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Essays on Energy Economics and Environmental Policies

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ESSAYS ON ENERGY ECONOMICS AND ENVIRONMENTAL POLICIES

by

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M.A., Economics, University of New Mexico, 2014

DISSERTATION

Submitted in Partial Fulfillment of the
Requirements for the Degree of

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DEDICATION

To my parents

Bishnu Bhakta Josh and Parbati Devi Joshi

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ABSTRACT

This dissertation contains three distinct empirical chapters in applied energy and environmental economics. Each chapter focuses on a unique set of research questions, methods, and data. The unifying motivation therein concerns the development of renewable or alternative low-carbon energy sources as a policy response to the challenges of climate change mitigation, local and regional environmental quality issues, and energy security concerns. Economic and environmental evaluation of the energy policies coupled with understanding energy use patterns is of paramount importance. Together, the empirical chapters focus on demand, supply, and policy aspects of energy markets in the United States (US).

First, Chapter 2 evaluates the impacts of the Renewable Portfolio Standard (RPS) on renewable electricity capacity. RPS is a state-level policy that requires electricity suppliers to include a certain proportion (or quantity) of renewable electricity in their total electricity sales over a specified time period. The chapter employs a fixed-effects panel regression model and a spatial econometric methodology using panel data spanning 47 states between 1990 and 2014. Thus, and importantly, the analyses incorporate salient spatial and temporal heterogeneities of RPS (i.e., varying RPS features across states and years). The results illustrate that the RPS has driven a 194 MW increase in overall renewable capacity (representing more than one third of the average electricity capacity developed between 1990 and 2014 in 47 states). The results also suggest that the impacts of RPS, while exhibiting spatial dependencies, vary depending on the renewable energy source. RPS positively impacts renewable electricity capacity, the share of renewable electricity capacity in total electricity capacity, as well as the shares of solar and wind capacity in total electricity capacity (the impacts become 1.3 times larger for solar and about two thirds fold larger for wind with reference to their average counterparts). However, the impacts of RPS are not statistically significant for biomass or geothermal resources. With the consistent patterns of the impacts of RPS across modeling scenarios, RPS adoption or lack thereof in different states, policy age, provision of renewable energy certificates (REC), and annually mandated obligations for renewable electricity in the overall electricity mix are among the critical factors which determine the efficacy of RPS. The positive impacts of RPS on solar and wind capacity are consistent with the relatively emphasized focus of RPS legislation across states which serves to prioritize these two renewable energy sources. Notwithstanding limitations in the available data (and the possibility that improvements in this respect over time would enable a more nuanced and higher-resolution investigation), the current findings provide guidance on how RPS is performing. The significantly positive impact of flexible REC provisions (allowing REC to be generated in any state), coupled with spatial spillover effects indicate the interstate marketing possibilities of renewable energy (and energy credits). The results (with respect to the significant contribution of different RPS attributes) suggest that the critical role the state level policies can make to meet national level goals

about climate change and energy mix. More specifically, the results imply that scaling up RPS proliferation across the states (guided by policy treatment effects, coupled with spatial dependencies of both the RPS and renewable electricity) and specifying RPS mandates by renewable energy sources (guided by significantly positive impacts for solar and wind), at least up to the point where renewable energy sector obtains efficiency gains (economies of scales and allocative efficiency) or to the situation where better alternative to the RPS becomes available (e.g., market based carbon pricing policy, which can be least-cost carbon mitigation mechanism), can play an important role in generating transformative advances in renewable electricity sector.

Next, Chapter 3 reports on an economic and environmental assessment to determine the optimal manure management strategy for large dairies. More specifically, a cost-benefit analysis and a life cycle assessment are carried out based on publicly available secondary data, motivated by the fact that improper management of dairy manure can result in adverse environmental and public health impacts. The results illustrate the comparatively high economic and environmental benefits associated with an integrated framework of bioenergy production as an alternative approach to manure management. Analyses are conducted under several scenarios (exploring the potential market for nutrients and greenhouse gases), all of which confirm that co-producing bioenergy in this context is more profitable than traditional on-site management approaches. The results imply that the livestock sector can maximize economic and environmental gains by integrating nutrient recovery and bioenergy production in alternative manure management considerations (rather than simply considering dairy manure as a waste disposal problem).

