LUND UNIVERSITY
School of Economics and Management

Master's Program in Innovation and Sustainable Development

Carbon-Intensive Path Dependencies in the Electric Grid: Assessing the Effect of Coal-Fired Power Plant Closures on Future Renewable Energy Adoption

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Abstract
Increasingly severe consequences of fossil fuel consumption have proliferated the exigency of an energy transition to zero and low-carbon electricity generation technology. Despite its relative reduction in market share in the United States, coal continues to play a role in future energy scenarios. This study examines the contiguous U.S. by combining historical data on coal-fired power plants with modeled energy scenarios. It contemplates the theoretical concept of *carbon lock-in* and what effects historical reduction of coal capacity has on future renewable energy adoption. The study employs econometrics utilizing multivariate regression analysis to approach a set of hypotheses related to technical, economic, and political considerations of the energy transition. The main findings are that (1) historical reduction in available coal capacity from 2004-2019 is positively correlated with higher renewable energy capacity in 2050 in absolute volumes, yet (2) the greater capacity does not translate into an increased share of renewables as a fraction of the total energy portfolio in 2050. Therefore, coal closures may increase the capacity of renewables but renewable capacity growth does not axiomatically entail a contraction of fossil fuels. This distinction suggests that further research should be directed at policy approaches that not only generate higher renewable growth, but reduce the total quantity of fossil fuels to advance renewables as the dominant technological design.

Key words: Energy Transition, Coal Closures, Renewable Energy, Carbon Lock-In, Fuel-Switching

EKHM51
Master's Thesis (15 credits ECTS)
June 2020
Supervisor: Hana Nielsen
Examiner: Astrid Kander
Word Count: 15,311

Acknowledgements

The Winter and Spring months of 2020 were quite an interesting time to write a Master's Thesis. The unexpected absence of my return to Lund University in Sweden due to COVID-19 meant that I wrote my entire thesis from my home in the United States. Despite my aspiration to return to Sweden for the months when the sun was finally shining, I was relegated to reside abroad. Through this peculiar time, I would like to formally thank my thesis supervisor Hana Nielsen for providing me invaluable guidance and assistance regarding the thesis composition.

I am incredibly grateful for the love and support of my parents – Paul Steinberg and Cheryl Anderson – who have consistently supported me throughout my endeavors, academic and otherwise. I would not be where I am today without them and for that I am immensely appreciative.

The completion of this project only continues to fuel my ambitions towards making the world a better place. I aspire for future generations to experience a secure and prosperous natural environment in all its splendor as I have had the incredible opportunity to do so. I therefore dedicate this thesis to all the extraordinary efforts being made to reduce climate change and hope it serves as a constant reminder of my ambition to arrive at a sustainable future.

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1. Chapter One

1.1 Motivation

There is unequivocal evidence that anthropometric emissions have resulted in significant negative effects on the planet (IPCC, 2018). Modern climatic change since the Industrial Revolution is directly attributed to increases in anthropogenic emissions from a variety of activities, but largely from the combustion of fossil fuels leading to anthropogenic radiative forcing (Raupach and Canadell, 2010). Radiative forcing, also commonly called the greenhouse effect (IPCC, 2014), occurs when the Earth's atmosphere traps increased quantities of greenhouse gases (GHG) from human processes. This effect has induced anomalous concentrations of heat-inducing gases within the atmosphere. Based off current trends, temperatures are projected to reach 1.5 degrees Celsius above pre-industrial levels within two decades and increase well beyond 2 degrees Celsius without action (IPCC, 2018). The average temperature increases have resulted in expanded quantity and severity of extreme weather events such as droughts, hurricanes, fires, and floods, as well as increased sea level rise, ocean acidification, and biodiversity loss (NASA, 2019). These events are projected to have increasing negative consequences on the welfare of human and natural systems. There is international agreement that countries need to significantly limit GHG's to have a 50 percent chance to stay under 2 degrees Celsius, or 450 ppm of CO_2 increase (Bos and Gupta, 2019). All countries will need to substantially reduce emissions to mitigate the most significant effects of increased climatic change or face considerable damages in the present and of increasing severity in the future.

The major drivers of anthropogenic emissions in recent history have been the combustion of fossil fuels, mainly coal, oil, and gas for energy generation in transportation, electricity, and industrial processes (GCP, 2019). The by-products of these fuels consist mainly of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (NO_x), sulfur dioxide (SO_2) and fluorinated gases (NASA, 2019). Coal was historically the predominate fossil fuel used in energy generation. In today's global energy system, oil represents 39% of total energy generation, coal represents 33%, and natural gas represents 28% from fossil fuels (Ritchie and Roser, 2019). The market share of fossil fuels in the United States has changed dramatically in recent years with coal declining by 40% in the last 10 years (Gruenspecht, 2019). Natural gas has absorbed the position of dominant energy generation technology for the U.S. economy due to technological advances such as hydraulic fracking and horizontal drilling. The U.S. is now the global leader in oil and gas production (EIA, 2019a). These fossil fuels have different impacts on the release of emissions.

Each type of fossil fuel releases different quantities of CO_2 to achieve the same amount of energy. Coal in electricity generation releases approximately 95 kilograms (kg) of CO_2 per million British thermal units (mmBtu), natural gas releases approximately 53 kg of CO_2 per mmBtu, while crude oil releases approximately 74 kg of CO_2 per mmBtu (EPA, 2014). Past efforts to diversify the portfolio of fossil fuels has had substantial benefits by reducing the carbon-intensity of electricity generation.

Coal has been the single largest contributor to GHG emissions in the history of fossil fuels causing approximately 30% of the temperature increase in the last 200 years (IEA, 2019a). Coal continues to generate substantial emissions accounting for almost a quarter of U.S. energy emissions in 2017 (Gruenspecht, 2019). Coal in the U.S. has decreased its share in electricity generation mainly due to low natural gas and renewable energy prices and rising costs of inefficient coal plants (Fleischman et al. 2013). Despite the decline in coal consumption, coal still generated 23% of electricity in the U.S. in 2019, behind natural gas at 38% and ahead of nuclear at 20% and renewables at 17% (EIA, 2019b). Figure 1 portrays the electricity generation technology market share in 2019.

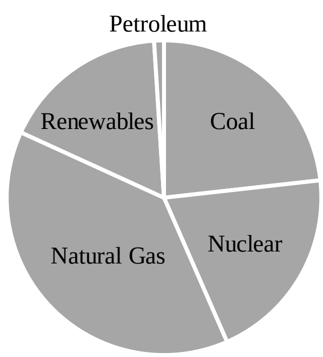

Figure 1: US Electricity Generation Technology by Market Share in 2019

Source: Own construction based on (EIA, 2019b)

Coal is currently projected to generate 118 GW of U.S. electricity in 2050, approximately 10% of total electricity generation (Wesley et al. 2019). Electricity generation from coal is substantially more costly and inefficient than alternative sources of energy generation. The negative externalities of coal are primarily observed through negative impacts on human health, the environment, and economic welfare (Machol and Rizk, 2012). Coal for electricity generation must be practically phased out globally by 2050 to have a chance to stay below 1.5-2 degrees Celsius (IPCC, 2018). Contrary to coal as a source of electricity, there are multiple zero and low-carbon energy technologies that represent viable replacements. Renewable technologies in the

U.S. have been estimated to have the potential to replace approximately 86 percent of existing coal generation by 2025 (Gimon et al. 2019). In an advanced economy like the United States, the presence of such an impotent fuel to meet human needs is anachronous.

1.2 Research Background

The urgency of climate change mitigation through decarbonization of all sectors of the economy is fundamental to ensure a sustainable, and secure environment, economy, and society. A *Deep Decarbonization* future as highlighted in the report *Pathways to Deep Decarbonization in the U.S.* (2014), aims to examine avenues to reduce U.S. GHG emissions by 80% below 1990 levels by 2050. Their findings are that deep decarbonization is technically feasible and not cost-prohibitive (Williams et al., 2014). The power sector in the U.S. is considered the most accessible option for immediate decarbonization (Jenkins and Thernstrom, 2017). The energy transition to a zero or low-carbon future powered by alternative energy technologies has been significantly researched. The existing literature concurs regarding the feasibility of a U.S. low-carbon electricity system (Becker et al. 2014; Mai et al. 2014; Williams et al. 2014; Jacobson et al. 2015; Brick and Thernstrom, 2016; Jenkins et al. 2018). Existing literature use multiple variable models of the electric system representing different assumptions about endogenous factors of the models such as cost and feasibility of technologies (Berkhout et al., 2012). Despite the differences among models, the studies largely agree on the opportunity for a deeply decarbonized future with the electric sector as the most evident target for immediate decarbonization to a zero or low-carbon grid. The theoretical availability of technologies does not translate to increased decarbonization. A prevailing ideology argues transitions "require some combination of economic, political, institutional and socio-cultural changes" (Berkhout et al. 2009; Cohen et al. 2010; Stephens et al. 2008) (Berkhout et al., 2012, p. 109). The literature adheres to the need for coordination across technological, political, economic and social domains to generate an equitable environment for clean energy to drive the energy transition.

To generate the most impact, a zero or low-carbon energy transition must focus on phasing out the most polluting and carbon-intensive fuel in its arsenal – coal – to work towards reducing emissions and staying below 2 degrees Celsius. The transition must simultaneously introduce renewables as well as eliminate fossil fuels. Coal continues to play a significant role in electricity generation globally, whereas in advanced economies like the U.S. coal has declined. A large portion of the reduction has been due to fuel-switching coal-fired power plants to natural gas. Despite this contraction, coal is still projected to play a substantial role in future U.S. energy scenarios of an estimated 10% of total electricity generation in 2050 (NREL, 2019).

Additionally, with about 28% of existing global coal reserves located in the U.S. (Epstein et al. 2019), there is an opportunity to considerably contract the supply of coal. Only five states have currently eliminated coal from their energy portfolio entirely. The inadequacies of coal as an energy technology in modern day advanced economies are evident due to relatively higher direct and indirect costs compared to other energy technologies. The discussion of how to eliminate coal from the electric grid has been researched in recent years as the economic and environmental costs of coal become less palpable (Fleischman et al. 2013; Feaster, 2017; Zhao and Alexandroff, 2019; Cui et al. 2019; Blondeel et al. 2019). The push for an unequivocal ban on coal-fired power in the electricity sector has been pursued by the Powering Past Coal Alliance who aim to facilitate an internationally recognized ban of coal (Blondeel et al. 2019). Therefore, existing research on the U.S. coal industry focuses on looking at the constraints to closing coal plants, the availability of replacement through cleaner forms of energy, and potential avenues for existing coal plants in the interim.

1.3 Aim and Objective

Climate change is rapidly increasing the urgency of an energy transition to cleaner forms of energy. This study will aim to provide insight into the phase out of coal capacity and its impact on the adoption of renewable electricity sources in the United States energy system. A greater understanding of coal closures effects may help lead to a more sustainable energy transition. The U.S. will benefit from gaining knowledge related to the efficacy of eliminating coal-fired power generation and its relationship to renewable energy. More specifically, policy makers in state governments can benefit from increased knowledge surrounding the effects of eliminating coal and supporting policies that promote renewables. The research will additionally provide acumen to other countries with substantial coal capacity in their efforts to transition away from coal. The existing research on energy transitions has mainly looked at the viability of zero or low-carbon power systems as well as technological, economic, political, and social considerations. The existing literature on the rapid elimination of coal has looked at constraints to reducing use. To the best of our knowledge, there has not been a concerted effort to investigate the effects of retiring coal-fired power plants on future renewable energy in the United States. There is a critical need to understand the mechanisms of what happens when we close coal-fired power plants. The combination of coal and its effects on future renewable energy present an important facet of energy transitions – do actors that reduce path-dependencies now see substantially more clean energy later? It begets the question: Are areas more dependent on carbon-intensive technologies not achieving similar quantities of renewables in a future low-carbon electric system? The study will formally address the following overarching research question:

1. **What is the effect of retiring coal-fired power plants on renewable energy in the future in the United States?**

A thorough state-level analysis of how coal-fired power plants affect the transition could provide further evidence to eliminate coal-fired power immediately from the electric generation system. The current empirical evidence exhibits the significant potential for energy transition away from coal in the U.S. satisfying low-cost economic and environmental goals. This study will address an existing research gap regarding the effects of coal on the energy transition by combining historical data on coal-fired power plants and future energy scenarios to observe how coal generation affects projected future renewable generation. This study will be novel in its approach to analyze the relationship between how eliminating coal capacity in the past will impact the future of clean energy for states. To achieve its goal, the study will provide a theoretical background of the effects of reliance on carbon-intensive energy generation. It will then present a broad review of literature and empirical evidence related to domains of the energy transition. The study will employ a quantitative analysis addressing several hypotheses using econometrics tools to assess the role of market behavior on future energy technologies. The hypotheses addressed are as follows:

Hypothesis 1: The retirement of coal capacity will lead to more renewable energy
Hypothesis 2: The continuation of operational coal capacity will lead to more natural gas
Hypothesis 3: A state with a Renewable Portfolio Standard (RPS) will have more renewable energy
Hypothesis 4: A state Republican government will have less renewable energy
Hypothesis 5: A state that is less economically prosperous will have less renewable energy

These hypotheses address considerations related to technological, economic, and political factors involved in transitioning from coal to renewables.

