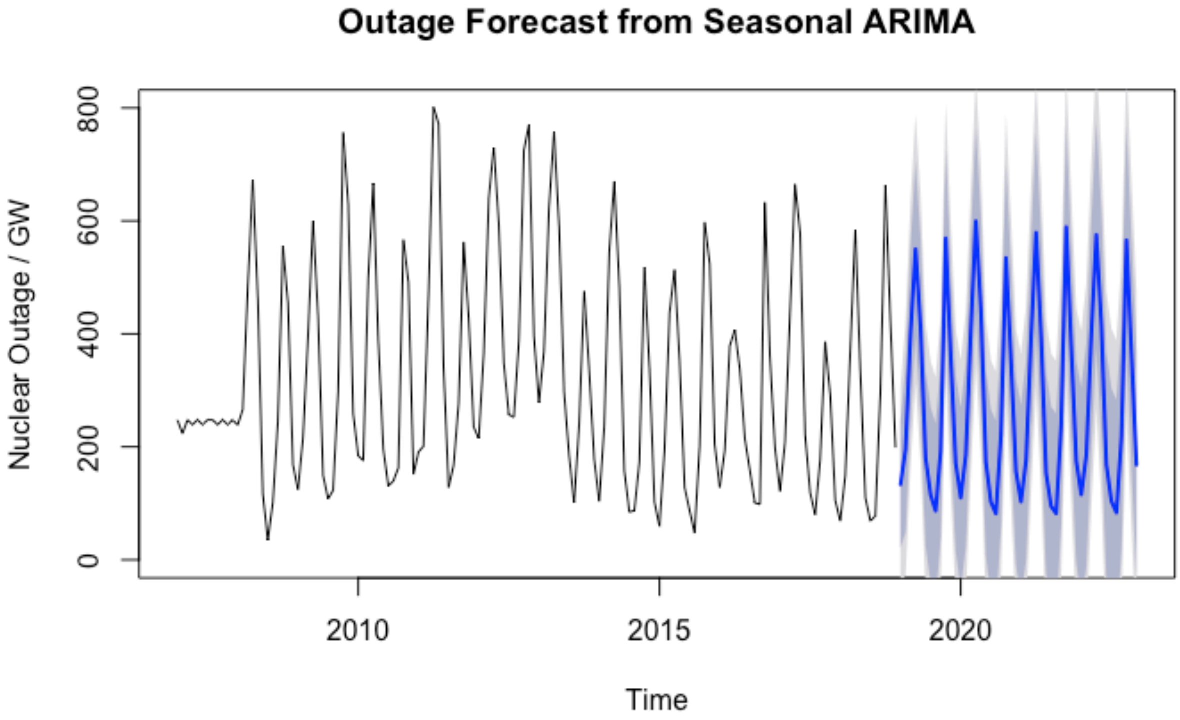

Figure 3: Outage Forecast from Seasonal ARIMA

We incorporated future nuclear retirement into our model by adding the capacity of retirement to nuclear outage. If a plant retires in year x, we will add the capacity of that plant to nuclear outage for the year afterward.

Then we built 7 scenarios including the reference scenario, and other scenarios considering high/low oil and gas technologies, high/low oil prices, and high/low economic development. Under different scenarios, the demand and energy mix are different. (see Appendix 2 for more details)

3.2 Temoa

Temoa is an energy system optimization model that optimizes the installation and utilization of generation capacity over the planning horizon with parameters inputted from the user. The model generates the optimal decision of capacity installation at the minimum cost that satisfies the projected demand for electric power. Temoa is also a comprehensive model that entails different sectors of the system including electric, residential, commercial and industrial sectors. Key features of the core Temoa model features flexible time resolution by season and by day, a changeable time period of the planning horizon, technology vintage, user-defined technology loan periods and lifetimes, technology-specific discount rate, stochastic optimization ability and modeling-to-generate alternatives (MGA) ability. Moreover, the model also outputs emission information and technology portfolio. Temoa generates outputs from 2015 to 2040 with 5-year intervals.

We built multiple scenarios to assess variability and sensitivity of carbon emission under various circumstances. The two parameters we included were early retirement rate of nuclear capacity and natural gas prices. In terms of nuclear capacity, apart from nuclear retirement data from NEEDS, we made assumptions about early retirement rates of the remaining capacity before 2030. And we assumed that high natural gas price would be 1.2 of the base case, and the low natural gas price would be 0.8 of the base case. With 0%, 20%, 50% and 80% of early nuclear retirement rates, and high, base, and low natural gas prices, we built 12 scenarios in total to examine the sensitivity of carbon emissions to those changes. Performance of the scenarios will be quantified as the difference in total cost, total emission from the system and total emission from the electric sector only.

4. Results

4.1 Regression

The study includes monthly time series of nuclear outage, demand for electricity, and generation percentages of coal, natural gas, nuclear and renewable. The data analysis shows that only coal and renewable percentages have statistically significant trends in the time interval of our study. The percentage of coal exhibits a significant decreasing trend while the percentage of renewable has a significant upward trend. In terms of seasonality, all seven variables demonstrate significant seasonality. More electric power is consumed in summer and winter and less in spring and fall. This is in accordance with the expectation as peak seasons of demand happen in summer and winter when cooling and heating are necessary.

Figure 4 and Figure 5 are time series data of outage and emission data with trends and seasonality removed. The remainders of these time series are standardized to be consistent. Figure

6 shows the correlation between the remainders of the outage, demand, emission, coal, natural gas, nuclear power and renewable energy after the removals of trends and seasonality. The result indicates that emission is highly correlated to coal and natural gas percentages in the energy mix, while nuclear outage does not have a high correlation to the emission. This is due to the fact that the nuclear outage amount is too small to be significant compared to other energy loads from coal and natural gas. Instead, nuclear outage demonstrates a high correlation to the nuclear percentage in the energy mix.