The final empirical investigation, Chapter 4, explores the temporal and spatial variation of sectoral natural gas demand in the US. A fixed-effects panel regression model is configured to analyze monthly data between 2001 and 2015. The results demonstrate the inelastic price responses at state, regional, and national levels across natural gas consumption sectors in the US, reflecting the importance of natural gas in contemporary energy systems. The implication is that price based policies, such as energy efficiency standards or energy saving targets in building codes, in the natural gas sector may not be effective (but, since the magnitudes of price elasticity vary across economic sectors, states and regions, efficacy of such price based policies will vary across these different dimensions). On the other hand, the inelastic price responses may reveal resiliency (i.e., stable market) of natural gas market to the changes in natural gas prices that may be driven by policy changes in other segment of the energy market (e.g., renewable energy supporting policies may increase natural gas prices). The resulting implication can be that natural gas that holds critical significance in the contemporary energy system from both environmental and economic perspectives can also serve as a transition fuel. The statistically significant weather impacts in terms of heating degree days (HDD) and cooling degree days (CDD) revealed in this analysis are consistent with the extant energy demand literature, where higher HDD stimulates greater consumption of natural gas in the residential sector while CDD appears to increase natural gas consumption for electricity production. The impacts with regard to weather attributes (HDD and CDD) also help to design informed policies to achieve various energy management goals (e.g., attaining energy efficiency or promoting alternative clean energy by quantifying the repercussions of changes in consumers’ responses to natural gas demand across climatic seasons in the energy market stability).

Collectively, these empirical chapters offer novel and important implications concerning energy market structures (supply and demand aspects), the environmental and economic assessment for renewable energy production potentials, and the policy responses, which have been or should be designed, to ensure the multi-dimensional sustainability of complex energy systems.

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Chapter 1: Issues in Energy Economics and Environmental Policies: Background, Objective and Method