1.4 Purpose, Limitations, and Outline

The purpose of this research is to contribute to the energy transition field by providing insights regarding the long-term effects of coal generation on future renewable energy generation in U.S. state energy portfolios. A comprehensive analysis of how reducing coal affects the energy transition may provide further evidence to the exigency of transitioning the energy system. This can be achieved by examining specific technical, economic and political characteristics that potentially influence the adoption of clean energy. It may also allow the U.S. to lead in demonstrating to the global community a commitment to a future absolved of coal. This study will be focused on effects of the U.S. energy transition specifically. This means the analytical findings are applicable only to the U.S. and may not necessarily apply for other countries in their efforts to transition their energy systems. Additionally, the use of future modeled scenarios for technology reflect assumptions regarding current and projected trends. The data is scenario-based and can differ depending on the assumptions made within the model regarding cost and technology. The following results are therefore theoretical as future projections. Accordingly, the empirical findings of this study contain potential ambiguities. Additional limitations will be addressed throughout the paper in the following sections regarding data and methodology.

The remainder of the paper will proceed as follows. Chapter Two will explore a review of relevant literature and empirical evidence related to the technical, economic, and political domains of the energy transition surrounding the recession of coal and surge of renewable energy. Chapter Three will present the research design and describe the data and methodology used for investigating the long-term influence of coal. Chapter Four will perform the empirical inquiry using multivariate regression analysis to gather information about the effects of coal closures and other variables on renewable energy. Chapter Five will discuss the associated results and the relation to existing literature. Chapter Six will present a conclusion with policy implications and potential areas for future research.

2. Chapter Two

2.1 Theory

The energy transition is a prevailing term which describes a switch from the existing dominant energy technology to an alternative (Araújo, 2014). The historical deployment and exploitation of fossil fuels have provided dramatic increases amongst living standards for the developed world (Smil, 2004). This has been accomplished by supplying substantial quantities of useful energy reducing the need for manual labor. Although, this large-scale use of fossil fuels has been a driving force of environmental degradation (Smil, 2004). The current levels of environmental harm from fossil fuels and their austere consequences for the human species have led to a decisive point in human history. There is an immediate obligation to reduce fossil fuel consumption to provide a tolerable climate for future generations. As Grubler (2012, p. 8) states, "the need for the next energy transition is apparent as current energy systems are simply unsustainable on all accounts of social, economic, and environmental criteria". The existing theory on energy transitions from fossil fuels to renewable energy is broad regarding the competence of a transition that meets temporal demands to deter the greatest effects of environmental degradation (Grubler, 2012; Araújo, 2014; O'Connor and Clevelan, 2014; Sovacool, 2016; Li and Strachan, 2017). Despite controversy regarding specificities of a transition, one of the most common themes in energy transitions literature is the requirement of technological innovation or learning by alternative energy technology (Henderson and Newell, 2010). Patterns of technological learning are typically stylized as learning or experience curves which describe economies of scale and diffusion of a technology (Grubler et al. 1999). The experience curve generates a positive feedback loop of increasing the scale of adoption of a certain technological design which leads the total cost per unit to fall. This phenomenon produces economies of scale which provide opportunity to control a larger percentage of the market share. Figure 2 portrays a basic representation of an experience curve.

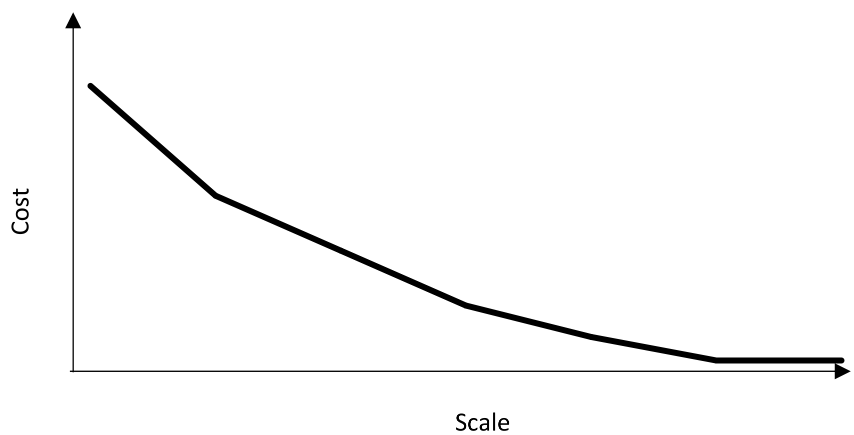

Figure 2: Experience Curve

Source: Own construction based on Grubler et al. (1999)

The opportunity for experience curves to occur is substantially more difficult, particularly for nascent technologies who stand to disrupt incumbent technological systems (Hayward and Graham, 2013). The myriad of obstacles for innovation amongst energy supply technologies are considerable. The most pertinent hurdle applicable to this research is the effect of inertia by incumbent actors and technologies in the existing system (Li and Strachan, 2017). "*Carbon lock-in*" as coined by Unruh (2000, p. 817) is the effect of developed economies becoming inexorably dependent on fossil-fuel based energy systems. The author argues that this has occurred because of the increasing returns to scale experienced by the development of path-dependencies across components related to carbon-intensive infrastructure. A positive feedback loop occurs when countries invest in a certain system of technologies, proliferating the diffusion of a certain technical design upon society. He introduces the idea of a "*Techno-Institutional Complex"* (TIC) (2000, p. 818) which is a framework to describe the feedbacks developed between a technological system and institutions. Figure 2 represents a rudimentary representation of the TIC as the U.S. electric grid.

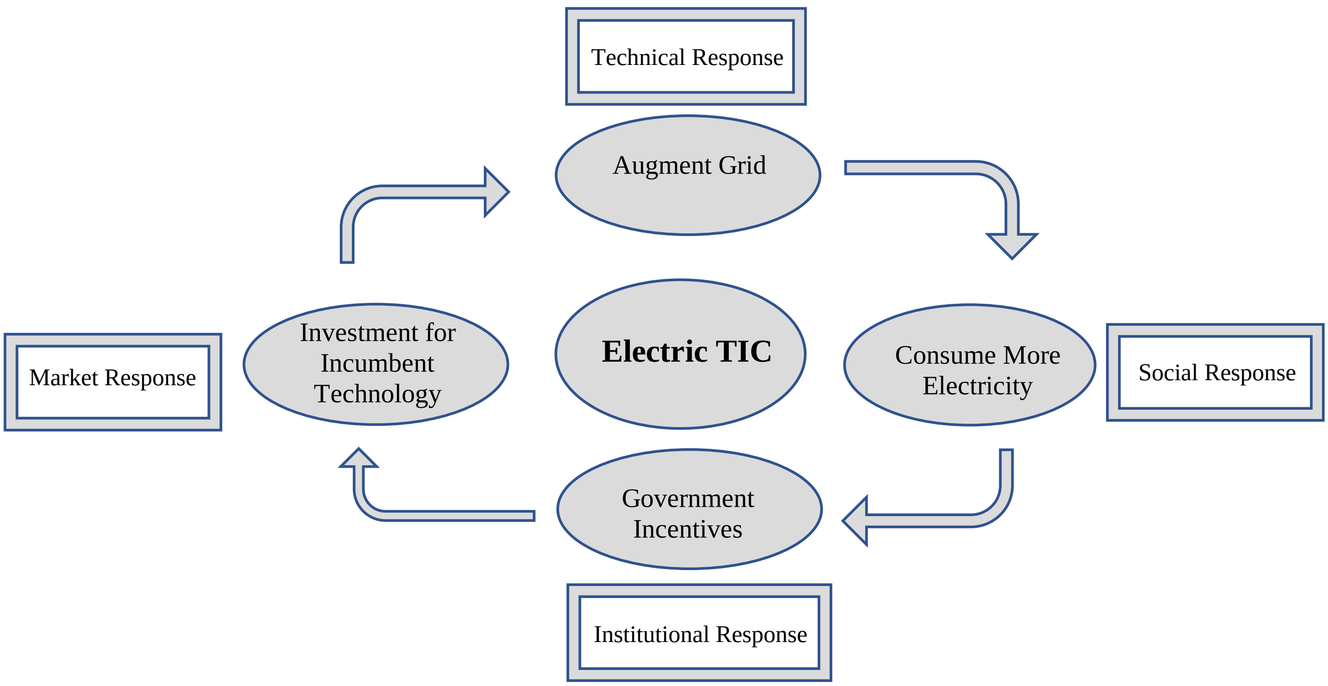

Figure 3: The Electric Techno-Institutional Complex

Source: Own construction based on Unruh (2000)

As markets invest in a certain technological design, the response of the technological system is to increase capacity to expand access. The augmentation of availability leads to increased consumption of electricity by society. As consumers use more electricity, the costs of electricity from generation technology fall. As prices fall, the demand curve shifts and more consumers are incentivized to use electricity. The surge in demand stimulates government regulation to promote investment in the existing generation technology to expand access. This feedback loop describes the electric TIC which establishes path-dependencies and enables carbon lock-in of the existing dominant technological design. These relationships establish societal norms surrounding fossil fuel consumption and lobby for preferential treatment of the incumbent system. The U.S. power sector has experienced substantial path-dependencies. This has materialized through the development of a centralized grid dependent on carbon-intensive thermal generation sources which have stymied the influence of alternative zero and low-carbon technologies. By understanding the influence of carbon lock-in on the established TIC, the difficulties encountered from transitioning away from carbon-intensive resources to clean energy are more distinguishable.

The inertia of a carbon-based electric TIC present significant difficulties in transitioning to a system that concedes to reduce environmental degradation. The follow-up to the previously discussed paper introduces policy approaches to "*escape carbon lock in*" (Unruh, 2002, p. 317). The author argues to remediate the consequences of the effects a carbon-intensive TIC, action is taken by: addressing the emissions of the system, incrementally altering minor elements of the system (*continuation*), or reconstituting the system in its entirety (*discontinuation*) (2002, p. 318). Figure 4 depicts the options for remediation of the established path-dependencies and an example from the transport sector.

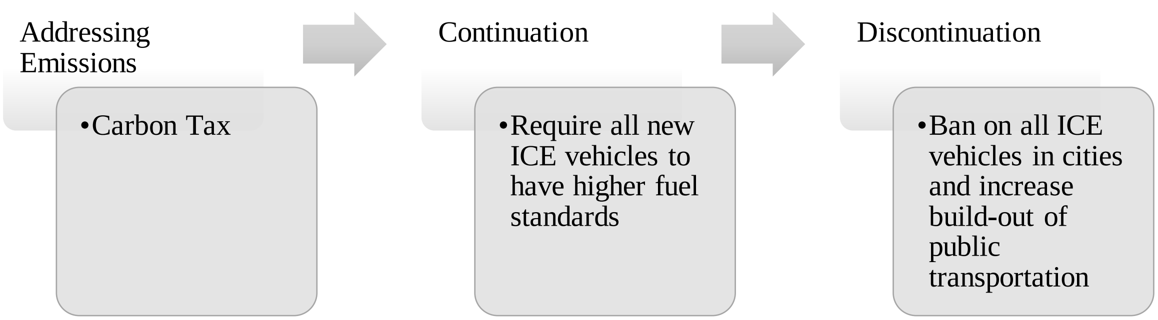

Figure 4: Policy Options to Address Carbon Lock-in

Note: ICE = Internal Combustion Engine
Source: Own construction based on Unruh (2002)

The expectation when proposing innovation to the existing system is for inertia to increase because of what incumbent actors stand to lose. The previously stated approaches are then generally implemented in successive order, as the effects of climate impacts are felt, the lowest-impact approach is advanced. The opportunity to advance to the third, most consequential approach to change the system requires a significant shock. System change through innovation is driven by scale across technological and market access. As the feasibility of technology gains traction, this provides more institutional incentive to act against the existing TIC. The solution to transition then lies in building progress through scale. This approach has practical implications for clean energy technologies as they attempt to replace the existing dominant technology. The U.S. has participated in modest approaches to remediate emissions through continuation of the existing system by fuel-switching to natural gas and increasing investment in renewable technology. A focus on (1) continuing to increase opportunity for market share of a broad swath of zero and low-carbon technologies through economies of scale and (2) supporting policy that reduces inertia through discontinuation should serve to reduce carbon lock-in experienced by the U.S. electric TIC.