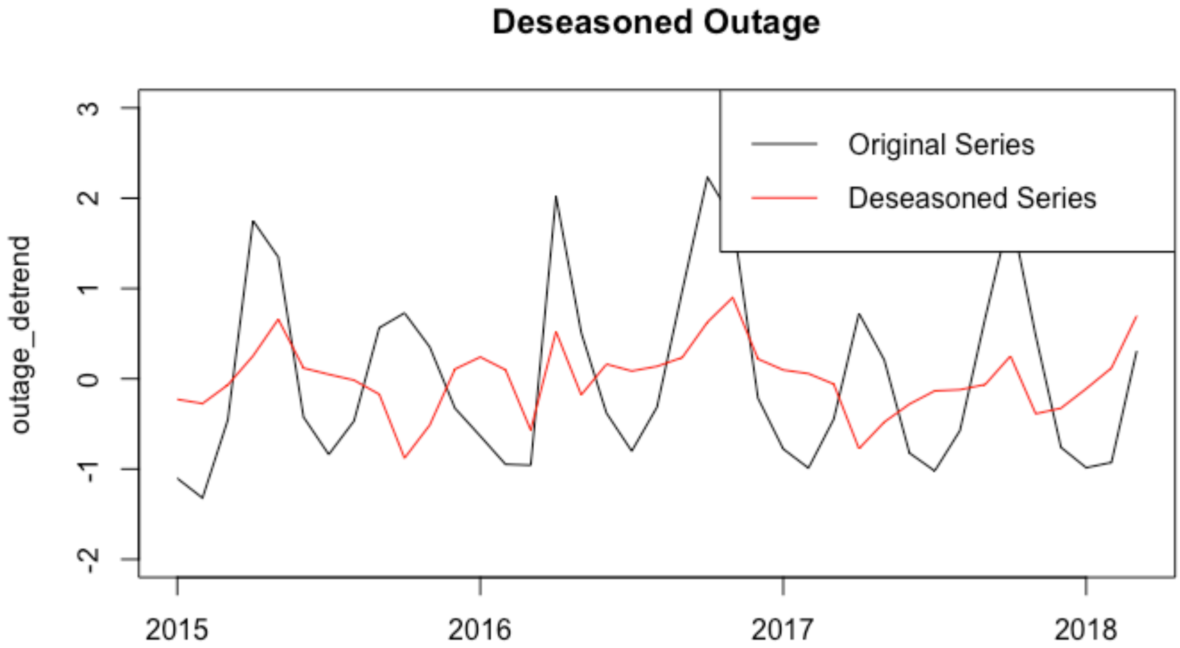

Figure 4: The Detrended and De-seasoned Data of Nuclear Outage

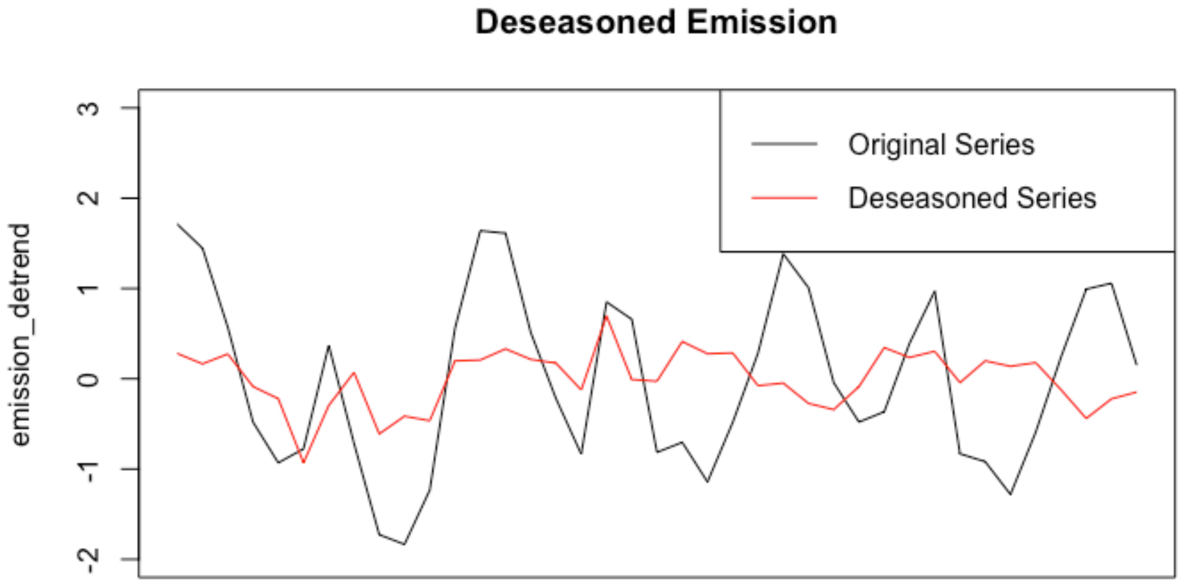

Figure 5: The Detrended and De-seasoned Data of Carbon Emission

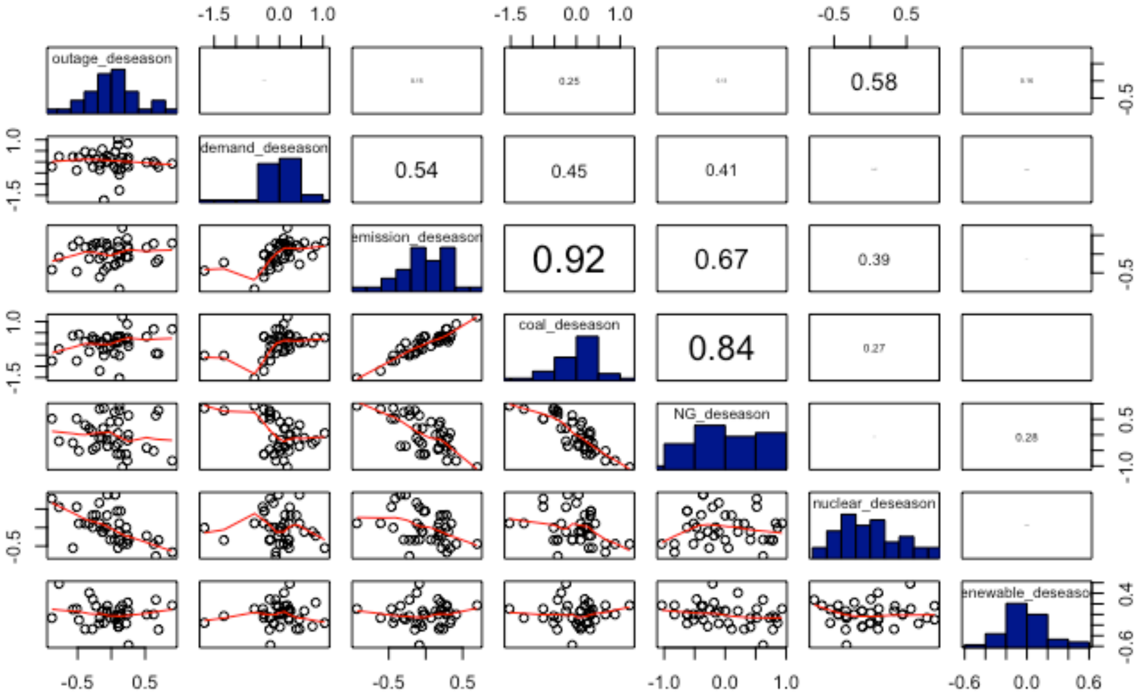

Figure 6: The Correlation between the Remainders of all Variables Included

The p-value of the regression model is lower than 0.05, and thus this model is statistically significant in terms of explaining the changes in emissions. The coefficients of the nuclear outage, demand, the percentage of coal, natural gas and nuclear in the energy mix are all statistically significant. More specifically, the coefficient of the nuclear outage is negative, which suggests that the higher the nuclear outage is, the lower emissions will be. Again, we believe that the relationship between high carbon emission and low nuclear outage during peak seasons have not been fully addressed yet and there could be further analysis to this issue.

Figure 7 shows the comparison between forecast and real emissions data. To achieve a quantitative comparison, we generated an error report as exhibited in Table 4. The mean error (ME) is -13.68, root mean squared error (RMSE) is 18.65, mean absolute error (MAE) is 14.75, mean percentage error (MPE) is -14.62, mean absolute percentage error (MAPE) is 15.47, and autocorrelation of errors at lag 1 (ACF1) is 0.47. The regression model generates decent results in spite of the short time period of available data.

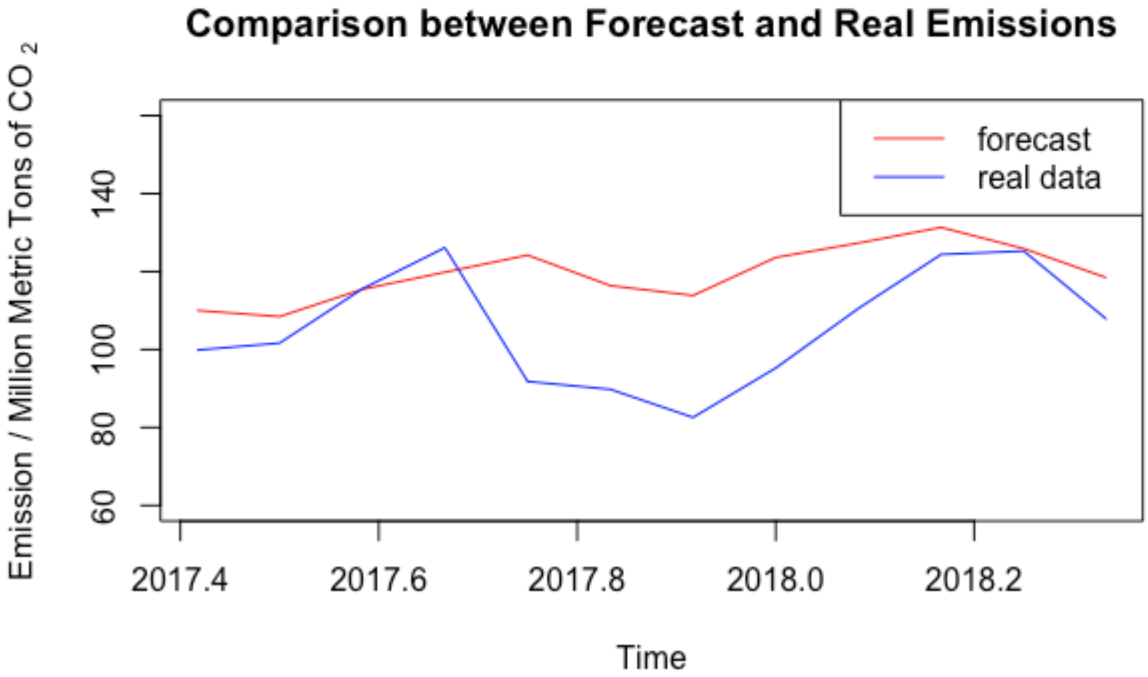

Figure 7: Comparison between Predicted and Real Emissions

Table 4: Error Report of Predicted Emissions

ME	RMSE	MAE	MPE	MAPE	ACF1
-13.68084	18.64733	14.7482	-14.62388	15.47149	0.4674885

With projections of demand, energy mix, and nuclear outage for 7 scenarios (reference scenario, high oil and gas technologies as scenario 1, low oil and gas technologies as scenario 2, high oil prices as scenario 3, low oil prices as scenario 4, high economic development as scenario 5, and low economic development as scenario 6), we used the result of the regression model to project carbon emissions in 2019, 2020, 2021, and 2022.