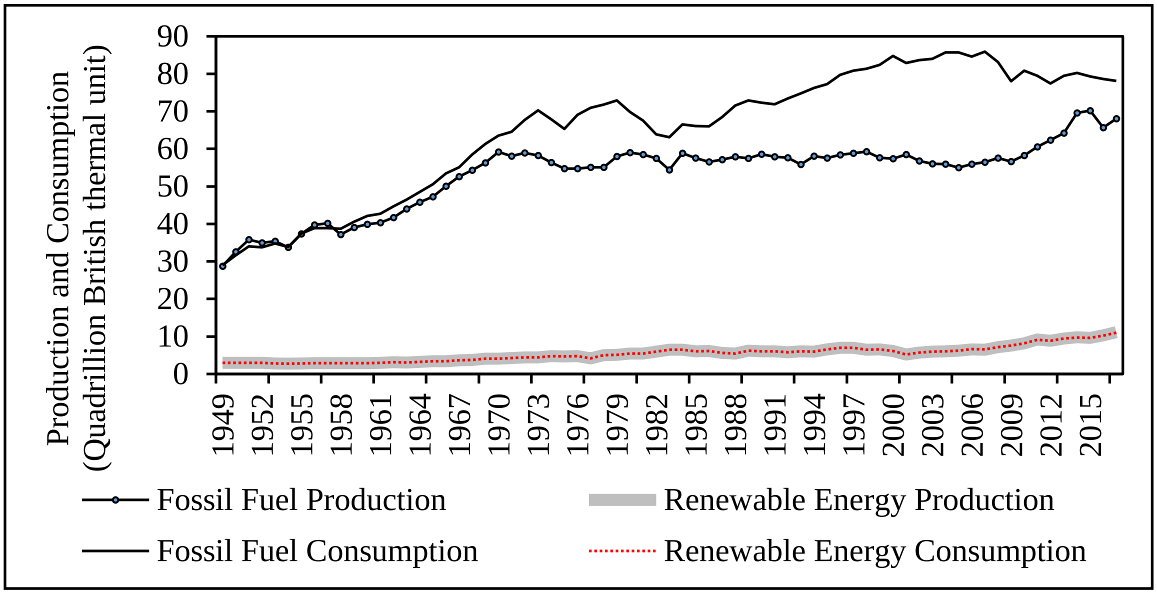
[redacted] Background

Energy is an essential human need, and it is also an important input into production functions (critical determinant of economic growth and economic development). Continued increases in the global population and improved living standards are expected to increase future demand for energy resources. The World Economic Outlook (International Energy Agency, 2017a) projects that global demand for energy will increase by 30% between 2017 and 2040. In the United States (US), the annual increase in demand for energy is projected to range from 0.4% to 0.7% from 2017 through 2050 according to low and high economic growth scenarios (i.e., projected annual growth in gross domestic product from 2% to 2.6%), respectively (US Energy Information Administration, 2018a).

Energy markets demonstrate a dynamic interplay between supply diversity (variety of identified energy resources) and demand heterogeneity (different uses of solid, liquid and gaseous energy across different sectors of the economy and society). Changing economic and environmental conditions, coupled with technological advances (e.g., continued innovations with respect to wind, solar, shale oil, and gas), result in a complex dynamic industry structure, impacted by shifts in supply and demand for energy across time and geographies. Beyond the economic and societal value of energy, the link between energy commodities (and services) and environmental concerns (e.g., global climate change or local air quality) has expanded discussions of the market and nonmarket aspects of energy production and consumption. Therefore, the energy industry encompasses both challenges and opportunities concerning economic impacts (e.g., income and employment), energy security (e.g., reliability of energy supply), and environmental quality.

Despite heterogeneities in the supply and demand of energy goods and services across space and time, more than 70% of current global energy is derived from fossil fuels (International Energy Agency, 2017). Figure 1.1 shows total primary energy production and consumption by source in the US, illustrating the predominance of fossil fuels relative to renewables in the US energy market. Importantly, while the production and consumption of renewable energy are equalized (since production and consumption of renewable energy often occur locally), there is a discrepancy between the domestic production and consumption of fossil fuels, which is equalized through imports.

Figure 1.1: Energy production and consumption by sources in the US



Data Source: US Energy Information Administration (2018b)

Although achieving energy security and self-sufficiency is also widely discussed due to geopolitical complexities in the global energy market (which are hard to capture or proxy for in economic models), most countries rely heavily on imported fuels to meet domestic energy demand (see Figure 1.1 to see foreign fuel dependency of the US). For instance, the US imported approximately 10.1 million barrels of petroleum per day from 84 countries in 2017 while exporting petroleum to 180 countries in the same year (Energy Information Administration, 2018a). Indeed, from comparative advantage point of view, dependence on foreign fuels may be an economically efficient choice (e.g., international trading of energy commodities driven by comparative advantage or opportunity cost). However, there are important potential economic consequences of energy insecurity, such as increased risk of trade fluctuations impacting both quantities and prices of energy commodities (Bohi and Toman, 2012). This means that, regardless of comparative advantages, stimulating investment in domestic fuel sources (exploration and development) remains a salient policy objective. Moreover, fossil fuels that supply a large share of energy needs (e.g., currently about 80% in the US), are often considered exhaustible resources with limited stock. Thus, achieving energy security with source diversification (e.g., utilizing a range of renewable energy technologies, including bioenergy production by using livestock manure) is also an important issue.

Burning fossil fuels is also responsible for negative environmental externalities, such as local and regional air pollution (e.g., particulate matter and sulfur dioxide) and greenhouse gas (GHG) emissions (e.g., carbon dioxide). Global energy sector activities, namely, extraction, processing, distribution, and consumption, are responsible for about two thirds of global GHG emissions (International Energy Agency, 2017b), and in the US this figure is even higher at around 75% (US Energy Information Administration, 2018c). These environmental externalities are also widely discussed as leading causes of market failures, because they impose non-monetized costs on society (Covert et al., 2016; Gillingham and Sweeney, 2010). Thus, while fossil fuels have been vital contributors to economic well-being (i.e., rising living standards), excessive reliance on them also generates concerns about energy security and environmental sustainability.