2.2 Literature Review and Empirical Evidence

2.2.1 Technology

This section will address literature and empirical evidence surrounding technical considerations of the energy transition. The decarbonization of the U.S. power sector to reduce GHG's to net-zero is the driving motivation of phasing out the use of coal as rapidly as possible. Many studies have surveyed the practical opportunity for a U.S. energy transition. Most studies on the energy transition concur regarding the technical feasibility of reaching a U.S. electric grid that reduces emissions up to 80% with commercially available technologies such as; renewables, mainly variable renewable resources such as wind and solar (VRE), and other low and zero-carbon options such as hydropower, biomass, nuclear, and natural gas fitted with carbon capture and storage (CCS), combined with increased transmission and storage capacity (Jenkins and Thernstrom, 2017; Frew et al. 2016; Sepulveda et al. 2018, Mileva et al. 2016). These studies describe differing scenarios regarding the system penetration of different technologies depending on model-specific endogenous assumptions of cost and diffusion. Most studies assent regarding the technical feasibility of reaching a grid with an 80% share of VRE or higher (Jacobson et al. 2015), but often agree that penetration levels above 80% would be significantly more difficult and expensive.

The main issues in higher VRE penetration scenarios (>80%) are the cost of building larger systems to accommodate intermittency of renewables (Brick & Thernstrom, 2016), bulk energy storage (Safaei and Keith, 2015; Bistline, 2017, Hart et al. 2018), and long-distance transmission capacity (Jenkins and Thernstrom, 2017; Becker et al. 2014). VRE's are characterized by dependency on radiation and wind. This is termed intermittency due to the opportunity for a lack of consistent generation leading to lower capacity factors of systems depending on seasonal and geographical areas. Wind in 2019 produced at approximately 35% capacity and solar photovoltaics (PV) produced at approximately 25% capacity (EIA, 2019c). Fossil fuel systems can produce at approximately 90-95% of existing capacity when required (Brick & Thernstrom, 2016). This deficiency in constant capacity availability means that models that focus on high penetration VRE's are feasible but risk discounting the potential of other low-carbon technologies to achieve decarbonization in a more cost-friendly manner (Brick & Thernstrom, 2016; Sepulveda et al. 2018; Jenkins et al. 2018). Alternatives for dispatchable, baseload generation such as biomass, nuclear, geothermal, concentrated solar power (CSP) and natural gas fitted with CCS all represent potential zero or low-carbon technologies that can solve issues related to curtailment of excess production or a dearth of production of VRE's. This can be accomplished by establishing a more flexible, reliable grid which reduces emissions and costs. Although, many of these technologies face challenges to be deployed at large scale (Jenkins et al. 2018). By supporting a broad portfolio of potential zero and low-carbon options, the electric system can lower long-run costs and path dependencies by allowing for the most cost-competitive and efficient technologies to succeed in the overall mission of reducing GHG emissions and decarbonizing the power sector.

The decarbonization of the power sector will rely on multiple measures to adequately meet future demand for electrification and reduced GHG emissions. The bulk of generation will ideally come from VRE resources, solar, mainly solar PV, and wind to maximize cheap, zero-carbon electricity. Solar has experienced an annual average growth rate of 48% over the last decade, with 40% of new grid capacity in 2019 coming from solar, and total existing capacity projected to double by 2025 (SEIA, 2019). Land-based wind has similarly experienced immense growth tripling in total capacity within the last decade (AWEA, 2020). Off-shore wind is more nascent in the U.S. but expected to experience large growth in areas that do not have extensive land wind resources (AWEA, 2019). Besides VRE's, hydropower generation represents a potential for a baseload zero-carbon generation technology (IHA, 2020). Other zero or low-carbon technologies that are less discussed are concentrated solar power (CSP), geothermal and biomass. These have currently been deployed less at scale but represent options for different regions to augment their existing renewable technology bases. Other technological factors affecting decarbonization of the power sector are increased investment in high-voltage transmission and long-duration storage technologies. Future energy scenarios reliant on VRE's often require significant investment in high-voltage transmission with an increase of 56-105% in capacity (Mai et al. 2014). Additionally, large grid-scale storage is a fundamental asset in these scenarios by allowing for increased grid flexibility and resiliency while reducing curtailment of VRE's (Hart et al. 2018).

Clean energy technologies are substantially more beneficial when accounting for all direct and indirect costs associated with energy generation. VRE's have become much more cost-competitive in recent years with solar prices declining 80% and land-based wind falling 40% in the last decade (IRENA, 2017). Future cost declines could potentially continue with solar PV projected to fall by 59%, CSP by 43%, land and off-shore wind by approximately 30%, and storage technologies such as lithium-ion batteries projected to drop 54% by 2030 (IRENA, 2017). Clean energy technologies represent numerous avoided economic damages to society by replacing coal, besides lower retail costs of electricity. Coal produces local air pollutants from combustion in addition to CO_2, such as SO_2, NO_x, mercury and other particulates (EIA, 2019d). The estimated mortalities from fossil-fueled power plant pollution in the U.S. in 2011 was estimated at approximately 30,000 people per year (Fischetti, 2011), with estimated health costs of coal valued at $0.19-$0.45/kWh, higher than the average retail value of coal generated electricity (Machol and Rizk, 2013). In addition, the health impacts on workers within the industry are substantial as approximately 10,000 former coal miners died of Black Lung disease between 1990 to 2000 (UCUSA, 2016). Coal also has extreme negative impacts on the environment from land disturbances and deforestation, to water contamination and increased emissions. The effect of coal on climate change is estimated to cost an average of $64 billion USD per year, with total economic damages due to the total life-cycle of coal valued at an average of $345 billion USD per year (Epstein et. al, 2019). Zero and low-carbon energy technology can substantially reduce these costs.

Renewable energy also presents the additional benefits of increased job growth and energy security. Solar and wind accounted for the 2nd and 3rd highest growth rates of employment in 2019, respectively (NASEO, 2020). VRE's positively impact economic growth and create more jobs per unit of energy than fossil fuels (Wei et al. 2009). Renewable energy also can provide energy resilience and security. Energy resiliency is the ability of the electricity system to perform throughout a disruptive event like a natural disaster or a cyberattack and recover quickly (Lin et al. 2018). The existing electricity infrastructure has been designed around fossil fuels which are located near populations and shipped through transmission and distribution networks which are subject to increased threats from natural disasters fueled by climate change (Bridle and Kitson, 2014). The decentralized, smaller scale of renewables and dearth of necessary fuel inputs enables increased resilience in the face of disruption as systems possess the opportunity for flexibility and independence (Schneider and Frogatt, 2018). Literature and empirical evidence on power systems regarding the technological capacity and ability of renewables to significantly replace coal present a convincing argument that the technical consequences of retiring coal will help diffuse carbon lock-in the electric TIC by promoting cleaner energy and acquiesce to a system with carbon-scarce electricity generation. Therefore, I present the following hypothesis:

Hypothesis 1: The retirement of coal capacity will lead to more renewable energy capacity

I hypothesize that states which, on average, have retired higher amounts of coal capacity in the past will experience greater amounts of renewable energy capacity in the future compared to other states.

2.2.2 Fuel-Switching

The extensive potential for alternative technologies for energy generation and the inadequacies of coal display the evident opportunity for a complete phase out of coal. One potential technological solution, and a feasible solution over the short-term (5-10 years) for reducing coal-fired emissions is fuel-switching from to coal to natural gas or biomass. Fuel-switching led to an avoided 40 million metric tons of CO_2 (Mmt/CO_2) in 2018 in the U.S. (IEA, 2019a). Switching outright from coal to natural gas reduces emissions by up to 40% (NACAA, 2015). Fuel-switching involves three different strategies; alternating multiple fuel sources, blending fuel types, or modifying the plant to utilize a lower carbon-intensive fuel entirely (NACAA, 2015). The preference for strategy mostly depends on plant characteristics such as installed emission controls, capacity factor, and dispatch availability (Geisbrecht & Dipietro, 2009). The most common strategy for power plants is cofiring or utilizing alternative fuel sources, as retrofitting a plant for an entirely new fuel is costly (Fantazzini and Maggi, 2014). A 2014 review found 7600 MW of U.S. coal capacity was scheduled to be repowered to a lower-emitting fuel, and other studies have exhibited the potential of reducing CO_2 emissions by 5% in the U.S. solely by using coal co-fired with biomass (NACAA, 2015). Additionally, fuel-switching to natural gas combined cycle (NGCC) from coal in Texas has been estimated to reduce yearly freshwater consumption by 60% due to lower rates of water consumption from natural gas (Grubert et al. 2012).

Future fuel-switching will likely be more feasible for plants with already existing approval for multiple fuels or with the capacity to co-fire alternative fuel types due to high capital costs of retrofitting a permanent switch. Fuel-switching represents a beneficial and immediate solution to coal-fired power that has allowed the U.S. to reduce carbon emissions from the power sector. Although, fuel-switching risks increasing the long-term utilization of a plant due to a lower emissions factor that may effectively lead to more emissions overall. This scenario is not compatible with longer decarbonization scenarios as natural gas emits between 40-65% of the CO_2 and CH_4 as coal depending on the source (Wilson & Staffell, 2018). A reliance on fuel-switching to natural gas (NG) can further exacerbate carbon lock-in. Fuel-switching to biomass to utilize waste products represents a more efficient net-zero carbon strategy (NACAA, 2015).

The effects of a carbon-intensive TIC make fuel-switching to a lower-carbon resource a more copacetic choice for incumbents in the present. Therefore, I offer the following hypothesis:

Hypothesis 2: The continuation of operational coal capacity will lead to increased natural gas

I hypothesize that states which, on average, have greater existing coal capacity in the present will experience greater natural gas capacity in the future. This is because they will experience fuel-switching due to the existing availability of carbon infrastructure and lower investment costs.

2.2.3 Policy

This section will address literature and empirical evidence related to the political considerations within the institutional component of the U.S. electric TIC. Policy determines a large amount of the opportunity that technology receives. The carbon lock-in of the U.S. electric TIC means that there are significant policies promoting the use of fossil fuels and negatively affecting the diffusion of renewables (Unruh, 2000). Despite the influential interests of incumbents, renewable portfolio standards (RPS) have been influential in promoting clean energy in the U.S. Approximately half of renewables growth since 2000 is associated with RPS policies (Barbose, 2018). An RPS is a minimum portion of electricity that is required to be sold by utilities from renewables (Rountree and Baldwin, 2018). Mandatory RPS' have been enacted in 30 states with 7 states enacting voluntary RPS' and 75% of the U.S. population living in a state with an RPS (Holt and Galligan, 2013). The main goals of an RPS are to generate economic and environmental benefits for society by decreasing GHG emissions and the retail cost of electricity to consumers and promoting energy security. Renewables represented an avoided 59 Mmt/CO_2 in 2013, reduced local air pollutants such as SO_2 and NO_x resulting in health and environmental benefits of $5.2 billion, and reduced water consumption by 2% of total power sector usage in 2013 (Wiser et al. 2016). Additional benefits of RPS policies have resulted in approximately 200,000 domestic jobs and an increase of $20 billion in GDP (Wiser et al. 2016). RPS costs averaged 2% of consumer retail electricity prices representing their ability to cost-effectively enable clean energy with over half of states raising their overall target in recent years (Barbose, 2018) .