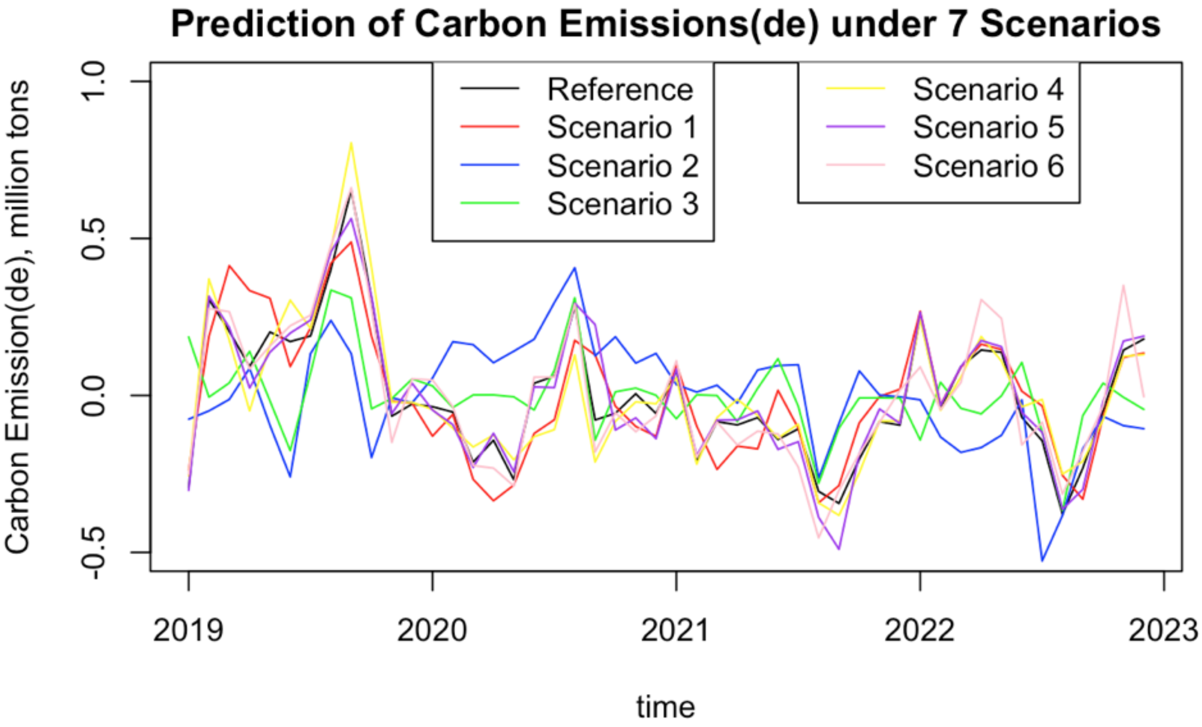

Figure 8: Prediction of Carbon Emissions (de) under 7 Scenarios

As the results of the regression model provided de-seasoned, detrended, and standardized emission, we added back the seasonal and trend components of the historical emission data, and de-standardized the results with the mean and standard deviation of the historical emission data as well. Figure 9 shows the result of the reference scenario. Figure 10 shows the results of the 7 scenarios. From this graph, the differences between the scenarios are less observable than the graph with only the random components of carbon emissions. Overall, the projections show that carbon emissions during peak seasons (i.e. summer and winter) will continue to be much higher than those of non-peak seasons (i.e. spring and fall). On the other hand, the 7 scenarios under EIA's AEO projections do not exhibit significant deviation from the reference case. As 7 scenarios correspond to the different levels of oil and gas technology, oil price and economic development, these three factors may not be the most influential determinants of future carbon emissions.

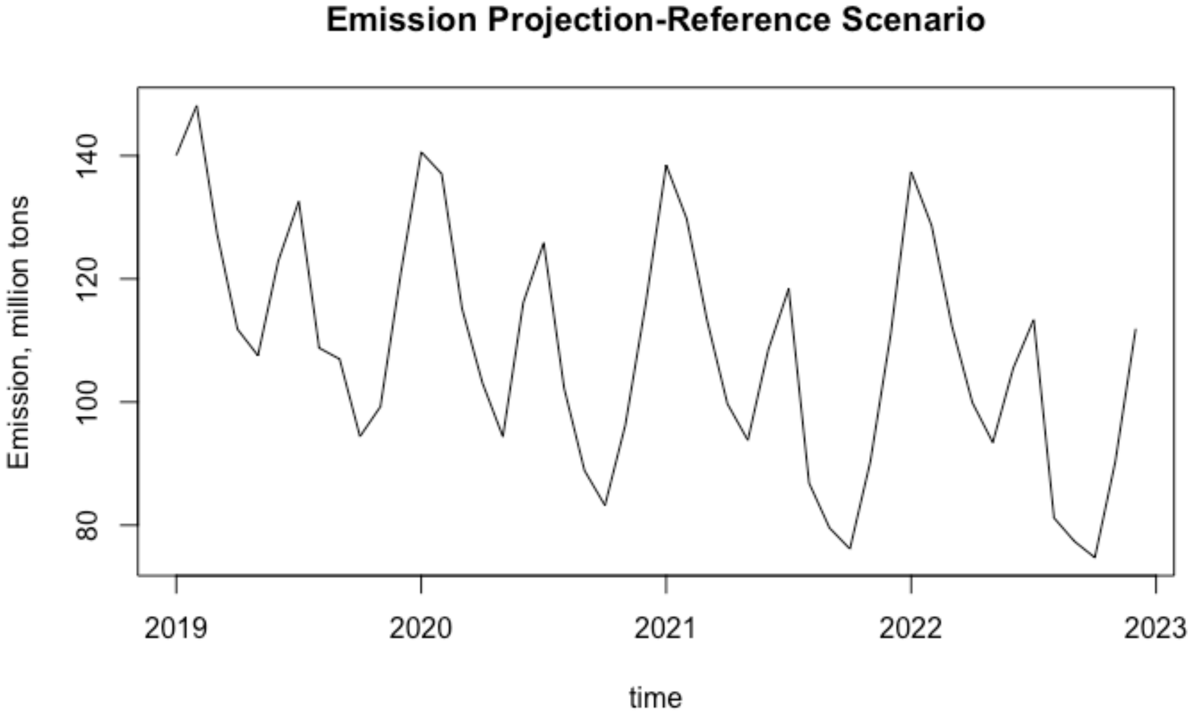

Figure 9: Emission Projection of the Reference Scenario

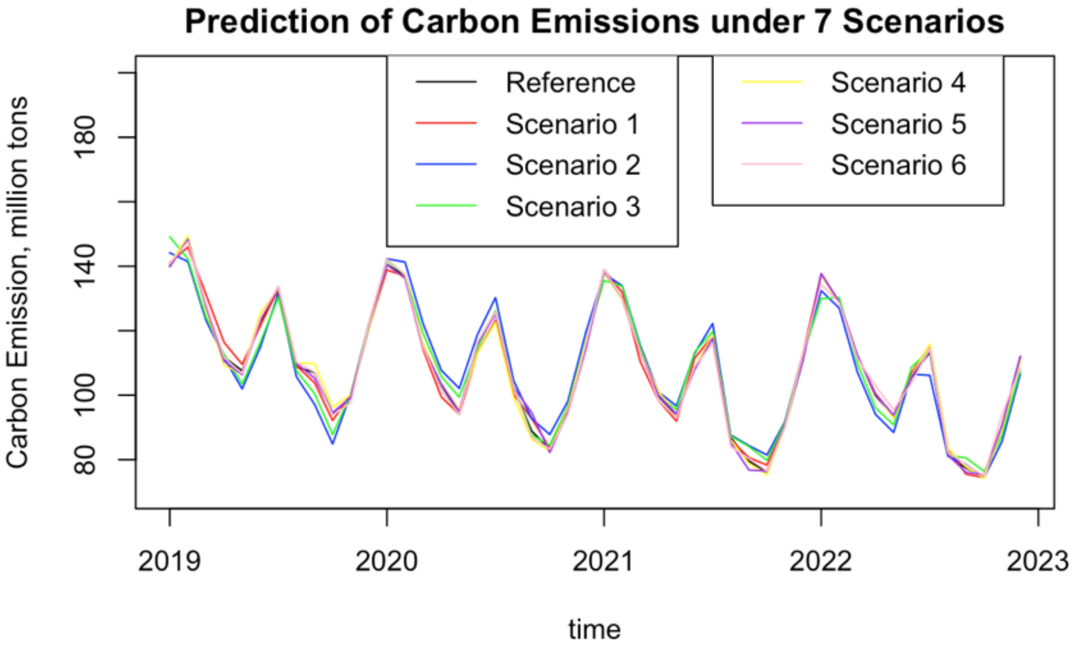

Figure 10: Comparison of Emissions from Different Scenarios

4.2 Temoa

The performance metrics of the energy system include three elements from the outputs of Temoa model: total cost for the energy system, cumulative carbon emission of the entire energy system and only of the electric sector from 2015 to 2040 with a five-year interval. Changes introduced by natural gas prices and early nuclear retirement rates are measured as differences in total system cost and cumulative carbon emissions between different scenarios. In the figures below, the reference case is the base 0 scenario where the natural gas price follows the EIA Annual Energy Outlook (2019) forecast and all the nuclear facilities will operate until their licensed retirement year with no early retirement.

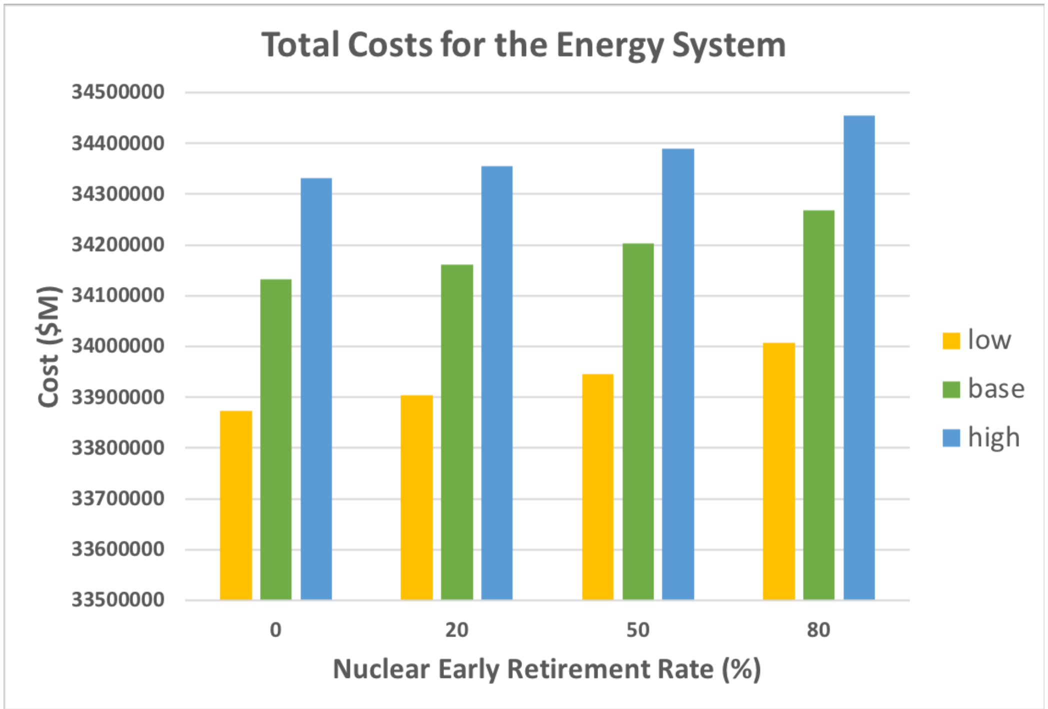

Figure 11: Total Costs for the Energy System

Figure. 11 shows modeled results of total costs for the energy system. 0, 20, 50 and 80 stands for percentages of nuclear retirement that will happen earlier than licensed. This figure indicates that under the same early nuclear retirement conditions, higher natural gas price will lead to increased total system cost. With all the other conditions remaining unchanged, the higher energy cost will inevitably drive up the total system costs. The total cost differences between base case and low natural gas prices are around $250 billion under the same early retirement conditions, and the difference between high and base-case natural gas price are about $200 billion with the same retirement rates. The natural gas prices under each scenario over the forecast horizon can be found in the Appendix 5.