Renewable energy sources are recognized as effective tools to mitigate the negative externalities of fossil fuels (Intergovernmental Panel on Climate Change, 2015; Pachauri et al., 2014). But, economic (cost competency) and technological (production efficiency) barriers are still prevalent in the renewable energy sector and thus limit the viability and diffusion of these low-carbon (or carbon-free) alternatives. Nevertheless, policies aimed at increasing the share of renewables in the energy market have gained widespread popularity in the US and around the world (Brown, 2001; Gillingham and Sweeney, 2010).

The energy market has transitioned through different phases throughout history in terms of reliance on different fuel sources. In the US, the share of wood based energy was 70% in 1870, before transitioning to 70% coal in 1900, and then to 70% oil and gas in 1960 (O’Connor, 2010). The economics literature often emphasizes that the exhaustible nature of fossil fuels is sufficient to lead shifts in energy consumption patterns towards a greater reliance on renewables (i.e., shifts in energy use patterns towards renewable sources, following the market driven changes in energy supply). As exhaustible fossil fuels become increasingly scarce, they could become more expensive than the gradually advancing renewable alternatives as postulated by the Hoteling rule that economical and easily accessible resources are exhausted first, and thus, the market itself creates incentives (increased marginal cost of extraction of fossil fuels) to switch to renewable energy following the least cost principle.

However, a transition to renewable energy following a self-correcting mechanism of functioning energy markets (i.e., an energy transition driven by the increased extraction costs of fossil fuels) does not seem plausible in the near future, as there continues to be a push to find and exploit new fossil fuel reserves (Covert et al., 2016; Miah et al., 2012). Moreover, extensive discussions among scientists, economists, and policymakers continue to emphasize the need for immediate action to address critical energy sector problems, because the negative externalities therein pose serious risks to the economy, environment, and society (Edenhofer et al., 2011; Intergovernmental Panel on Climate Change, 2015).

Economic theories and relevant empirical methodologies can be leveraged to help develop effective energy policies. Economists primarily focus on effective policy interventions in the form of binding regulations or the creation of market institutions (e.g., allocating property rights to public goods) to address optimal resource allocation problems and non-monetized energy sector externalities. The first best solution to concerns about energy sector externalities is the adoption of market based policies (e.g., influencing supply, demand or both for different energy sources by creating an active market for carbon trading and low carbon technologies). However, various barriers, such as complexities in identifying sources or agents of environmental emissions, the capability of existing technologies to precisely track such emissions, the embedded costs of tracking such emissions and consumers' willingness to pay for such environmental goods, exist in advancing first best solution policies. Therefore, the growing demand for energy coupled with a myriad of environmental challenges associated with contemporary energy systems raises important questions about the nature and role of appropriate energy policies in transforming the energy sector from a fossil fuel dominated system to an alternative where renewable energy proliferates. As such, understanding energy market structures (spatial and temporal heterogeneities of supply and demand) and the efficacy of energy policies in the development of renewable energy sources is critically important.

A policy or combination of policies can play a critical role in changing the existing energy market structure (i.e., supply and demand) to achieve the intended objectives of fuel efficiency, energy transition, and environmental sustainability (Gillingham and Sweeney, 2010). For instance, decision makers can institute policies that either directly mandate private parties to comply with specific rules and regulations (e.g., restricting activities of harmful environmental impacts) or create market institutions to allow the market to efficiently manage externalities (e.g., cap and trade policies). Importantly, existing energy policies may not necessarily be the first best solutions (due to embedded economic and technological barriers to effectively institutionalize such policies). However, increasing the scale and scope of empirical evidence with regard to the role of such policies in increasing renewable energy capacity can help to better determine if extant policies are effective in achieving their intended objectives.