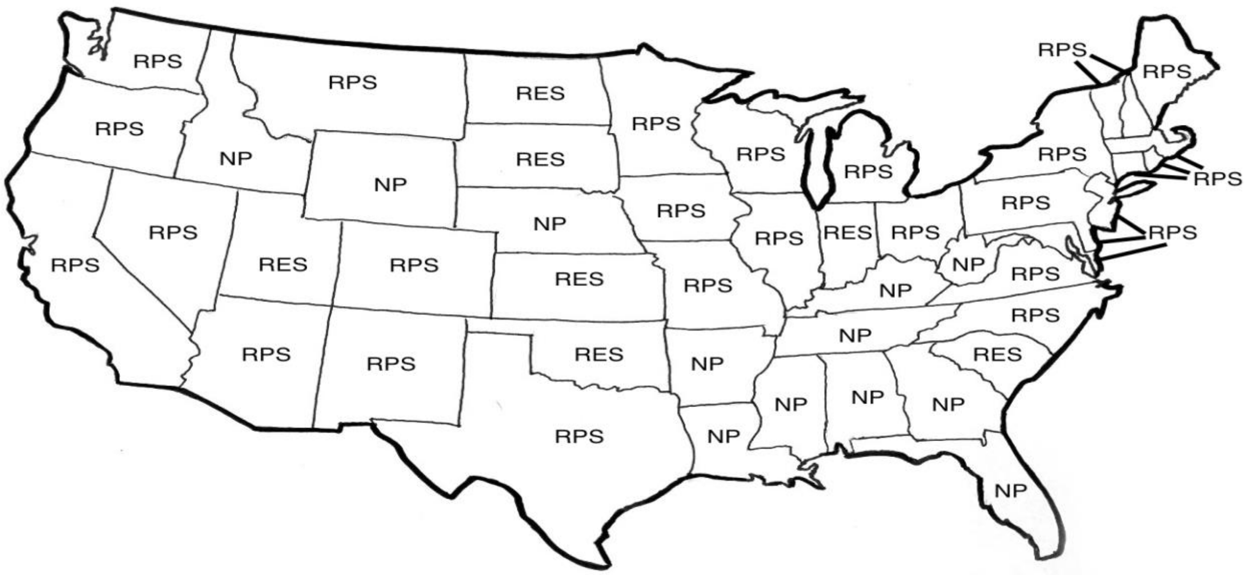

Figure 5: Description of Renewable Energy Policy by State

Note: RPS = Renewable Portfolio Standard, RES = Renewable Energy Standard or Goal, NP = No renewable energy policy
Source: Own construction based off (NCSL, 2020a)

RPS policies are significantly different by state and represent a sub-optimal approach to decarbonization (Holt and Galligan, 2013) due to their statewide limitations and nature as a quota. A quota requires a minimum amount of renewable electricity provided to consumers (Kilinc-Ata, 2016). There is significant dispute in the literature about the effectiveness of RPS versus other policy instruments (Carley, 2009; Dong, 2011). In addition to RPS and RES standards, each state has its own regional policies and incentives for renewable energy. These policies differ substantially by state. For example, California has 218 regional policies and incentives supporting renewables from energy efficiency incentive programs to green building standards. Conversely, Nevada has 39 policies and incentives (DSIRE, 2019), despite the fact that both states have substantial RPS commitments. Regional policies are more disaggregated than a RPS in scope but may be more effective due to their role as a tangible action rather than solely a target. Although, in a constrained political environment, RPS have had significant impacts on decarbonization efforts in the energy transition by supporting renewable development (Menz and Vachon, 2005; Yin and Powers, 2009). RPS are projected to increase total renewable energy capacity from between 122 GW to 331 GW and provide directly attributed economic benefits from avoided environmental damage from $258 billion to $1.157 trillion in the U.S. by 2050 (Mai et al. 2016). The opportunity for secure long-term pricing in states with RPS' enhances the attractiveness of renewables. Many purchasers of VRE's will buy purchase power agreements (PPA) which set a price for retail electricity over a long-term period. This price stability represents an asset in times of fluctuating primary energy costs for fossil fuels (Holt and Galligan, 2013). Despite their limitations, RPS have driven renewable adoption (Yin and Powers, 2009), promoted technological development and fostered economic competitiveness (Tzankova, 2020). Some states that do not have RPS policies have adopted renewable energy standards (RES), which are voluntary commitments to reach certain percentages of renewable energy. These are less robust compared to RPS as they are not mandatory.

Based on the evidence of RPS benefits towards renewable energy, I offer the following hypothesis.

Hypothesis 3: A state with a Renewable Portfolio Standard (RPS) will have more renewable energy

I hypothesize that states which, on average, have adopted a RPS will be more efficient at abdicating fossil fuels and will experience greater renewable energy capacity in the future.

2.2.4 Political Influence

The influence of incumbents in the TIC on the energy transition has resulted in continued use of uneconomic coal in many areas of the U.S. Global energy subsidies when accounting for all direct and indirect costs were estimated at 6.5% of total global GDP in 2013, with coal accounting for over half of this cost (Coady et al. 2017). Economic theory suggests the most efficient option would be to remove all subsidies so that the most cost-competitive technology can dominate the market share (Bridle and Kitson, 2014). Although, the existing electric TIC promotes continued support for fossil fuels as tax breaks in the U.S. favor fossil fuels seven-to-one over the renewable energy sector (Redman et al. 2017). Existing fossil fuel subsidies alter the competition environment for low or zero-carbon alternatives. They also lead to improper pricing of the negative environmental and social externalities of fossil fuel generation which are not observed in the price currently (Coady et al. 2017). The quantity of subsidies in the U.S. for coal was approximately more than $4 billion annually in 2015 and 2016 (Redman et al. 2017). The survival of coal is heavily reliant on subsidies due to the inefficacy of coal to compete on cost in the current energy environment. Fossil fuel subsidies create a perverse environment that uses public money to finance and lock-in inefficient and costly energy infrastructure (Coady et al. 2017). Subsidies for alternative technologies represent a second-best option to enhance a zero or low-carbon grid due to the difficulty in removing distortions caused by fossil fuel subsidies.

Maintaining subsidies to enhance competition of renewables can provide opportunity for clean energy generation which is already significantly due to existing policy support.

The opportunity for subsidies to influence the electric grid are driven by political influence. Political ideology in many cases significantly influences support for types of energy generation. A Pew Research study in 2019 showed that 90% of Democrats surveyed agreed on the need for more government efforts to reduce climate change, in contrast to 39% of Republicans. The percentage of Democrats who think the federal government should prioritize alternative energy over fossil fuels was 90%, with about 65% of Republicans saying the same (Funk and Hefferon, 2019). There were also significant differences among age with younger generations more likely to support action on climate change and utilization of clean energy. There was near unanimous consensus among Democrats that anthropogenic activities influence climate change, with 45% of self-identified conservative Republicans saying anthropogenic activities play little or no role in influencing the climate and 62% of them saying climate policies harm the environment and economy more than they help (Funk and Hefferon, 2019). The energy transition therefore has become divided across political ideologies due to the influence of actors in the electric TIC on the political process. This divide means that Democratic states are more likely to support renewable energy than Republican states (Coley and Hess, 2012; Mayer, 2019).

Partisan identification pushes individuals to align their viewpoints based off information from their party representatives. These beliefs additionally influence not only policy but worldviews about issues such as climate change (Mayer, 2019). The effects of informational elite cues signal that Republicans oppose renewables often not based on fact about the effects of fossil fuel generation or the effects of renewables, but because their party leaders disapprove of renewables and climate policy (Coley and Hess, 2012; Clarke and Evensen, 2019). Broad Republican disapproval of clean energy is largely based on campaign spending and lobbying from the fossil fuel industry which incentivizes politicians to support the incumbent TIC (Brown and Hess, 2016). The total spending in the election cycle by the fossil fuel industry was approximately $359 million USD in 2017-2018, with coal companies giving 95% of their contributions to Republicans (Kirk, 2020). Partisanship can ultimately act as a significant barrier to the energy transition, though there has been evidence of Republican states supporting renewables (Mayer, 2019). The framing of policy is important to disaggregate the effects of partisanship on voters. Energy policy should work towards generating synergies between ideological values across parties that uses framing depending on the context (Giddens, 2009) (Hazboun et al. 2019). This framing can also help educate individuals surrounding perceived effects and terminology of energy development (Clarke et al. 2015). Figure 5 denotes the control of state government in

2019 by dominant party, Republican, Democrat, or divided/ split – a governorship held by one party and the legislature by the other.

Figure 6: Description of Dominant Political Party by State

Note: R = Republican, D = Democrat, S = Split/ Divided
Source: Own construction based off (NCSL, 2019b)

The effects of partisanship enable difficulties in altering the electric TIC and have largely been bolstered by the current Republican administration. Policies surrounding coal generation in the U.S. have been focused on reducing coal generation for many years. The Clean Power Plan was introduced in 2015 under the Clean Air Act. It set standards for the quantity of emissions from power plants and was estimated that it would reduce CO_2 emissions from the power sector by 32% nationwide in 2030 relative to 2005 levels (NRDC, 2017). It established specific performance rates for fossil fuel plants to reduce the existing amount of coal in the U.S. guaranteeing that the national government can act against states who do not comply (NRDC, 2017). The current administration has focused on easing regulations against the fossil fuel industry by challenging enhanced fuel standards for automobiles, ending the moratorium of coal leases on public lands, and reducing regulations on hydraulic fracking and the release of methane emissions (IEA, 2019b). The administration also repealed the Clean Power Plan and imposed the Affordable Clean Energy rule in 2019. This rule does not establish a target for GHG reductions and allows for extended lifetimes of coal-fired power plants. The current administration has also heavily de-funded the Office of Energy Efficiency and Renewable Energy cutting the budget in 2020 by 75% from 2019 (Nuccitelli, 2019), while the current Department of Energy budget contains money for research and development (R&D) on lower emissions coal plants (Merchant, 2019). The untenable support for the fossil fuel industry and its most egregious emitter coal, in the face of the negative externalities and more competent alternatives, provides evidence for why energy policy has become polarized across parties. Continuing to invest in incumbent technologies when faced with superior alternatives has historically only delayed innovation (Unruh, 2000), and will likely have similar consequences now. Following the significant evidence of partisanship on political and economic support for energy, I propose the following hypothesis:

Hypothesis 4: A state Republican government will have less renewable energy

I hypothesize that states which have a Republican-majority government in 2019, on average, will experience lower quantities of renewable energy in the future due to the effects of partisanship on energy policy.

2.2.5 Wealth and Investment

This section will address literature related to economic factors involved in the energy transition. The opportunity for modern energy is inherently linked to wealth. One commonly discussed theorem in literature related to the effects of wealth on energy is the environmental Kuznets curve (EKC) (Stern et al. 1996; Ekins, 1997; Stern, 2004). The environmental Kuznets curve (EKC) represents a theoretical effect of wealth on energy. Figure 4 depicts the theoretical EKC as an inverted U-shape which describes the relationship between wealth and environmental degradation.

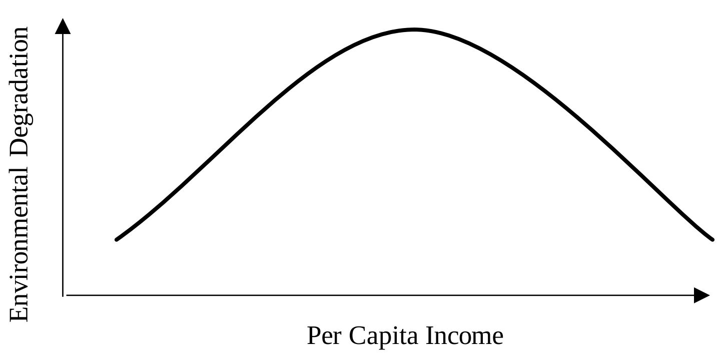

Figure 7: Environmental Kuznets Curve

Source: Own construction based on Ekins (1997)

As society becomes significantly wealthier they are less likely to degrade the environment (van Ruijven et al. 2008). There is significant debate around the veracity of the EKC (Ekins, 1997; Stern, 1998; Perman and Stern, 2003; Stern, 2004) but the global energy transition is positively correlated with the trend of economic growth and less carbon-intensive forms of energy generation (van der Kroon, 2013). The application of the EKC to the U.S. electric system is eristic due to the influence of continued reliance on fossil fuels, specifically coal. There is contrasting evidence that as states become wealthier they end up emitting more due to increased consumption (Jorgenson et al. 2017). If the EKC holds, applied to the state-level it implies that states who are less wealthy will be more likely to have coal in their energy portfolio. The opportunity for wealth to influence energy generation likely influences the availability of capital for states to invest in renewable energy.