Meanwhile, with the same natural gas price, higher early retirement rate also results in higher system cost. The differences in total system cost are about $20 billion between 0% and 20% early retirement rate, about $40 billion between 20% and 50% early retirement rate, and about $60 billion between 50% and 80% early retirement rate. This is the result of early retirement that more investments of power generating facilities need to be made to make up for the reduction in the nuclear capacities, which, are mostly base-load capacities.

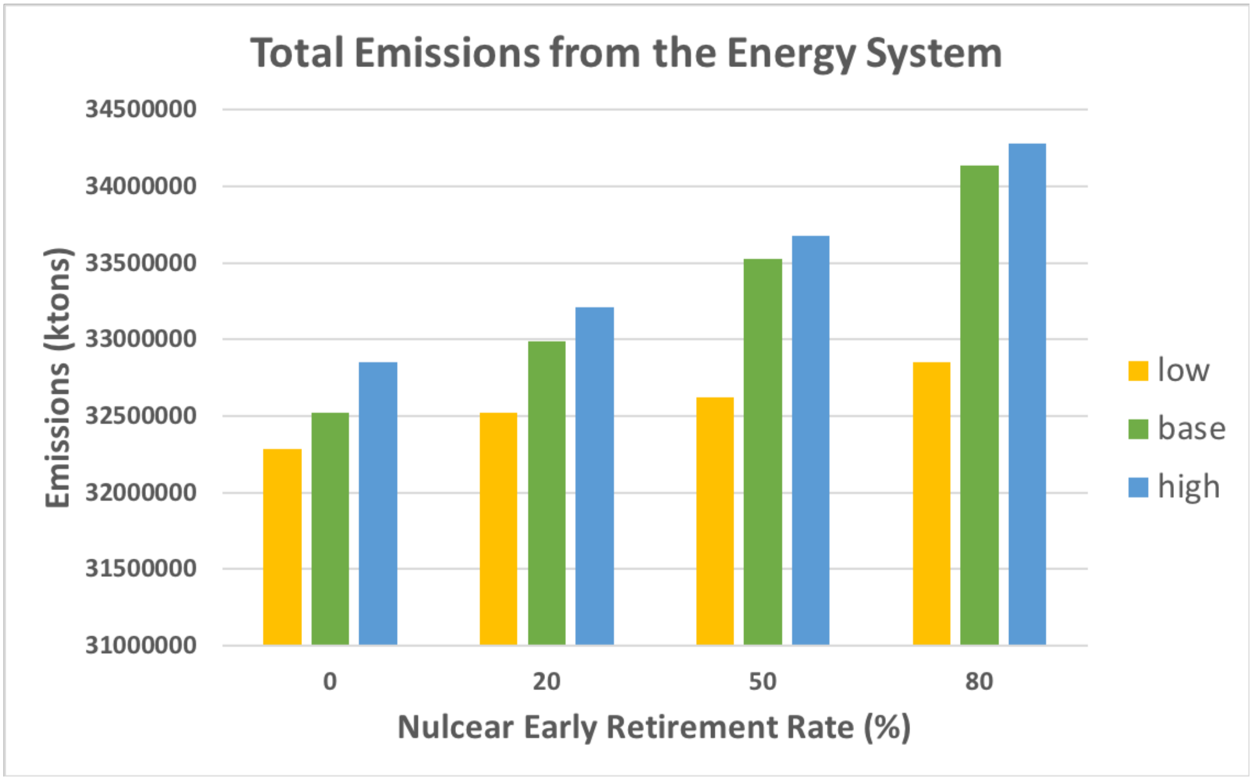

Figure 12: Total Emission from the Energy System

Figure 12 shows the differences between total carbon emissions from 2015 to 2040 under the 12 scenarios. The emission here includes emissions from **all sectors**, and the total emissions with the same early retirement rate grow with the natural gas price. In addition, the total carbon emission is also greater with higher early retirement rate. Natural gas is not used for the purpose of electric generation only. Residential and commercial heating and cooling can also be important factors influencing carbon emission.

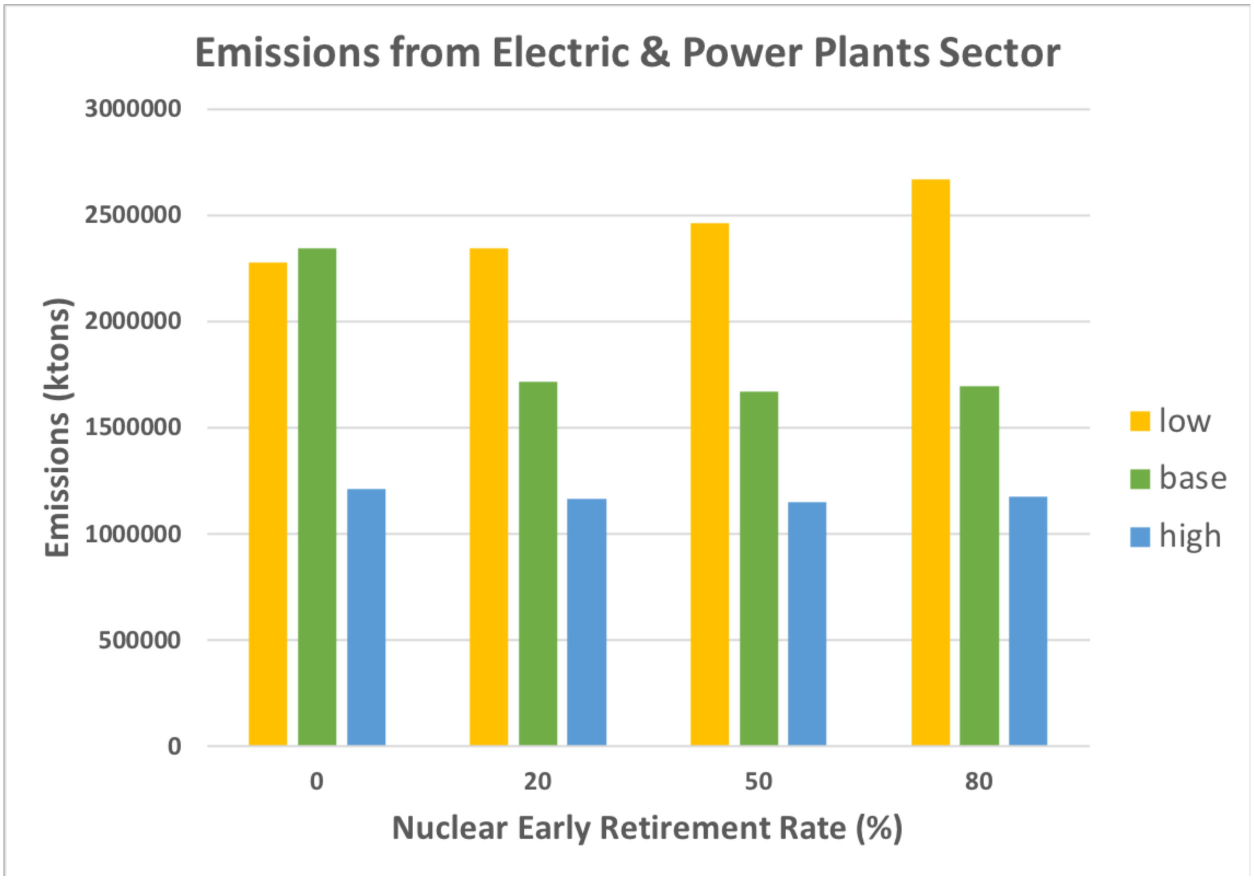

Figure 13: Emission from the Electric Power Plants Sector

Figure 13 shows the different carbon emissions in 2015 - 2040 under 12 scenarios from the **electric sector only**. The carbon dioxide here is emitted from mostly coal-fired and natural gas-fired power plants and the remainder from some small biomass, diesel and oil plants. As natural gas is the main fuel source in the electric industry, it has an overwhelming impact on the carbon emission. With the same early retirement rate, all of the higher natural gas price scenarios lead to lower emissions and the early retirement rate does not have an as significant impact as the natural gas price does.