Energy policies, particularly those designed to minimize environmental externalities and energy security risks, are gaining momentum in the US. The history of energy, including the energy crisis of the 1970s, through to contemporary concerns about climate change since the 1980s (including concerns over acid rain and escalating ozone levels), has led to the development of various policies supporting renewable energy technologies in the US (Fischer and Preonas, 2010). For example, the US adopted the Clean Air Act in 1970 to address local environmental concerns such as air particulate matters emitted from both mobile and stationary sources. The Clean Air Act was amended in 1990 to address concerns over emissions of sulfur dioxide and nitrogen oxide from the electricity sector. The federal production and investment tax credits have been available since 1992 covering a range of renewable energy technologies, and represent a significant federal policy in the US (Mai et al., 2016). The American Recovery and Reinvestment Act of 2009 contained a provision of providing a grant covering 30% capital costs for renewable energy projects.

Various renewable energy policies also have been adopted by individual states to promote the renewable energy sector. For example, 12 states have adopted Mandatory Green Power Options (MPGO) that mandates electric utilities to provide options to the consumers to purchase electricity generated from eligible renewable sources. In 41 states, the net metering policy allows consumers to sell back surplus electricity to electric grid. The renewable portfolio standard (RPS) is the prominent state level renewable energy policy in the US (Stauffer, 2017). Iowa was the first state to adopt RPS in 1983, and 29 states in the US have adopted it to date. The RPS is a state-level policy that mandates the electricity industry to include a specified fraction of renewable power in total electricity sales over a specified period, although the size of this fraction and other specificities vary by state. RPS design can also be voluntary in some states (voluntary RPS goals), and its mandated targets can be met through in-state, out-of-state renewable energy credits or both.

[redacted] Objective

Addressing the full range of economic and technological challenges facing the renewable energy sector requires advances in favorable public policies, as fossil fuels continue to be a reliable fuel source to meet current energy needs. For instance, in the US, the shares of primary energy production from major fossil fuels (petroleum, natural gas, and coal), renewable energy, and nuclear power were approximately 78%, 13% and 9%, respectively, which collectively met around 90% of total domestic energy demand in 2017 (the remaining fraction of demand was met by imported fuels) (US Energy Information Administration, 2018d). This dissertation aims to empirically examine practices and policies with respect to renewable energy and natural gas in the US at the regional and national levels. The unifying theme across the chapters pertains to the development of renewable or low-carbon energy, coupled with demand side assessment of natural gas as a reliable backstop energy source. While a complete transition from fossil fuels to renewables may be feasible in the long-run, this dissertation focuses on short-run issues and examines spatial and temporal aspects in energy market structure (e.g., changes in supply and demand) in conjunction with relevant energy policies.

Thus, dissertation chapters collectively aim to provide insights into key energy market attributes (supply, demand, and policies). More specifically, the empirical chapters focus on evaluations of the effectiveness of renewable energy policy (Chapter 2), the economic and environmental viability of using dairy manure in renewable energy production (Chapter 3), and examination of regional variation in natural gas demand across the US (Chapter 4). As such, this dissertation attempts to address salient broad questions including: (i) Are existing renewable energy policies effective in increasing renewable energy production? (ii) Is it economically and environmentally viable to produce renewable energy from the dairy manure? (iii) What is the current demand for natural gas across different consumption sectors, and how does it vary as a function of price, weather variables, and spatial dimensions? While specifics with respect to contexts, methods, finding and policy implications are summarized in the following sub-section of this first dissertation chapter (i.e., sub-section 1.3, Methods and Findings), a brief contextual background behind each empirical chapter is presented in next three paragraphs.

In more detail, in terms of Chapter 2, while renewable energy sources have long been recognized as crucial components of sustainable energy systems, their economic viability in supplying growing energy demands needs attention from short- and long-run perspectives. Despite the identified advantages of renewable fuels, the sector currently falls behind in the market economy because of lacking cost competency, inadequate technological advances and built infrastructure, and reliability (e.g., intermittent supply). Moreover, the energy developed from renewable sources is not always fully substitutable for traditional fossil fuel based energy. This is because the current focus in advancing renewable energy is from the perspective of electricity, but some existing consumption technologies solely rely on other forms of energy, such as liquid, solid, and gas (e.g., petroleum in the transportation sector). Given this context, the first empirical chapter (i.e., Chapter 2) of this dissertation aims to evaluate the efficacy of the RPS, a state level renewable electricity policy, in increasing renewable electricity capacity in the US.