Capital for energy transitions is a requirement (Costa Campi, 2019). Total clean energy investment in the U.S. was over $55 billion USD in 2019 (Rathi and Hodges, 2020). Despite the fortitude of a carbon-based TIC, private and public actors in the U.S. are recognizing the societal need to phase out high carbon fuel sources by reducing the availability of capital. Fossil fuel companies have performed significantly worse recently, placing last in the S&P 500 in 2018 as they have decoupled from economic indicators (Sanzillo and Hipple, 2019). Due to the average 46-year lifespan of coal-fired power plants (Cui et al. 2019), and the long-term necessity of decarbonization, continuous support for long-term thermal generation plants means producing stranded assets. A stranded asset is an asset which loses economic value significantly sooner than anticipated due to political, economic, social, or environmental factors (Bos and Gupta, 2019). The estimated cost of existing stranded assets totals approximately $304 billion USD by 2035 (IEA, 2014) (Baron and Fischer, 2015). Divestment from fossil fuels has become increasingly salient as private actors become aware of the dwindling long-term viability of fossil fuel companies, particularly coal. Despite the urgency of reducing fossil fuel consumption and the possibility of stranded assets, the top 200 fossil fuels companies invested more than $674 billion USD in future extraction and consumption of fuels in 2014 (Baron and Fischer, 2015). This capital would provide better returns by investing in clean energy and producing positive environmental and economic impacts (Kaminker and Stewart, 2015). Wealth and investment drives the opportunity for energy expansion and the replacement of existing, carbon-intensive infrastructure within the electric TIC. Following this, I offer the following hypothesis:

Hypothesis 5: A state that is less economically prosperous will have less renewable energy

I hypothesize that states which, on average, are less economically prosperous in the present will experience lower renewable energy capacity in the future due to limited economic resources for investment in renewable technologies.

2.3 Summary

In summary, the issue of climate change and the associated negative economic and environmental consequences require action. The U.S. power sector presents the most accessible sector for decarbonization. The existing consensus of literature surrounding energy transitions agrees that coal is inefficient and costly to use as an energy source and the benefits from renewables are significantly greater. State governments have been mixed in their response to retiring support for coal generation with some states pushing for zero-carbon energy systems, while others have increased commitments to the incumbent system. By focusing on phasing out the most polluting carbon-intensive resources to diminish path-dependencies and by supporting the scale and diffusion of zero and low-carbon energy sources, the U.S. can reduce GHG emissions significantly. This requires substantial efforts to work across technological, economic, political and social domains to provide the greatest opportunity for success and address the immense constraints in the system. This research contributes by helping understand the influence of coal on renewable generation and whether states that have dissented from carbon lock-in in the past are better poised to embrace renewable energy. The combination of historical data on coal plant retirements and the use of modeled energy scenarios support a novel method of analyzing if the effects of coal closures yield more renewable energy for states in the future.

3. Chapter Three

3.1 Data

The following chapter will discuss the data and methodology implicit in creating the study. The study constructed a database from multiple secondary sources. This method of constructing a database from a variety of sources helps preclude correlation among errors terms (Wooldridge, 2012). The data represents a cross-section of the contiguous United States, representing 48 states. It is from a variety of reliable and acknowledged institutions representing a mix of direct evidence and estimates. The pooled data compares input in the years 2018 and 2050. Hawaii and Alaska were not included, nor were Districts of the United States. The construction of the database and description of the variables and their operationalization will be described below.

3.1.1 Future Energy Portfolio

The main dependent variables were the capacity of renewable energy in 2050 in megawatts (MW), the share of renewable energy as a percentage of the energy portfolio in 2050 and capacity of natural gas in 2050 in MW. The data for future energy was from the 2019 Standard Scenarios Openei Tool from the National Renewable Energy Laboratory (NREL, 2019). This data was generated from a U.S. power sector simulation run by NREL utilizing the Regional Energy Deployment System (ReEDS), the Distributed Generation Market Demand Model (dGen), and the PLEXOS production cost model (NREL, 2019a). These models simulated potential scenarios for future U.S. energy technology based off multiple factors affecting energy development from 2010 – 2050. The data for the power sector simulation is from the mid-case scenario. This represents the most likely scenario based off current projections for cost and technology, although future values are estimates. The main variables extracted from the data were the total capacity of renewable energy in 2018, the total capacity of renewable energy in 2050, the total fraction of renewable energy in 2050 and the total natural gas capacity in 2050. This period of data was utilized because it represents the most available information from the scenario in year-2018, until the end of the scenario in year-2050.

The capacity of total renewable energy in 2018 and 2050 was calculated by aggregating the capacity of hydropower, land-based wind, off-shore wind, residential photovoltaics (PV) solar, utility PV solar, biomass, concentrated solar power (CSP), geothermal, and storage. The values indicate the total capacity of renewables measured in gigawatts (GW). The mean of the total renewable capacity in 2050 was 25,261 MW with a large range due to size differences of states. The share of renewables as a portion of the aggregate energy portfolio in 2050 was calculated by adding the total amount of renewable energy capacity and dividing it by the total projected capacity of all energy technology in 2050. The mean value of the share of renewables in 2050 was 61% with a minimum value of 14% and a maximum value of 100%. The variable for total natural gas (NG) capacity in 2050 was created by aggregating the total capacity of natural gas combined cycle (NGCC) and natural gas combustion turbine (NGCT). The database contains technology specific variables for the previous renewable technologies mentioned in addition to total NG capacity. Due to size differences, the study generates the natural logarithms of the capacity factor variables to more accurately compare energy capacities across states.

3.1.2 Coal

The main independent variables used throughout the models were the capacity of retired coal, capacity of operating coal and fraction of coal retired by 2018 as part of the existing coal fleet. The data used to observe the total quantities of retired and operating coal capacity in the U.S. was taken from the Energy Information Administration's coal database (EIA, 2020). This data provided all operable coal plants in the U.S. with information related to their location, nameplate capacity, and operating year, among other variables. The data also provided all retired coal plants from 2000 until present with similar characteristics. The variables constructed from this data were the capacity of retired coal by state, the capacity of operational coal by state, and the fraction of retired coal to date. The variables were all measured in MW. The capacity of retired coal was found by aggregating all retired coal capacity from 2004 – 2019. This 15-year period was used to provide time for potential effects of coal closures to manifest over a medium length time-span. The mean value was 1807 MW with a standard deviation of 2340 MW. The capacity of operating coal was found by aggregating all currently operating coal capacity including those with scheduled future retirement. The mean value was 5,218 MW with a minimum of 0 and a maximum of 20,443 MW. The fraction of retired coal was constructed by dividing the current quantity of retired coal capacity by the total capacity from 2004. This calculation derived the share of coal retired from the total capacity of the state. The mean value was 34%. Due to the size differences across states in terms of total energy capacity, the study generates the natural logarithms of the capacity factors for coal.

3.1.3 Economic

The data for per capita income in 2018 was sourced from regional data from the Bureau of Economic Analysis (BEA, 2020). Annual per capita income is the total income received by the state divided by the total population. Per capita income is measured in thousands USD, not adjusted for inflation. The mean was $52,268 USD. The data for unemployment rate in 2018 was sourced from the Bureau of Labor Statistics (BLS). The unemployment rate is measured as a percentage. The mean was 3.73%.

3.1.4 Environmental

The data for energy and environmental policy was sourced from the National Conference of State Legislatures (NCSL, 2020). This data describes whether states have a renewable portfolio standard (RPS), arguably the most significant clean energy policy to date. Three dummy variables were coded specifying whether a state had a RPS, a voluntary renewable energy standard (RES), or no clean energy policy. One significant characteristic of a RPS is that they are specific to each state. Therefore, the policy can differ widely across states depending on energy goals. Although, we feel this is a sufficient variable to control for policy as it is widely viewed as the most significant driver of renewable energy. The dummy variables were transformed into a categorical variable to group states according to their energy policy. In the contiguous U.S., 29 states have an existing RPS policy, 7 states have an RES policy and 12 have no renewable energy policy. The dataset also includes an additional environmental control variable. The total quantity of incentives by state for renewable energy and energy efficiency was sourced from the NC Clean Energy Technology Center (DSIRE). This variable directs the quantity of state-level policies and incentives to promote increased renewable energy and energy efficiency. The mean value was approximately 71 policies.

3.1.5 Political

The data for political party affiliation of state government was sourced from the National Conference of State Legislatures (NCSL, 2020). The data used was from the post-2019 election regarding the partisan composition of the state at that time. Three dummy variables were coded specifying whether state control was held by the Democratic party, the Republican party, or divided between the Democratic and Republican party. A divided state government consisted of a Republican legislature and a Democratic governor or a Democratic legislature and a Republican governor. Full control of a state for one party occurs when the legislature and the governor's office are held by the same party. The dummy variables were transformed into a categorical variable grouping states by dominant political party. The composition of state governments in the contiguous U.S. was 20 states with Republican state control, 14 states with Democrat state control, and 14 divided states.

3.1.6 Geographic

The data for the geographic variables was sourced from National Geographic regarding distinct regions of the U.S. (National Geographic, 2012). The regions specified are the West, Southwest, Midwest, Southeast and Northeast. These five regions cover the entire contiguous U.S. and represent areas with geographic similarities. A dummy variable was coded for each of these five regions with the state assigned to the region depending on its location. These dummy variables were transformed into a categorical variable grouping states by region. In the contiguous U.S., the West consists of 11 states, the Southwest 4 states, the Midwest 12 states, the Southeast 14 states, and the Northeast 9 states. The distinct areas are controlled to observe any substantial differences across regions.

3.1.7 Control

The technical potential of renewables by state was included to control for potential effects of areas that had either high-range or low-range resource sets. The technical potential is measured in MW. The mean was 4.35 million MW. This data is sourced from a NREL report on the U.S. technical potential by state (Lopez et al. 2012). Population was assessed but not included in the models because of a high correlation with capacity variables. The capacity variables adequately control for size effects across states.

3.2 Limitations

The major limitation of this dataset is the variability in the Standard Scenarios modeling tool from the National Renewable Energy Laboratory (NREL). The model is dependent on endogenous technical and economic assumptions made for the diffusion of energy technology. This means if current projections change drastically, the reliability of the models will be potentially ambiguous. Due to the self-constructed nature of the database, there is no missing data. The scope of the data only focuses on variables related to the U.S. This means the specific findings are only applicable to the U.S. Although, general concepts likely are relevant for advanced economies with a large coal market. One additional noteworthy piece of information is that not all states in the U.S. produce coal. There are three states who produce a preponderance of U.S. coal which are Montana, Wyoming, and West Virginia. This means they may be outliers relative to other states energy markets due to a considerable effect of local coal.

3.3 Descriptive Data

Table I will depict the sample descriptive statistics.

Table I. Descriptive Statistics

Variable	Mean	Standard Deviation	Minimum	Maximum	Observations
Capacity of Total RE in 2050 (MW)	25,261.13	26,747	1529	134,161	48
Capacity of Retired Coal 2004-2019 (MW)	1806.94	2340.49	0	11,137	48
Capacity of Operating Coal 2004-Present (MW)	5218.51	4893.46	0	20443.50	48

Capacity of Total NG in 2050 (MW)	11,251.21	13,194.51	210	67,568.38	48
Capacity of Total NG in 2020 (MW)	9,006.44	11,020.61	244	60,216.87	48
Total Fraction of RE in Portfolio in 2050	.61	.26	.14	1	48
Share of Coal Capacity Retired 2004-2019	.34	.32	0	1	48
Per Capita Income 2018 (Thousands USD)	52,268.85	8,538.25	37,904	76,481	48
Unemployment Rate 2018 (%)	3.73	.68	2.50	5.20	48
Technical Potential of RE (MW)	4,359,237	5,050,881	34,098.64	30,900,000	48
State RE Incentives	70.96	41.97	13	219	48

Source: Own construction

4. Chapter Four

4.1 Methods

The following section will discuss the quantitative methodology utilized in this study to look at the long-term effects of retiring coal generation on renewable energy adoption. The empirical analysis will be descriptive in nature by analyzing a constructed database of the 48 states in the contiguous United States. The study will employ econometrics using a classic linear regression model (CLRM) with ordinary least squares (OLS). The CLRM is explained by the following equation.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \ldots u$$

It aims to explain how the dependent variable y changes in relation to changes in the independent variables $x_1, x_2 \ldots x_i$, holding other variables u equal (Wooldridge, 2012). OLS is employed to estimate the parameters of the regression model. The key assumptions of OLS are:

1. The parameters of the model are linear
2. There is random sampling among the population
3. The error term is equivalent to zero across all values of the independent variables
4. There is no multicollinearity among the independent variables
5. The presence of homoscedasticity as the error term has an equal variance across all values of the independent variables

If these properties are adequately met, OLS is considered a best linear unbiased estimator (BLUE) under the Gauss-Markov theorem (Wooldridge, 2012). A BLUE estimate provides unbiased estimates. The regression models for this analysis will run a multivariate regression on an independently pooled cross-sectional dataset. A pooled cross-section combines data for two separate years to analyze the influence of a set of variables over time. The regression will perform hypothesis testing on multiple hypotheses related to the influence of a set of variables on renewable energy. There will be alternate models to test additional hypotheses as well as a sensitivity analysis regarding the effects of coal and other control variables on renewables. All coefficients in the models are standardized to account for differences in units of measurement. The following baseline equation will test for hypothesis 1, 3, 4 and 5.