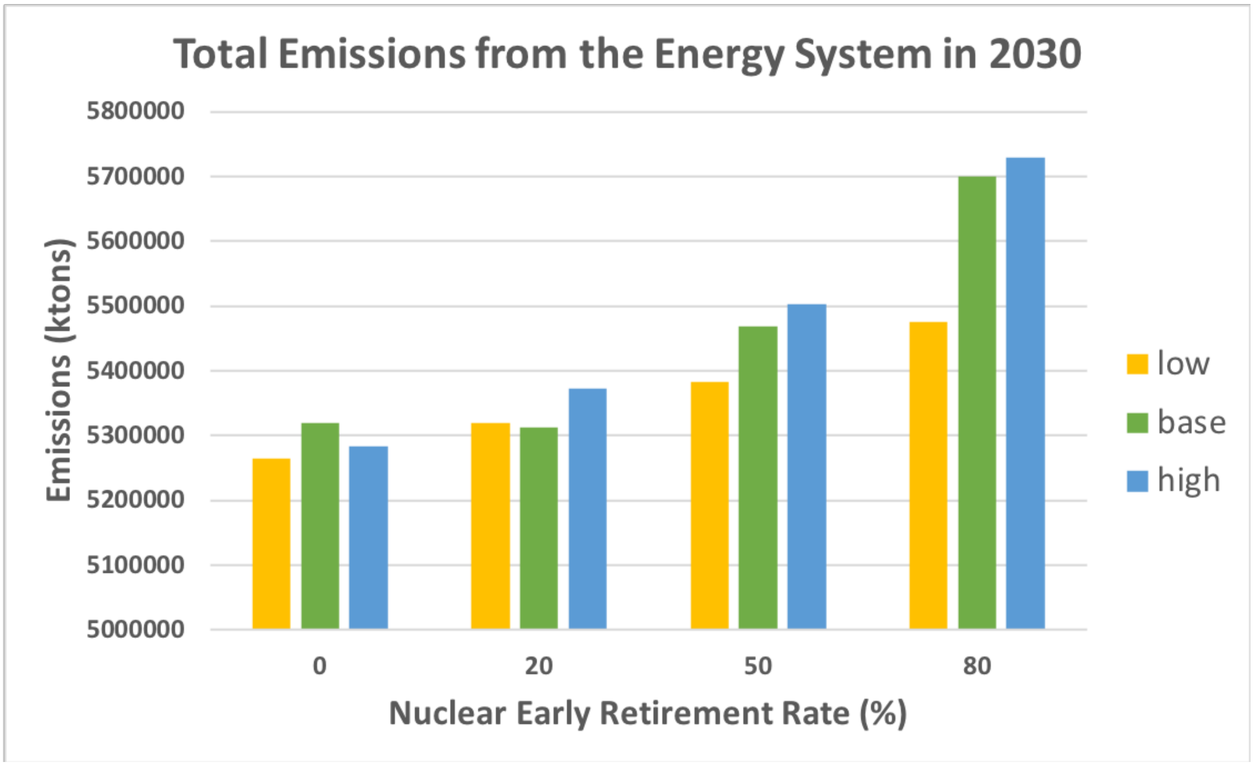

Figure 14: Total Emission from the Energy System in 2030

Figure 14 shows carbon emissions from the entire energy system in the year of 2030 only. The results are in accordance with the total emission from 2015 to 2040 that higher natural gas price incurs a higher carbon emission. The source of emission is not solely the electric sector again and the differences are not so significant in the scenarios of 0% and 20% of nuclear retirement.

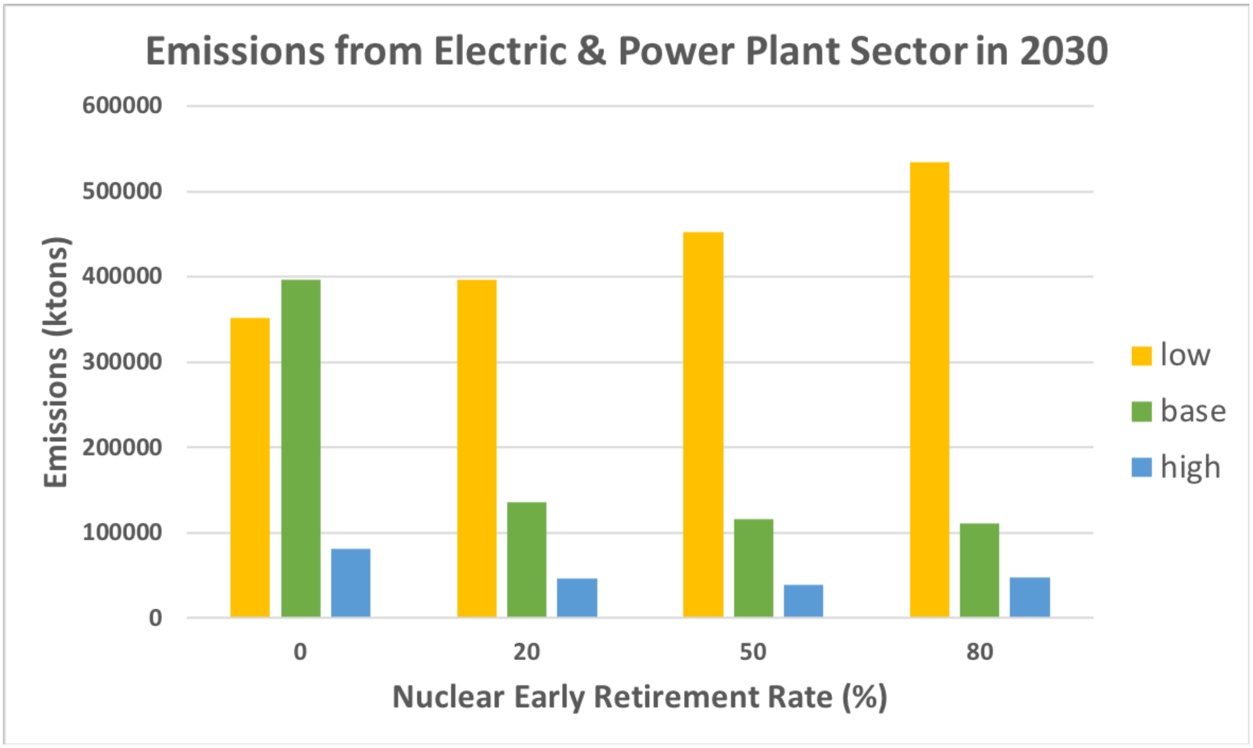

Figure 15: Emission from Electric & Power Plant Sector in 2030

Figure 15 shows the carbon emissions from the electric sector only in the year of 2030. Similar to the total electric sector emission from 2015 to 2040, the carbon emission is completely driven by the natural gas price. When the natural gas price is low, carbon emissions increase with the increase in early retirement rate. However, when the natural gas price is base or high, emissions will decrease. It is also worth noticing that when the natural gas price is the base case, carbon emission drops-off more than 260000 kilo-ton (66% of the emission of the reference case) from the 0% early retirement scenario to the 20% early retirement scenario. In general, carbon emissions are more sensitive to the change in natural gas price in the electric sector. With the higher cost of natural gas as the fuel type, the industry will switch to other technologies for power. The substitutes include renewables like solar as depicted in Figure 16.

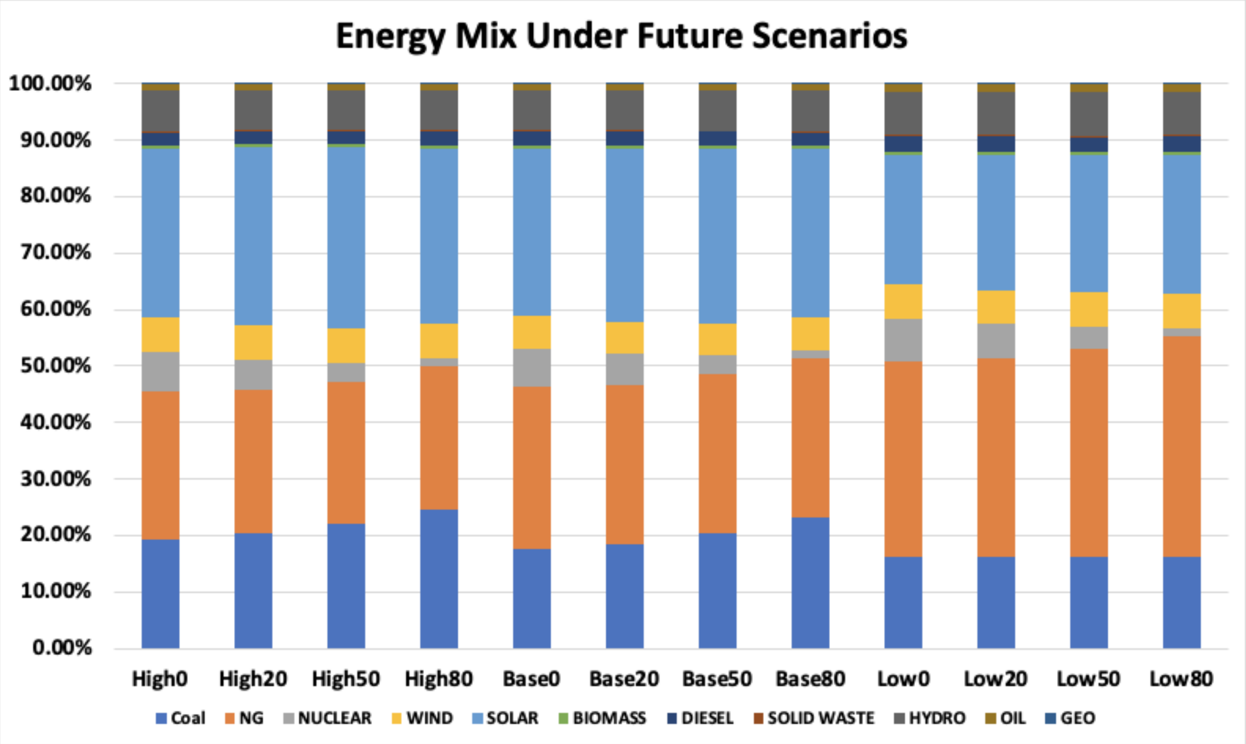

Figure 16: Energy Mix under Different Scenarios in 2030

Figure 16 demonstrates the energy capacity mix in the year 2030 under future scenarios. Within all the scenarios, coal, natural gas and solar turn out to be the dominant player while wind, hydro and geothermal remain constant among all scenarios. The different nuclear capacity reductions are not compensated by the same fuel type in these circumstances. Solar power and coal are the two main fuel types to switch to after the nuclear capacities are shut down, and natural gas capacities remain greatly affected by natural gas price. In the scenarios with low natural gas price in the future, the system expansion will favor lower energy costs and consequently natural gas capacity accounts for higher percentages in the energy mix. For those scenarios of high natural gas price, solar energy turns out to be the most economic choice of all and makes up most of the capacity reduction from nuclear power.