In Chapter 3, an economic and environmental assessment of bioenergy production is conducted as an alternative approach for dairy manure management. The assessment accounts for the interlinked aspects among the energy, water, and agricultural sectors in the context of a typical large dairy farm in New Mexico by incorporating economic (e.g., cost-benefit analysis) and environmental impacts (e.g., environmental footprint analysis) for bio-energy production potentials. The additional value this study generates is in identifying best alternative methods of dairy manure management (in terms of economic and environmental favorability), given that improper manure management can result in various deleterious environmental and public health impacts.

Natural gas has emerged as an important fuel source from both environmental and economic perspectives. Importantly, natural gas emits less carbon dioxide per thermal unit compared to other fossil fuels and recent technological advances have served to increase the effective supply of this energy source through shale gas developments. Thus, natural gas is often considered to be a transitional fuel towards sustainable energy futures. Approximately 32% of total primary energy production in the US is attributable to natural gas, and this proportion is expected to increase in the foreseeable future (Outlook, 2015; US Energy Information Administration, 2018d). With the recognized significance of natural gas in the contemporary complex energy industry, Chapter 4 examines spatial and temporal variations in sectoral natural gas consumption patterns across the US as a function of sectoral prices and regional weather attributes.

[redacted] Methods and Findings

Each empirical chapter of this dissertation focuses on a unique set of research questions, methods, and data as summarized below.

Chapter 2 conducts an empirical evaluation of the RPS in the US. Policy designs vary considerably across states; even the motives of renewable portfolio standards are defined differently across states. Nonetheless, minimizing the impacts of environmental externalities, ensuring a path to energy security, and promoting economic prosperity (e.g., job creation) appear as intersecting themes of RPS adoption across all states. Although related work exists in the literature (e.g., Berry and Jaccard, 2001; Delmas and Montes-Sancho, 2011; Yin and Powers, 2010), the efficacy of this policy intervention in terms of stimulating and sustaining renewable energy capacity is not currently well understood. To address this, the empirical analysis, with robust identification strategies, uses data from 1990-2014 for 47 states. A fixed-effects panel regression model and spatial econometric methods are used for estimation purposes. The difference-in-difference (DID) econometric method is used as quasi-experimental inferential design to account for potential selection differential into adopting the RPS across the states. Validation approaches for these findings have followed various empirical specifications by incorporating the limitations of past studies (particularly, assumptions and limitation on data).

The results from Chapter 2 indicate that the RPS has driven a 194 MW increase in overall renewable capacity (representing more than one third of the average electricity capacity developed between 1990 and 2014). These impacts even become larger for recent year data (particularly, under the sub-samples containing data beyond 2000). However, the impacts are heterogeneous across renewable sources. While the RPS contributes positively to solar (about 1.3 times higher than average solar capacity) and wind (about two thirds of average wind capacity) capacity, it is statistically insignificant in terms of biomass and geothermal. The chapter explores not only the treatment effect from the adoption of the RPS, but also examines the impacts of differential RPS provisions (e.g., age and provisions for renewable energy certificates) across states. For instance, incorporating provisions for renewable energy credits in the policy through the generation of renewable energy certificates positively contributes to the development of renewable electricity capacity. These findings align with recent developments in renewable energy from distributed generation technologies (e.g., economic incentives created for distributed generators through the provision of renewable energy certificates). Policy age, measured in terms of the number of years between when the RPS became effective in a state and 2014, also has a significantly positive impact on renewable electricity capacity.