4.1.1 Model A

$$y_i = \beta_0 + \beta_1 x_i + \beta_2 x_i + \beta_3 x_i + \alpha'_i\gamma + C'_i\gamma + \mu_i$$

$$\ln(\text{totalrecap2050})_i = \beta_0 + \beta_1 \ln(\text{retiredcoalcap})_i + \beta_2 \ln(\text{epincent})_i + \beta_3 \ln(\text{retech})_i + \alpha_1 \ln(\text{percap})_i + \alpha_2 \text{umprate}_i + C_1 \text{region}_i + C_2 \text{ep}_i + C_3 \text{politicaldom}_i + \mu_i$$

Model A analyzes the total capacity of renewable energy in 2050 as a function of the total retired coal capacity from 2004 - 2019 for each state. The model uses a log-log regression to observe a constant elasticity model of the dependent variable with respect to the main independent variable (Wooldridge, 2012). The dependent variable $\ln(\text{totalrecap2050}_i)$ is the total capacity of renewable energy in the state of observation *i* in the year 2050. It is transformed to a natural logarithm to compare for size differences in total energy capacity across states. The main independent variable $\ln(\text{retiredcoalcap})_i$ is the total retired coal capacity from 2004-2019. This variable is also transformed to a natural logarithm to control for size differences. epincent_i is the total quantity of state incentives for renewable energy and energy efficiency in each state measured as an absolute number transformed to a natural logarithm. retech_i displays the renewable energy technical potential for each state to control for availability of energy generation from renewable energy measured in MW transformed to a natural logarithm. α_i is a vector of economic control variables which include the per capita income in 2018 transformed to a natural logarithm and the unemployment rate in 2018. These variables are included to assess the impact of the different degrees of economic prosperity of states and gauge future economic welfare. C_i is a vector of categorical control variables spanning geographic, policy, and political considerations. This vector includes a regional variable which construes the region of each state in the contiguous United States, an environmental variable which defines states with an RPS, RES, or no renewable energy policy and a political variable which denotes states with a Democratic, Republican, or divided government in 2019. μ_i is the error term for the regression. The model tests to ensure the properties of OLS are satisfied looking for non-normal residuals, heteroscedasticity and multicollinearity. Minnesota and Mississippi appeared as extreme outliers in the data for this model. After dropping Minnesota and Mississippi, the properties appear satisfied using ocular and statistical tests to observe the residuals. The study justifies dropping these two observations to obtain a BLUE estimator.

4.1.2 Model B

The following equation analyzes the effect of continuing operation of coal plants on natural gas capacity in 2050 testing hypothesis 2a.

$$y_i = \beta_0 + \beta_1 x_i + \beta_2 x_i + \alpha'_i\gamma + C'_i\gamma + \mu_i$$

$$\ln(\text{totalngcap2050})_i = \beta_0 + \beta_1 \ln(\text{operationalcoalcap})_i + \beta_2 \ln(\text{epincent})_i + \alpha_1 \ln(\text{percap})_i + \alpha_2 \text{umprate}_i + C_1 \text{region}_i + C_2 \text{ep}_i + C_3 \text{politicaldom}_i + \mu_i$$

Model B analyzes the total natural gas capacity in 2050 as a function of the operational coal capacity in 2018 for each state. The model uses a log-log regression. The dependent variable $\ln(\text{totalngcap2050})_i$ is the total natural gas capacity in state of observation *i* in the year 2050. The main independent variable $\ln(\text{operationalcoalcap})_i$ is the total operational coal capacity in 2018. These variables are both transformed to a natural logarithm to account for differences in size of energy markets across states. The model includes the control $\ln(\text{epincent})_i$ for the total quantity of state incentives for renewable energy. The same vector of control variables (α_i) used in model A for economic effects were included. Additionally, the vector of controls (C_i) for geographic, policy and political factors were included. The variable controlling for renewable energy technical potential was not included. The model uses the same methodology for ensuring the properties of OLS are satisfied. The model displays an issue with the normality of residuals as the data is negatively skewed. Minnesota appears to substantially influence the skewness and kurtosis of the data. All other properties of OLS appear satisfied once Minnesota is dropped.

4.1.3 Model C

The following equation is presented as a sensitivity analysis to observe the effects of the share of retired coal capacity on the share of renewable energy in 2050. The model does not test any of the stated hypotheses but aims to describe the effect of the relative shares of the variables.

$$y_i = \beta_0 + \beta_1 x_i + \beta_2 x_i + \beta_3 x_i + \alpha'_i\gamma + C'_i\gamma + \mu_i$$

$$y(\text{totalrefract2050})_i = \beta_0 + \beta_1(\text{sharecoalret})_i + \beta_2\ln(\text{epincent})_i + \beta_3\ln(\text{retech})_i + \alpha_1\ln(\text{percap})_i + \alpha_2\text{umprate}_i + C_1\text{region}_i + C_2\text{ep}_i + C_3\text{politicaldom}_i + \mu_i$$

Model C analyzes the total share of renewable energy as part of the total energy portfolio in 2050 as a function of the share of coal retired from states current operating coal capacity. This model provides an alternative view of the effects of coal closure on renewables. The dependent variable $(\text{totalrefract2050})_i$ is the fraction of renewable energy as a percentage of the total energy capacity in 2050. The main independent variable $(\text{sharecoalret})_i$ is the fraction of coal retired from 2004 – 2019 as a percentage of the total operating capacity of existing coal from 2004 until present. The model adds the variable total renewable technical potential as in Model A. It also includes the same vector of control variables as Model A accounting for geographic, economic, environmental and political factors. The model tests the assumptions of OLS as in previous models. All other ocular and statistical tests show the model satisfies the properties of OLS.

Table II will summarize the hypotheses and their expected signs.

Table II: Expected Hypotheses

Hypothesis	Expected Sign	Model
H1: Retirement of coal capacity will lead to more renewable energy	+	A
H2: Continuation of operational coal capacity will lead to more natural gas	+	B
H3: RPS will lead to more renewable energy	+	A
H4: State Republican government will have less renewable energy	-	A
H5: State that is less economically prosperous will have less renewable energy	-	A

Source: Own construction

4.2 Limitations

The main limitation using the CLRM as a form of assessing data in econometrics is the lack of ability to illustrate causality from the analysis. The models only provide the opportunity to construe a correlation between contemplated variables. The existence of an error term means that some amount of the model is not explained by the existing variables. Additional limitations of this methodology are that using pooled data can result in obscuring unique effects of cross-sectional data. This can portray homogeneity across observations and inaccurately characterize unique data. One example of this could be the observations of Montana, Wyoming and West Virginia as outliers due to their substantial role in coal production. Finally, the use of a small sample size lends limited statistical powers to the methodology. Due to a sample size ranging between 46 to 48, a more detailed analysis using a grander dataset may possess more opportunity to infer significant effects of the models. For example, one could use even more disaggregated data for individual counties across states. Although the stated limitations do not preclude the validity of the following analysis, they should be considered when discussing the results.

I present the analysis in the sections below. Each of the models stated above contain different subsets of variables. Therefore, not all mentioned variables are included in the models for answering specific hypotheses.

5. Chapter Five

5.1.1 Model A Results

The results from the multivariate pooled regression from Model A are presented in Table III. Model A specifically looks at Hypotheses 1, 3, 4 and 5 which are discussed below.

Table III: Relationship between Retired Coal Capacity and Future Renewable Energy Capacity

	Dependent variable is log renewable energy capacity in 2050, ln *y*			
	(1)	(2)	(3)	(4)
ln (capacity of retired coal)	0.146***	0.104***	0.0893***	0.0585*
	(0.0386)	(0.0271)	(0.0262)	(0.0291)
ln (RE technical potential)		0.184***	0.204***	0.191**
		(0.0558)	(0.0589)	(0.0877)

ln (state-level RE incentives)		1.010***	0.971***	1.183***
		(0.164)	(0.178)	(0.193)
ln (per capita income)			0.221	0.819
			(0.684)	(0.758)
Unemployment rate			0.362***	0.449***
			(0.126)	(0.147)
West				-0.116
				(0.364)
Southwest				0.231
				(0.521)
Midwest				0.506
				(0.368)
Southeast				0.588*
				(0.345)
RPS				-0.409
				(0.285)
No policy				-0.121
				(0.294)
Democrat				0.0135
				(0.226)
Republican				-0.130
				(0.218)
Region effects	No	No	No	Yes
Observations	46	46	46	46
R-squared	.247	.682	.736	.829

Notes: Coefficients are reported as the first number. Standard errors are reported in parentheses. Coefficients of .000 were numbers too small to report. *** 99% CL, ** 95% CL, 90% CL.

Hypothesis 1 considers the effect of retiring coal capacity from state energy portfolios from 2004 - 2019 on future renewable energy capacity in 2050. Retiring coal capacity has a significant, positive relationship with renewable energy capacity in 2050. The log-log regression describes the total estimated elasticity. By increasing the capacity of retired coal by 1%, we expect the capacity of renewable energy in 2050 to increase by .059%. The effect is significant through column 1-4. When including all covariates in column 4, the finding is significant at the 90% confidence level. I therefore find Hypothesis 1 supported. This suggests that states which have retired more coal in the past 15 years, on average, are more likely to experience higher capacities of renewable energy in 2050. This advances the possibility that retiring coal can lead to a higher capacity of renewable energy and help dissuade carbon lock-in. The finding also suggests that states which have not retired coal capacity in the past 15-years are less likely to have renewable energy. The explanatory power and size of coefficient of the variable log capacity of retired coal decreases in later columns when including covariates. This explains the necessity of considering other factors affecting the model, although the result maintains its robustness.

Hypothesis 3 is concerned with the effect of renewable portfolio standard (RPS) on renewable energy capacity in 2050. The analysis finds no significant impact of an RPS on future renewable energy capacity in 2050. Additionally, I find no significant linkage of a renewable energy standard (RES) or no policy on affecting total renewable capacity. Thus, Hypothesis 3 is not supported. This is surprising to an extent, as I expected to observe an increase in total capacity when under a RPS or RES scenario, but there are a few potential explanations. The most likely explanation is that the RPS as a quota is not the most effective renewable energy policy tool to drive capacity growth. There are likely other policy mechanisms that may be more influential. Alternatively, states may experience growth in renewable capacity despite an official policy due to least-cost build and resource availability for future renewable generation. Additional areas that warrant discussion related to policy variables from the output are the relationship between the quantity of state incentives for renewable energy and energy efficiency and renewable energy capacity. This relationship was significant and positive at the 99% confidence level. By increasing the quantity of state incentives by 1%, we expect renewable energy capacity in 2050 to increase by 1.183%. This relationship portrays state incentives as a substantial promoter of growth of renewables and partially supports Hypothesis 3. This potentially could show that the number of policies in place by state are more effective than one overarching policy like an RPS.

Hypothesis 4 tests the effect of a state Republican government on renewable energy capacity in 2050. I find a negative coefficient but no significant relationship of a Republican government in 2019 with renewable capacity. I also do not find any impact of a Democratic government increasing the capacity of renewables. Therefore, Hypothesis 4 is not supported. This finding is unanticipated. It is possible that the current political environment does not affect the long-term energy technology of a state. Another potential reason for the insignificance is due to the nature of variable being measured. The capacity defines the total quantity of renewable energy and not the total percentage of energy in the state portfolio. A Republican government may have no effect on reducing overall capacity, but may influence energy portfolios in a different manner. This speculation will be further addressed in Model C.

Hypothesis 5 examines the effect of wealth on renewable energy in 2050. Per capita income in 2018 is found to be positive, but have no significant correlation with renewable energy capacity in 2050. I thus find Hypothesis 5 not supported. This finding is again unexpected. A possible explanation is the use of per capita income as the proxy for wealth. Individual income may not signify renewable energy capacity growth, it might require a variable that focuses more on macroeconomic welfare of the state. Although, due to the high correlation between GDP and capacity because of size effects, per capita income seems to be a more feasible variable for this analysis. One additional possible confounding relationship is between wealth and a Republican government which may reduce the likelihood of promoting renewable energy not due to wealth, but due to government influence.