5. Discussion

The study is divided into two parts, with the first part focusing on the multivariate regression model with historical data and the second part emphasizing the output results from the Temoa model with capacity expansion.

The first part of the study aims to provide a first order analysis as demand, outage and energy mix are the only variables taken into consideration since there are different variables that are left behind. It was expected that the increase in nuclear outage would lead to more carbon-emitting fuel types being dispatch and more carbon dioxide released into the atmosphere consequently. However, the raw data indicates that the carbon emission actually is inversely related to nuclear outage. This happens as summer and winter have higher peak demands of electricity and the system cannot afford too much nuclear outage. Due to the high demand for electric power, the carbon emission will also be higher in summer and winter and more nuclear retirement will be scheduled in spring and fall. This directly leads to the inverse relationship between nuclear outage and carbon emission, if no other variable is taken into consideration. Consequently, we chose to include the factor of demand into our analysis to address this issue related to nuclear outage. In addition, nuclear outage only accounts for a small fraction of entire nuclear generation capacity, so the effect of nuclear outage may not be significant from a broader view. We used nuclear outage as a proxy of nuclear retirement impact and applied the dependency between nuclear outage and carbon emission to existing nuclear capacity to extrapolate the impact of nuclear retirement.

The results of the Temoa model suggests that the impacts of nuclear retirement on carbon emissions depend on future natural gas prices. If natural gas price is low, natural gas will be a favorable replacement for nuclear power and thus emissions will increase substantially. However, if natural gas price is increasing, natural gas will be less economically competitive and nuclear power will be likely to be replaced by clean energy such as solar, which will result in considerable carbon reduction. It is meaningful to think about nuclear retirement's impact on carbon emission in the context of other system parameters. For example, if we incorporate the fact that the cost of renewables is going down, the patterns of energy mix and carbon emissions will also change accordingly.

Finally, further analysis can be achieved from many other perspectives. One of the drawbacks of our study is the short period of available data. Due to the limit of the website, only three years of demand data are available for the study, which fails to capture many critical energy issues such as the diving of natural gas price and the oil embargo crisis.

6. Conclusion and Recommendations

As our results indicated, nuclear retirement will not cause a great difference in emissions unless skyrocketing the shutdown. However, many nuclear plants are at risk of early retirement before the expiration of their license due to high costs with low electricity prices. To improve the tough economic reality faced by nuclear facilities and avoid a mass of closure, we recommend that the federal and state government come up with a pragmatic approach. For example, they can provide subsidies for nuclear generating facilities to support their current operation so that they have time to schedule a comprehensive and thoughtful plan for nuclear retirement.

In the long term, it seems that decommissioning of nuclear power plants is a trend. Extreme weather intensified by climate change leads to increased drought and water supply risk, which will threaten nuclear plant operations as nuclear power cycle needs abundant water to extract and process uranium fuel, produce electricity, as well as control wastes and risks (Harto et al., 2012). In addition, with the increasing frequency of extreme weather, coal fails to provide grid resilience as expected (O'Boyle and Marcacci, 2019). According to the Australia Institute, solar performs the best of all energy sources during the record-breaking Australian heatwave (The Australia Institute, 2019). Moreover, in spite of the concern about grid disruption after nuclear retirement as nuclear power serves the energy demand as baseload in the current power market, PJM has released a report indicating that the grid reliability can be maintained as long as the rate of nuclear retirement is not too high that allows development of facilities of substitute fuel types. (PJM_Fuel Security, 2018).

To better prepare for future climate change, we recommend more emphasis should be placed on renewable energy and energy storage technology development, which is a promising path toward a resilient grid.

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Appendix

Appendix 1: Statistic Explanation on Error Report

Assume X and Y are variables that express the same phenomenon. For example, Y versus X are comparisons of predicted versus observed values.

In statistics, the mean error (ME) refers to the average of all the errors in a set.

$$\text{Mean Error} = \frac{1}{n} * \sum_{i=1}^{n} (y_i - x_i)$$

The mean error usually is not useful because positive and negative values cancel each other out. To remedy this, people use the mean absolute error (MAE) instead. The MAE uses absolute values of errors in the calculations.

$$\text{Mean Absolute Error} = \frac{1}{n} * \sum_{i=1}^{n} |y_i - x_i|$$

Root Mean Square Error (RMSE) is the standard deviation of the residuals (prediction errors). Residuals are a measure of how far from the regression line data points are; RMSE is a measure of how spread out these residuals are.

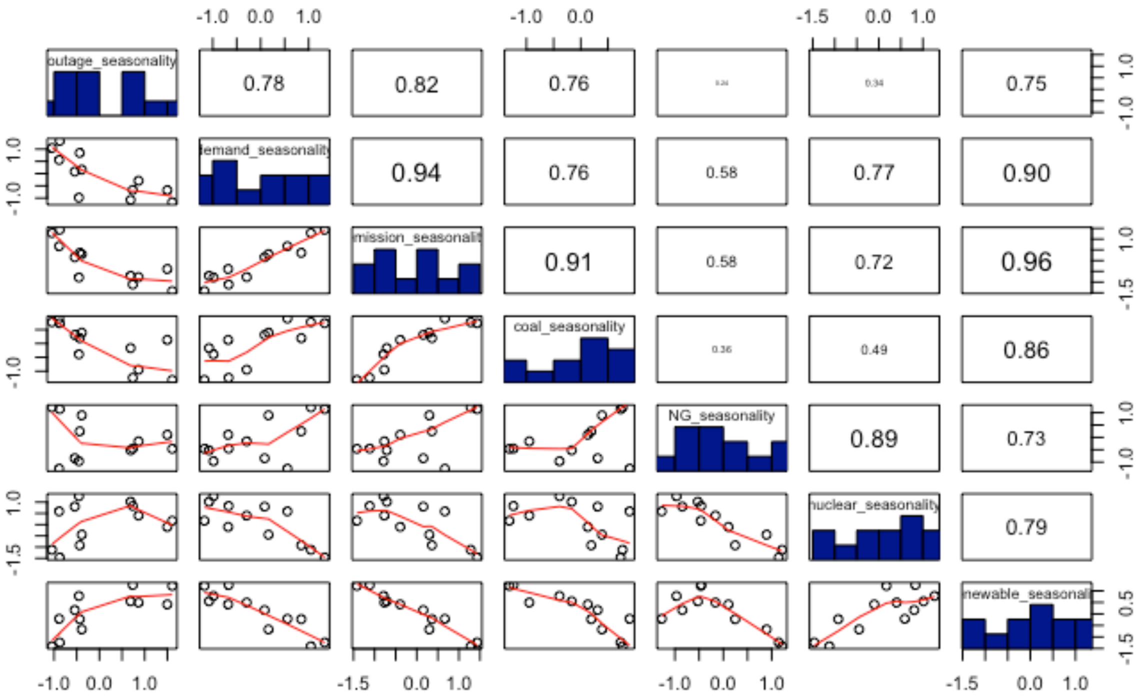
$$\text{Root Mean Square Error} = \sqrt{\frac{1}{n} * \sum_{i=1}^{n} (y_i - x_i)^2}$$

The mean (absolute) percentage error (MPE/MAPE) is the (absolute) average of percentage errors by which forecasts of a model differ from actual values of the quantity being forecast.

$$\text{Mean Percentage Error} = (\frac{1}{n} * \sum_{i=1}^{n} \frac{x_i - y_i}{x_i}) * 100\%$$

$$\text{Mean Absolute Percentage Error} = (\frac{1}{n} * \sum_{i=1}^{n} \left|\frac{x_i - y_i}{x_i}\right|) * 100\%$$

Appendix 2: The Correlation between Seasonality of the Variables



Appendix 3: Scenarios

Scenario 1

Table 1: Growth Rates of Demand and Energy Mix for High Oil and Gas Technology

	2019	**2020**	**2021**	**2022**
Demand	-0.30%	1.50%	1.03%	0.83%
Coal	-3.61%	-14.32%	-6.01%	-4.09%
Natural Gas	2.07%	9.78%	2.72%	5.08%
Nuclear	-1.01%	-2.96%	-3.80%	-5.85%
Renewables	3.42%	7.36%	6.67%	0.32%

Scenario 2

Table 2: Growth Rates of Demand and Energy Mix for Low Oil and Gas Technology

	2019	**2020**	**2021**	**2022**
Demand	-0.88%	1.27%	0.65%	0.55%
Coal	-4.76%	2.25%	-0.47%	-0.28%
Natural Gas	2.35%	-4.60%	-2.85%	-3.14%
Nuclear	-0.36%	-2.80%	-3.43%	-3.57%
Renewables	4.08%	8.60%	9.65%	8.41%

Scenario 3

Table 3: Growth Rates of Demand and Energy Mix for the High Oil Price

	2019	**2020**	**2021**	**2022**
Demand	3.01%	-0.56%	1.75%	1.30%
Coal	-0.56%	1.75%	1.30%	1.23%
Natural Gas	1.98%	5.40%	4.48%	3.91%
Nuclear	-0.80%	-3.16%	-4.06%	-6.24%

Renewables	3.66%	7.57%	8.36%	4.35%

Scenario 4

Table 4: Growth Rates of Demand and Energy Mix for the Low Oil Price

	2019	**2020**	**2021**	**2022**
Demand	-0.57%	1.30%	0.71%	0.54%
Coal	-4.22%	-6.57%	-1.78%	-0.41%
Natural Gas	2.19%	3.12%	-0.75%	1.18%
Nuclear	-0.67%	-2.81%	-3.53%	-5.58%
Renewables	3.77%	7.56%	8.04%	3.66%

Scenario 5

Table 5: Growth Rates of Demand and Energy Mix for High Economic Development

	2019	**2020**	**2021**	**2022**
Demand	-0.55%	1.72%	1.03%	0.87%
Coal	-4.54%	-7.16%	-4.02%	-1.53%
Natural Gas	2.54%	4.11%	1.03%	1.55%
Nuclear	-0.70%	-3.23%	-3.81%	-5.90%
Renewables	3.74%	7.07%	8.09%	4.60%

Scenario 6

Table 6: Growth Rates of Demand and Energy Mix for Low Economic Development

	2019	**2020**	**2021**	**2022**
Demand	-0.54%	1.12%	0.57%	0.45%
Coal	-4.27%	-7.92%	-5.01%	-1.32%
Natural Gas	2.43%	3.97%	1.17%	1.49%
Nuclear	-0.81%	-2.56%	-3.37%	-5.48%