Additional findings worthy of discussion are the positive, significant relationship between renewable technical potential and renewable capacity. This describes a relationship where a 1% increase in total renewable technical potential leads to a .191% increase in total renewable capacity in 2050 at the 95% confidence level. This is intuitive as states that have higher renewable resource potential are more likely to utilize those sources compared to states who do not. The unemployment rate was significant and positive as a 1% increase in the unemployment rate lead to a .449% increase in total renewable capacity at the 99% confidence level. This is likely due to a correlation between unemployment and the size of states. There was a significant, positive relationship of the geographic control variable Southeast at the 90% confidence level. This region is likely positive relative to the base category of the Northeast due to increased penetration in potential-rich areas that have yet to see substantial growth. The unrestricted output from Table 4 for Model A is included in Appendix A.

5.1.2 Model B Results

The results from Model B are presented in Table IV. Model B specifically looks at Hypothesis 2 which is discussed below.

Table IV: Relationship between Operating Coal and Future Natural Gas

	Dependent variable is log natural gas capacity in 2050, ln *y*			
	(1)	(2)	(3)	(4)
ln (capacity of operating coal)	0.188***	0.167***	0.148**	0.216**
	(0.0676)	(0.0588)	(0.0607)	(0.0801)
ln (state-level RE incentives)		1.237***	1.303***	1.651***
		(0.310)	(0.339)	(0.409)
ln (per capita income)			-0.465	-1.735

			(1.192)	(1.720)
Unemployment rate			0.384	0.198
			(0.250)	(0.319)
West				-1.493**
				(0.691)
RPS				-0.473
				(0.626)
No policy				0.00629
				(0.630)
Democrat				0.432
				(0.514)
Republican				-0.0984
				(0.404)
Region effects	No	No	No	Yes
Observations	47	47	47	47
R-squared	0.147	0.374	0.413	0.528

Notes: Coefficients are reported as the first number. Standard errors are reported in parentheses. Coefficients of .000 were numbers too small to report. *** 99% CL, ** 95% CL, 90% CL.

Hypothesis 2 explores the effect of operating coal capacity on natural gas capacity in 2050. Operating coal capacity has a significant, positive association with future NG capacity. The logged nature of both variables describes a constant elasticity as previously seen in Model A. A 1% increase in NG capacity in 2050 leads to a .216% increase in total operating coal capacity at a 95% confidence level. Thus, Hypothesis 2a is supported. I find evidence of longer-term fuel-switching from coal to natural gas capacity. The implications are that states who currently have more prominent carbon-intensive path-dependencies are possibly more likely to continue this trend advancing the concept of carbon lock-in.

There are a few other noteworthy findings. The influence of state renewable energy and energy efficiency energy incentives has a significant, positive relationship with natural gas capacity in 2050. If the quantity of incentives increases by 1%, we expect that the capacity of natural gas will increase by 1.651%. This is significant at the 99% confidence level. The antecedent result lends support to the quantity of incentives for renewable energy and energy efficiency increasing the rate of fuel-switching by possibly encouraging states to transition to less carbon-intensive energy generation. There appears to be a significant, negative relationship between the West region and natural gas capacity compared to the base category of the Northeast. We expect the West, on average, to have 1,493 MW less of natural gas capacity than the Northeast. This is significant at the 95% confidence level. An explanation may be a stronger influence and commercial availability of renewable energy in the West over natural gas in the Northeast. Geothermal opportunity is specific to the West and represents an efficient zero-carbon alternative baseload source compared to natural gas. Other controls such as policy and political party are not found to have a significant relationship with natural gas capacity. The unconsolidated Table 5 can be found in Appendix A.

5.1.3 Model C Results

Model C is presented as a sensitivity analysis to consider an alternative method of portraying renewable energy. The results are presented in Table V.

Table V: Relationship between Share of Coal Retired and Share of Renewables in 2050

	Dependent variable is share of renewable energy as percentage of total in 2050			
	(1)	(2)	(3)	(4)
Share of coal capacity retired	0.089	0.104	0.115	0.046
	(0.119)	(0.131)	(0.133)	(0.159)
ln (RE technical potential)		0.005	0.028	-0.045
		(0.026)	(0.030)	(0.042)
ln (state-level RE incentives)		0.075	0.0075	-0.030
		(0.071)	(0.084)	(0.096)
ln (per capita income)			0.485	0.189
			(0.320)	(0.403)
Unemployment rate			0.0140	-0.0323
			(0.0591)	(0.0726)
RPS				0.0424
				(0.147)
No policy				0.00209
				(0.144)
Republican				-0.264*
				(0.139)
Divided				-0.121
				(0.114)
Region effects	No	No	No	Yes
Observations	48	48	48	48

R-squared	0.012	0.040	0.090	0.348

Notes: Coefficients are reported as the first number. Standard errors are reported in parentheses. Coefficients of .000 were numbers too small to report. *** 99% CL, ** 95% CL, 90% CL.

Model C uses the fraction of renewable energy of the total state portfolio in 2050 and the fraction of coal capacity retired of total coal capacity since 2004. This methodology aims to provide an alternative view of the influence of coal on renewables, with respect to total capacity. It employs a methodology that describes the total percentage of renewables rather than the total capacity. The total percentage may be more salient because of its more substantial relevance for reducing absolute fossil fuel consumption. Percentage of the total portfolio would be a more impactful statistic to observe the reduction of fossil fuels, rather than solely an increase of renewables as realized in Model A. Model C finds no significant relationship between the fraction of coal retired from 2004 - 2019 and the fraction of renewables in 2050. This presents the possibility that retiring coal capacity leads to increased renewable capacity, but it does not necessarily mean that the transition will alter the total percentage of electricity in the state portfolio in the long-run to be more substantially renewables. The finding presents evidence of possible energy augmentation rather than substitution. This would mean that while the total capacity of renewables continues to grow in absolute levels, the additional capacity will augment the growing demand for electricity rather than substituting for fossil fuels. This evidence suggests further efforts should focus on how to not substitute energy capacity.

An additional point of interest is the significant, negative association of a Republican government with the fraction of renewables in 2050. We expect a Republican-majority government in comparison to a Democrat-majority government in 2019, on average, to have 26.4% less renewable energy in their energy portfolio in 2050. This relationship is significant at a 90% confidence level. Thus, this finding provides support for Hypothesis 4. The consequence of this discovery is that a Republican government may not significantly influence the total capacity of renewables in the long-run, but it may shape the total percentage of renewables in a state portfolio. This finding is supported by existing theory as some Republican states have adopted a substantial quantity of renewables, often due to availability or political feasibility, but likely do not dissuade the notion of fossil fuels. Therefore, this evidence would explain the insignificance of partisanship for determining total capacity of technology. Alternatively, it would also explain the significance of partisanship on the fraction of technology in the energy portfolio as Republicans likely take advantage of renewables when available in their respective states, but they do not vitiate fossil fuels. This analysis does not find a relationship between Democrats positively influencing the total fraction of renewable energy in the state portfolio.

Model C presents no other significant findings regarding environmental policy, economic indicators, geography or technical potential influencing total fraction of renewable energy in 2050. This insignificance likely means additional research is needed to better discern the impacts of the covariates and other possible areas of influence.

The following section will present an extended discussion of the results.

5.2 Discussion

The energy transition will be driven by coordination across numerous domains to achieve a decarbonized electric grid. The existing TIC provides plentiful support for fossil fuels. In the framework laid out by (Unruh, 2002) on methods to reduce carbon lock-in, supporting economies of scale and diffusion of clean energy technologies through continuation and discontinuation methods is paramount to advance a decarbonized electric grid. The results of the previous analysis will be related to this framework by discussing how to shape efforts to reduce the influence of incumbent inertia of existing technology. Coal closures have shown to be positively correlated with the capacity of renewables in states in the future. Concentrating efforts on reducing coal capacity in state energy portfolios would likely generate substantial economic, environmental and social benefits. To reach the scenarios that contain majority shares of renewable energy as described in power modeling scenarios in previous research (Jenkins and Thernstrom, 2017; Frew et al. 2016; Sepulveda et al. 2018, Mileva et al. 2016), a strategy of targeting early retirement of coal facilities likely would exhibit higher renewable capacity growth in the future. The corollary is that by retiring coal capacity in the present, states can possibly more forcefully dissuade carbon lock-in in the future. This escape from the path-dependencies generated by the existing TIC is fundamental to ensuring a successful energy transition. The expeditious retirement of coal characterizes an approach of discontinuation under the framework designated by (Unruh, 2002). States have an incentive to employ early retirement of coal with the awareness that states who retire coal may be more efficient at enabling higher capacities of renewable energy capacity in the future. The findings provide evidence to further investigate how states can reduce carbon lock-in and curtail the inertia behind existing fossil fuel interests. Alternatively, states who do not retire coal capacity are likely to be burdened with stranded fossil fuel assets (Bos and Gupta, 2019) who inadequately meet the needs of future generations.

The discussion of scaling renewables often resides around capacity as an adequate measure of their diffusion. By reducing cost through scale, the technologies become cheaper and are more accessible. Although, this dimension does not analyze their relative relationship to fossil fuels. A more pertinent measure for analyzing the performance of renewables is their total fraction of the entire energy portfolio. For example, if Texas increases its renewable capacity by 100 GW, this is substantial. Yet, if they also increase their energy generation from fossil fuels by 200 GW, the growth of renewables becomes less consequential. The energy transition demands not only the extensive aggrandizement of renewables to scale through energy augmentation, but that they will eventually transform to the dominant technical design of the electric TIC through energy substitution. Thus, the insignificance in the results of coal closures influencing the total share of renewable energy in terms of the total energy portfolio shows that path-dependencies evidently subsist even when alternative technologies experience growth. A concerted effort should be made to contemplate how to not only increase the total capacity of renewables, but how to increase their relative share of the total energy portfolio. A decarbonized future is dependent on renewables generating a dominant share of the total fraction of energy relative to fossil fuels. The difficulties of achieving this high share of renewables supports the literature that advocates for a broad mix of zero and low-carbon options that provide multiple avenues for the necessary technologies to reach scale. This involves not only convening on VRE's but encouraging alternatives such as biomass, geothermal and transmission and storage technologies amidst others (Brick & Thernstrom, 2016; Sepulveda et al. 2018; Jenkins et al. 2018). Generating mutual effort across technologies can likely provide an accelerated energy transition that yields scale and diffusion of renewables and reduces the path-dependencies of fossil fuels.

Reducing fossil fuel consumption in addition to increasing renewables has been aided by fuel-switching as an effective strategy for reducing emissions due to the lower carbon intensity of natural gas over coal. The tendency to fuel-switch when facing increased scrutiny over emissions represents a continuation approach under the framework of (Unruh, 2002) to reduce emissions but not alter the existing TIC dramatically. As a policy option, fuel-switching generates valuable results. Although, it also empowers continued carbon lock-in, albeit for a less intensive fossil fuel. The long-term goal of decarbonization resides in reducing energy sector emissions to net-zero. The role of natural gas in most power modeling scenarios is minor and fitted with CCS which is still commercially limited (Mileva et al. 2016). Therefore, indulging in further path-dependencies for fossil fuels is not compatible with the long-term goal of decarbonization (Wilson & Staffell, 2018). The examination of extended fuel-switching by observing operating coal capacities relationship with future natural gas capacity provides evidence that fuel-switching will be prevalent in the long-term. The evidence of long-term fuel-switching implies that states who are currently more intertwined in a carbon-intensive TIC are more likely to dwell in carbon lock-in. The observed positive relationship of renewable energy and energy efficiency policies on present fuel switching represent possible indirect consequences of rewarding reducing GHG emissions by any means. A cognizant technical policy approach applying the assemblage of available methods of continuation and discontinuation of the existing system will generate the most optimal outcome.