Renewables	3.62%	7.83%	8.69%	4.04%

Appendix 4: Results of Multivariate Linear Regression Model

Scenario 1

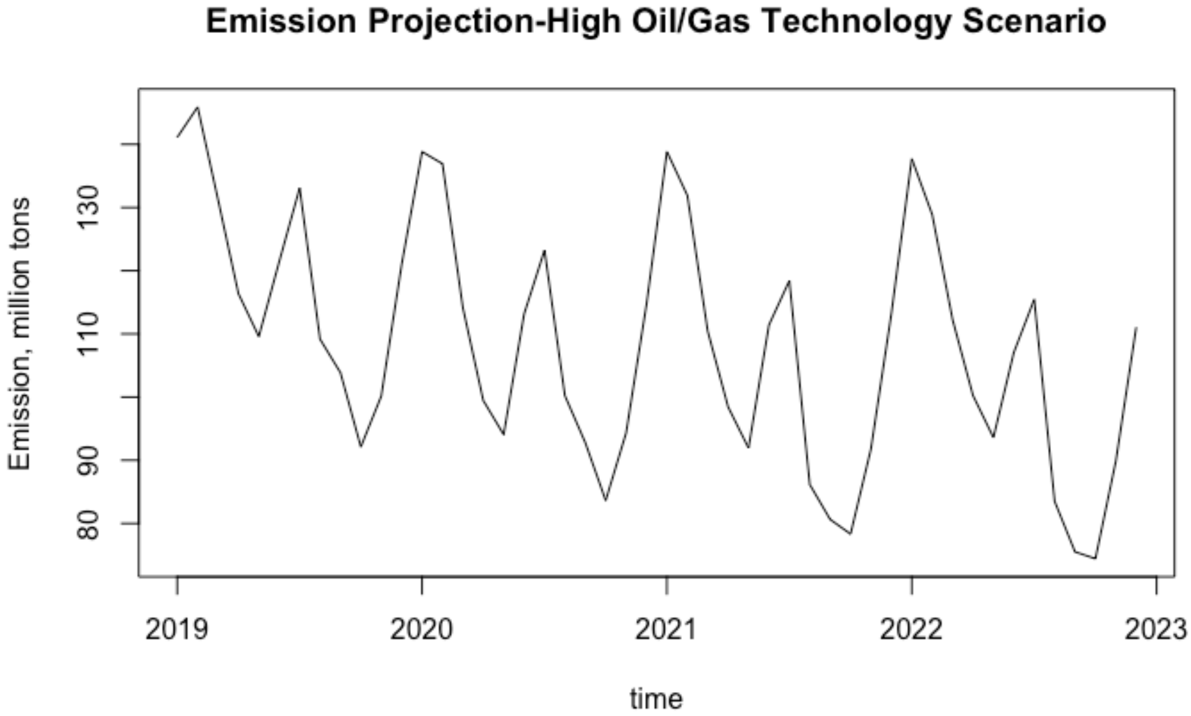


Figure 1: Emission Projection of the Scenario 1

Scenario 2

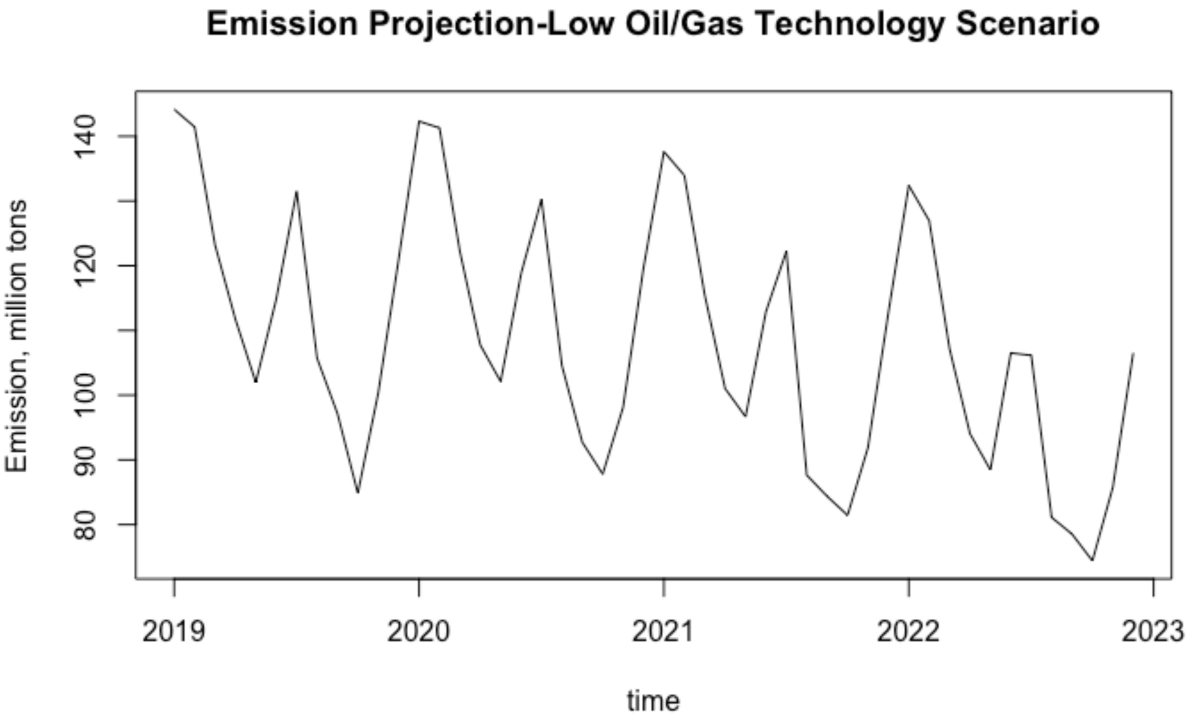


Figure 2: Emission Projection of the Scenario 2

Scenario 3

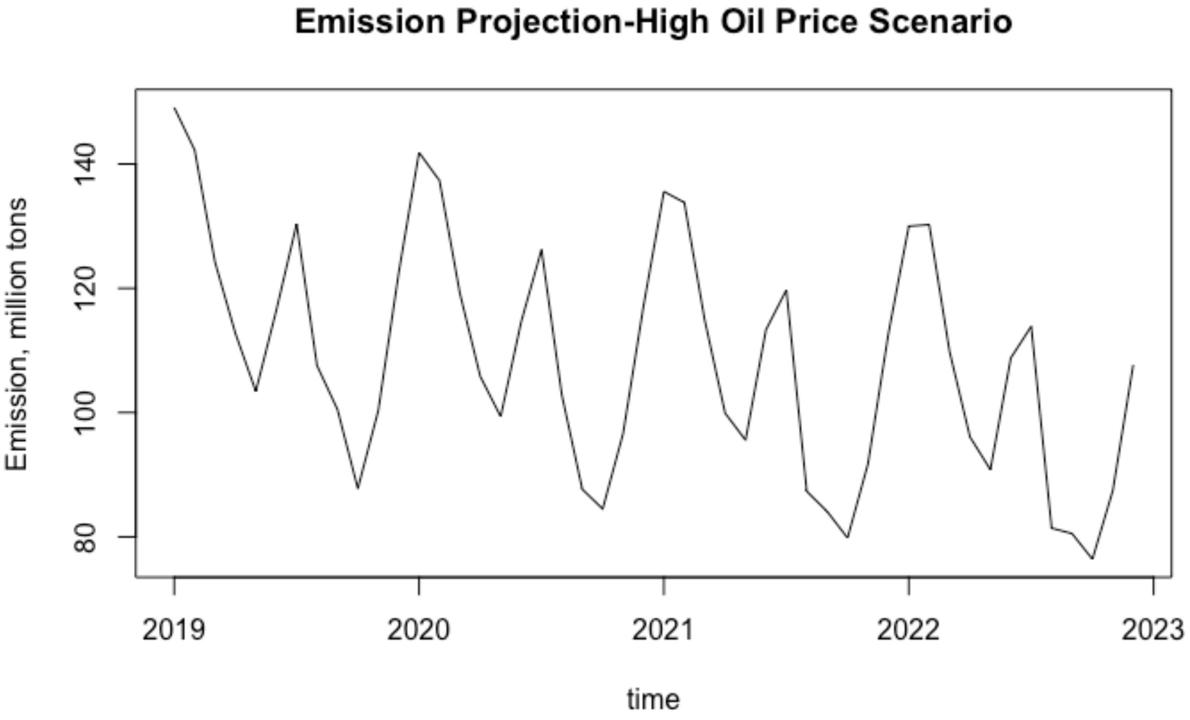


Figure 3: Emission Projection of the Scenario 3

Scenario 4

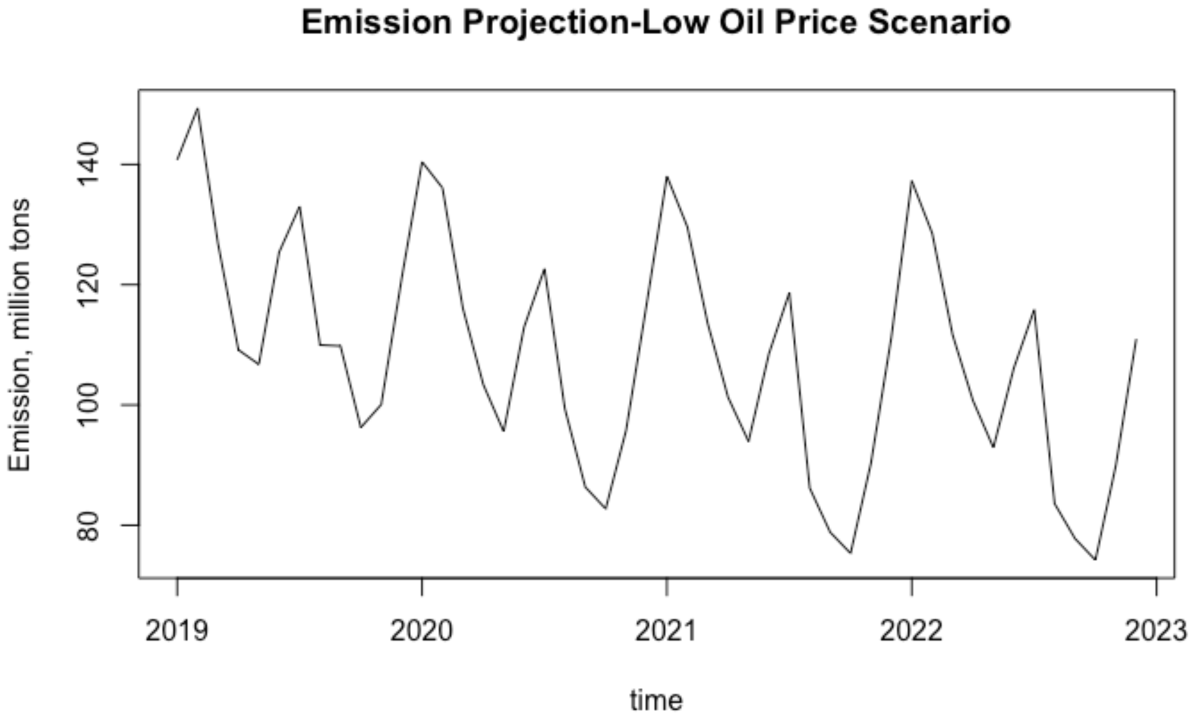


Figure 4: Emission Projection of the Scenario 4

Scenario 5

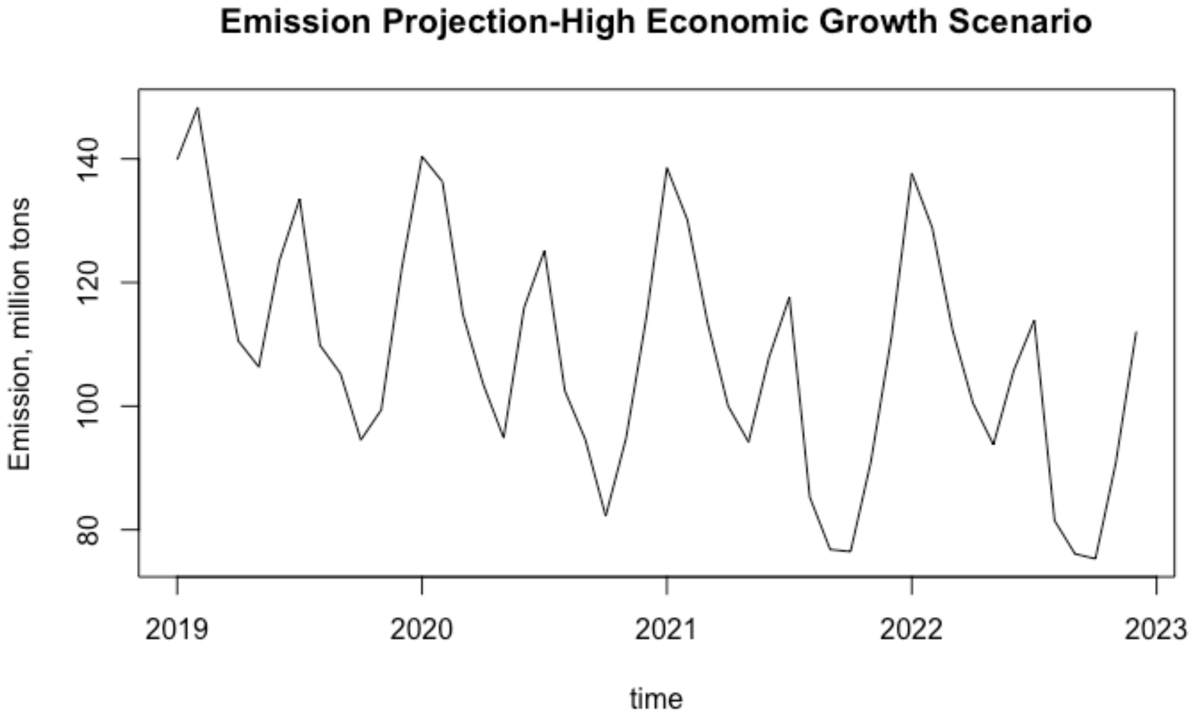


Figure 5: Emission Projection of the Scenario 5

Scenario 6

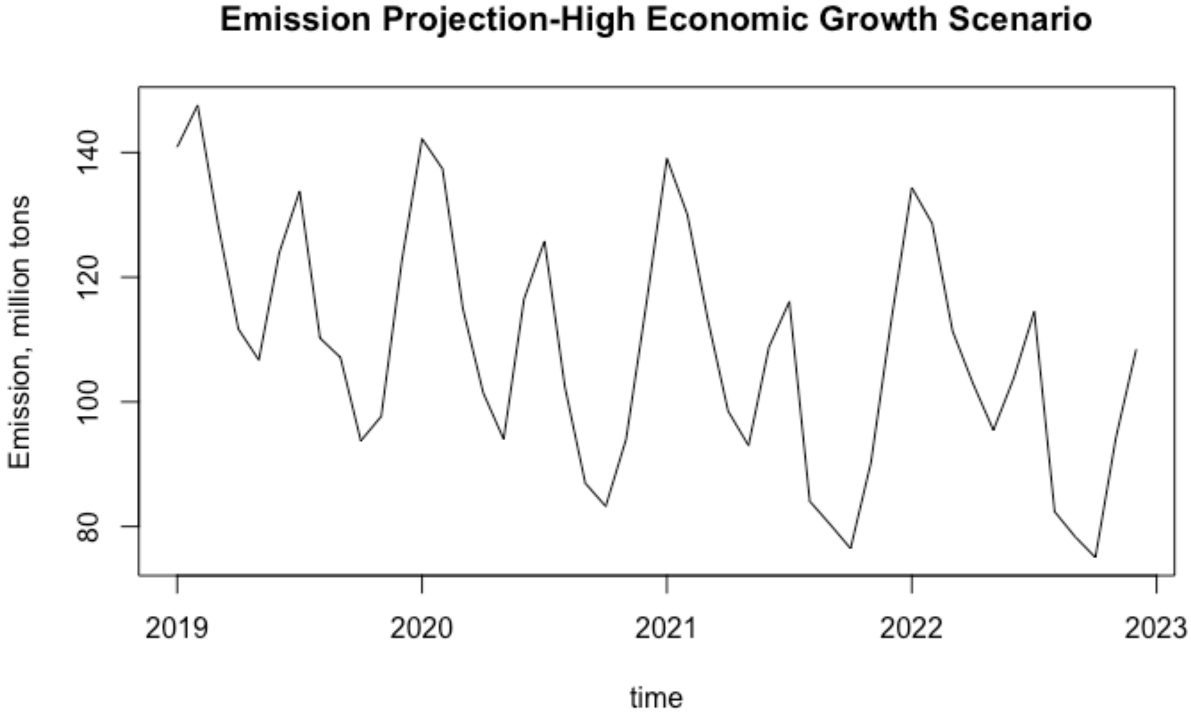


Figure 6: Emission Projection of the Scenario 6

Appendix 5: Natural Gas Price of Different Future Scenarios

Unit: ($/MMBtu)	**Year**	**2020**	**2025**	**2030**	**2035**	**2040**
Base						
	Residential	10.59	11.51	12.18	12.6	12.89
	Commercial	7.84	8.83	9.26	9.54	9.72
	Industrial	3.99	4.39	4.59	4.85	5.03
	Electricity	5.66	7.10	8.31	9.65	11.11
Low						
	Residential	12.71	13.81	14.62	15.12	15.47
	Commercial	9.41	10.60	11.11	11.45	11.66
	Industrial	4.79	5.27	5.51	5.82	6.04
	Electricity	6.79	8.52	9.97	11.58	13.33
High						
	Residential	8.47	9.21	9.74	10.08	10.31
	Commercial	6.27	7.06	7.41	7.632	7.78
	Industrial	3.19	3.51	3.67	3.88	4.02
	Electricity	4.53	5.68	6.65	7.72	8.89