The effects of RPS have had considerable impact on increasing the total capacity of renewables in the U.S. There is evident growth attributed to RPS (Barbose, 2018; Mai et al. 2016), despite their nature as a quota and sub-optimal policy mechanism. The absence of an observed impact of RPS on energy capacity of states is unexpected. An explanation for the insignificance is that RPS may not be the most momentous factor influencing renewable growth in the long-term. For example, some states such as Texas and Illinois have surpassed their RPS considerably with Texas almost achieving triple their renewable capacity requirement for 2025 by 2018 (NCSL, 2019). This is more likely due to substantial resources and bipartisan support rather than a specific policy measure. An additional possible explanation characterizing RPS' reduced influence is the disparity amongst policies across states. For example, Ohio has a 12.5% RPS by 2026, while California has a 100% RPS by 2045. The magnitude of these differences exemplifies the inadequacies of a RPS providing renewable growth to states on average. Recognition of the deficiency of RPS can be extrapolated to speculate that RPS are only one portion of the energy transition. They likely help diffuse and enable scale of renewables, but they are not the most optimal policy to influence carbon lock-in. Despite their insignificance, the opportunity for energy policy to positively influence renewable energy is numerous. The significant, positive relationship between regional renewable energy incentives and policies and renewable and natural gas capacity provides an example of the ability for policy to increase the utilization of lower carbon-intensive technologies. Regional incentives and policies are likely one of the main drivers of renewable capacity adoption. This provides evidence that continued regional initiatives can provide growth (Menz and Vachon, 2005; Yin and Powers, 2009) that will afford future opportunity for states who are still beguiled by the inertia of a carbon-intensive TIC.

Energy policy has become substantially divided across partisan lines. The considerable polarization of energy politics reduces the opportunity for a universal policy that weakens carbon lock-in. The findings did not provide evidence of a dominant political party altering the total capacity of renewables. This is despite the evidence of Republicans being less likely to support renewable energy (Coley and Hess, 2012). Although, there was a significant, negative relationship of Republicans reducing the total fraction of renewables as a portion of the energy portfolio. The association of Republicans and a lower total percentage of renewable energy elucidates to the nature of partisanship on energy. In states with substantial renewable energy and a Republican government, they likely take advantage of the benefits renewables represent, but they do not aim to reduce the influence of fossil fuels either. This would explain their impact on total percentage of the state portfolio rather than capacity. It is likely that Republicans in these states with renewables approve of growth of fossil fuels in unison with supporting growth of renewables. This conjecture provides evidence for the opportunity of bipartisan energy reform as there is proof of Republican support (Mayer, 2009). Future government cooperation should focus on not only the pronounced opportunity of renewable energy, but the incompatibility of fossil fuels with a net-zero carbon power sector. A competent policy approach would aim to reduce the influence of incumbent firms on politicians to reduce protection for subsidies for the fossil fuel industry. This would directly promote a discontinuation approach by cogently modifying the actors within the TIC by changing their incentive structure.

The relevance of wealth on influencing subsidies clearly generates significant disadvantages for renewables. Similarly, the scale and diffusion required for renewables to dissent from existing technological design demands capital. The results of this study found no increased likelihood for more wealthy states to have a higher renewable capacity. The EKC theorem in this regard was not substantiated (Stern, 2004) as one would expect an increased prevalence of less carbon-intensive energy resources when wealthier. The inadequacy of this measure for influencing renewables may be due to the comprehensive growth that renewables will experience in the future, mainly due to their ability to be the lowest-cost build. This interpretation implies that renewable energy may not be reserved for the wealthier states and that states who are less economically prosperous can also reduce carbon lock-in. The evidence of the insignificance of wealth on renewable capacity growth could provide evidence for clean energy to gain territory among states who are less economically prosperous. By redirecting capital to renewable energy, states can generate substantially better economic and environmental outcomes (Kaminker and Stewart, 2015). This approach would alter the TIC by reducing the torpidity of the system and promoting discontinuation of carbon lock-in.

6. Chapter Six

6.1 Conclusion

The main goal of this study was to evaluate how retiring coal capacity affects future renewable energy in the United States. It addressed a set of hypotheses related to domains of the energy transition focusing on technical, economic, and political considerations. The purpose was to acquire information on the long-term effects of deterring path-dependencies in the present on the

U.S. electric system. This is the first study to our knowledge that combined future modeled energy scenarios with historical data on coal capacity to gauge the long-term impacts of coal closures. The analysis yielded potentially valuable acumen by applying an econometrics methodology to a constructed database surrounding energy technologies. The main finding of the thesis is that coal closures from 2004 – 2019 are significantly, positively associated with renewable energy capacity in 2050. This result implies that states who have escalated coal closures may generate more renewable capacity than states who do not close coal-fired power plants. This implies by reducing path-dependencies on carbon now, states may be more capable of deterring carbon lock-in in the future. The second major finding when conducting a sensitivity analysis was that coal closures were not shown to increase renewables as a total percentage of the energy portfolio. Therefore, coal closures may increase renewable capacity but there is no evidence towards their ability to increase renewables as an overall share of the energy portfolio. Additional compelling findings are that states controlled by a Republican-majority government exhibited significantly less renewable energy than a state controlled by a Democrat-majority government, and high quantities of regional renewable incentives and policies appear to reduce the intensity of electricity generation from carbon resources more than a RPS. This signifies the influence of the polarization of energy policies despite the universal benefits of renewables, as well as the superiority of a high quantity of regional policies at promoting renewable growth rather than one large renewable policy. All regions appear to be poised for significant growth in capacity, while wealth was not found to significantly affect the opportunity for renewables.

6.2 Practical Implications

These results provide policy implications for government and actors within the electric TIC in the United States. Overall, the study indicates the potential for state energy portfolios to generate increased renewable energy capacity if states shutter coal-fired electric power plants. The past 15-years have provided evidence that action can possibly more adequately dissuade carbon lock-in and waiting may possibly further exacerbate carbon lock-in. The empirical evidence on coal-fired electricity in the U.S. demonstrates there will be substantial economic and environmental benefits of an energy transition that drastically reduces carbon emissions. These benefits will only be magnified when replacing existing coal with renewable energy to provide a low-carbon electric grid which can further enhance efforts to decarbonize other sectors of the economy. If policymakers can concentrate efforts towards besieging the existing carbon-intensive TIC with a mix of continuation policies i.e. fuel-switching to biomass and natural gas, and discontinuation policies i.e. moratorium on all coal-fired power in the United States, the electric grid will have an increased chance of reducing carbon-intensive infrastructure and diffusing clean energy.

6.3 Limitations

The major limitations of this study as previously highlighted are the potential ambiguity of results due to the necessity of using estimated data for future renewable energy. This research is limited in its generalizability as using forecasted energy scenario data signifies that there is substantial opportunity for variation if significant exogenous factors related to the modeling scenarios change. The modeling tools represent extensively reliable resources to generate presumptions of future projections, but this potential for uncertainty must be noted. For example, major shocks like the current global pandemic have far-reaching consequences for energy generation and can substantially influence the viability of modeled energy scenarios. Additionally, one notable concern is the National Renewable Energy Laboratory's (NREL) potential bias for projecting increased renewable energy capacity due to their favorable view of these technologies. Related to the veracity of the models presented, the small sample size likely leads to less specificity of the effects on renewable energy capacity. A larger sample size would likely allow for more robust findings. The effects of this study are only applicable to the United States due to the country-specific context. Although, similar assumptions may be made related to the different theoretical components of an energy transition for other developed economies with a robust domestic coal market.

6.4 Future Research

This study generated substantial questions about the effects of dissuading carbon lock-in. Future research should aim to look at different measures of calculating the diffusion of renewables. Renewable capacity growth does not axiomatically entail a contraction of fossil fuels. Research should aim to discern how to increase renewables as a total share of the energy portfolio to meet the desires of the energy scenarios that contain renewable energy as a dominant share of the energy mix. This could be undertaken by analyzing the United States on a smaller scale looking at specific regions to increase the sample size. An econometrics analysis using a panel regression model with time-series data would potentially provide more comprehensive findings. This analysis could account for more variation among observations including many potentially interesting dynamics excluded here. For example, the proposed analysis could additionally look at the specific effects of natural gas power plants and their relation to renewable energy which was not assessed here. Future research can aim to analyze a mix of practical examples of continuation and discontinuation of the TIC to reduce path-dependencies. The energy transition will require persistent effort to ascertain the quickest path to increase scale and diffusion of renewable energy and disincline the robust consequences of carbon lock-in.

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Appendix A – Econometrics Output Tables

Table III. Relationship between Retired Coal and Future Renewable Energy

	Dependent variable is log renewable energy capacity in 2050, ln *y*			
	(1)	(2)	(3)	(4)
ln (capacity of retired coal)	0.146***	0.104***	0.0893***	0.0585*
	(0.0386)	(0.0271)	(0.0262)	(0.0291)
ln (state-level RE incentives)		0.184***	0.204***	0.191**
		(0.0558)	(0.0589)	(0.0877)
ln (per capita income)		1.010***	0.971***	1.183***
		(0.164)	(0.178)	(0.193)
Unemployment rate			0.221	0.819
			(0.684)	(0.758)
West			0.362***	0.449***
			(0.126)	(0.147)
Southwest				-0.116
				(0.364)
Midwest				0.231
				(0.521)
Southeast				0.506
				(0.368)
RPS				0.588*
				(0.345)
No policy				-0.409
				(0.285)
Democrat				-0.121
				(0.294)
Republican				0.0135
				(0.226)
Constant	8.952***	2.385**	-1.409	-8.720
	(0.243)	(0.931)	(7.592)	(8.348)
Observations	46	46	46	46
R-squared	0.247	0.682	0.736	0.829

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table IV: Relationship between Operating Coal and Future Natural Gas

	Dependent variable is log natural gas capacity in 2050, ln *y*			
	(1)	(2)	(3)	(4)
ln (capacity of operating coal)	0.188***	0.167***	0.148**	0.216**
	(0.0676)	(0.0588)	(0.0607)	(0.0801)
State-level RE incentives		1.237***	1.303***	1.651***
		(0.310)	(0.339)	(0.409)
Per capita income			-0.465	-1.735
			(1.192)	(1.720)
Unemployment rate			0.384	0.198
			(0.250)	(0.319)
West				-1.493**
				(0.691)
Southwest				-0.788
				(1.003)
Midwest				-1.347*
				(0.757)
Southeast				-0.710
				(0.827)
RPS				-0.473
				(0.626)
No policy				0.00629
				(0.630)
Democrat				0.432
				(0.514)
Republican				-0.0984
				(0.476)
Constant	7.250***	2.346*	5.828	19.44
	(0.523)	(1.309)	(12.71)	(18.54)
Observations	47	47	47	47
R-squared	0.147	0.374	0.413	0.528

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table V: Relationship between Share of Coal Retired and Share of Renewables in 2050

	Dependent variable is share of renewable energy as percentage of total in 2050, *y*			
	(1)	(2)	(3)	(4)
Share of coal retired	0.0893	0.104	0.115	0.0462
	(0.119)	(0.131)	(0.133)	(0.159)
RE technical potential		0.00486	0.0277	-0.0448
		(0.0263)	(0.0304)	(0.0422)
State-level RE incentives		0.0753	0.00752	-0.0302
		(0.0711)	(0.0837)	(0.0957)
Per capita income			0.485	0.189
			(5.28e-06)	(7.35e-06)
Unemployment rate			0.0140	-0.0323
			(0.0591)	(0.0726)
Southwest				0.185
				(0.179)
Midwest				0.112
				(0.123)
Southeast				-0.125
				(0.136)
Northeast				-0.332*
				(0.191)
RPS				0.0424
				(0.147)
No policy				0.00209
				(0.144)
Republican				-0.264*
				(0.139)
Divided				-0.121
				(0.114)
Constant	0.584***	0.199	-5.175	-0.383
	(0.0557)	(0.447)	(3.597)	(4.505)
Observations	48	48	48	48
R-squared	0.012	0.040	0.090	0.348

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Appendix B - Glossary

GHG	Greenhouse gases
CO_2	Carbon Dioxide
NO_x	Nitrous Oxide
SO_2	Sulfur Dioxide
CH_4	Methane
Mmbtu	per Million British Thermal Units
GT	Gigatons
GW	Gigawatts
MW	Megawatts
TIC	Techno-Institutional Complex
VRE	Variable Renewable Energy
CCS	Carbon Capture and Sequestration
PV	Photovoltaics
CSP	Concentrated Solar Power
Mmt	Million Metric Tons
NG	Natural Gas
NGCC	Natural Gas Combined Cycle
NGCT	Natural Gas Combustion Turbine
RPS	Renewable Portfolio Standard
RES	Renewable Energy Standard (Voluntary)
PPA	Purchase Power Agreement
FIT	Feed-in Tariff
GDP	Gross Domestic Product
EKC	Environmental Kuznets Curve
ReEDS	Regional Energy Deployment System
dGEN	Distributed Generation Market Demand Model
PLEXOS	Production Cost Model
NREL	National Renewable Energy Laboratory
CLRM	Classic Linear Regression Model
OLS	Ordinary Least Squares
BLUE	Best Linear Unbiased Estimator
U.S.	United States
USD	United States Dollar