The results suggest that the insignificant impact of the RPS revealed by previous studies may be an artifact of data limitations (e.g., lack of sufficient data to reflect heterogeneous RPS attributes in the past). The findings also support the current focus of the RPS with respect to solar and wind technologies. The statistically significant spatial dependencies of the RPS signify that spatial RPS rearrangement in neighboring states can result in changes in renewable electricity capacity. This spatial spillover effect also testifies to the positive contributions of the flexible provisions of renewable energy certificates (REC) in the RPS. The flexible RPS allows renewables to be generated in any state (rather than restricting the REC within a state border or not incorporating REC provisions at all). Such spatial spillover effects imply that states with high technical potential for renewable energy receive financial incentives to develop renewable energy as additional revenues (expanded economic opportunities) can be generated through exporting surplus energy to other states. Moreover, the policy implication with respect to the findings is that state level energy policies (provided that many policies are under implementation or implementation consideration for experimental purposes across state and national levels, since policy outcomes are often unknown due to various embedded complexities of the energy market system) can serve a vital role to meet the targets of climate stabilization or diversification of energy mix of the national or local governments. Positive impacts of the RPS under different scenarios (specifically, for solar and wind), coupled with observed spatial dependencies with respect to the RPS and renewable electricity imply the regionalization of both the RPS and renewable electricity trading can contribute to enhance development of the renewable energy sector (e.g., achieving productive and allocative efficiency gains or economies of scales; which are among major barriers facing the current renewable energy sector). For instance, developing regional markets for the renewable electricity, coupled with crafting RPS design at regional scales can allow to fully utilize the intermittent generation of renewable electricity (generation from solar and wind vary across different points of time in a single day, depending on solar radiation and wind speed).

Chapter 3 provides a grounded reflection on supply side attributes, technologies, and policies in the renewable energy context. This chapter offers unique insights into the viable use of dairy manure in bioenergy production. Arid and semi-arid regions that support more than one-third of the global population and almost half of the world’s livestock and cultivated land are facing multiple challenges that call for integrated approaches to managing their food, water, and energy resources (Mortensen et al., 2016). A case study from New Mexico is used**;** this state ranks first in the US in terms of the number of dairy cows per farm. The core premise behind this investigation is that consolidating the dairy industry generates both opportunities (e.g., higher net farm income due to economies of scales) and challenges (e.g., eutrophication and greenhouse gas emissions). This study contributes to the extant literature by assessing the economic and environmental viability of three dairy manure management approaches: direct land application (DLA), anaerobic digestion (AD), and anaerobic digestion coupled with microalgae cultivation (ADMC). To this end, life cycle assessment and cost-benefit analyses are employed with sensitivity analyses to explore the robustness of findings. An inventory analysis of energy balance, water balance, eutrophication potential, and global warming potential, suggests that DLA is the least favorable, with the lowest net present value of benefits. The AD case is the most favorable regarding energy balance. While the ADMC is relatively more favorable than other cases in environmental aspect, as it is associated with the highest water balance, and the lowest eutrophication and global warming potentials. The present values of net benefits under the baseline scenario (excluding costs and benefits of relevant policies), a current policy scenario (incorporating existing policies applicable to the scenarios), and scenarios with additional cropland or rangeland availability suggest that DLA is the least profitable and that AD is the most cost-effective (from both environmental and economic perspectives). Analysis of the three cases (DLA, AD, and ADMC) under scenarios of a potential market for nutrients and carbon credit trading in New Mexico indicate that a market for environmental credits increases the net present value of benefits for bioenergy production in the AD and ADMC. Thus, the results imply that nutrients in dairy manure can be converted into various valuable products, such as nutrient supplements and renewable energy, while maintaining compliance with environmental regulations in the sector.

Chapter 4 investigates sectoral variations in natural gas demand across the US. Natural gas is an increasingly valuable fuel source in the context of growing environmental and energy security concerns. Demand-side management (e.g., providing incentives to alter consumption patterns) requires a high level of understanding about consumers' responses to variations in demand factors (such as price and weather). However, the literature remains surprisingly scant in terms of analyzing the impacts of changes in prices and weather on sectoral natural gas demand across the US.

Accordingly, the objective of Chapter 4 is to evaluate the patterns in sectoral natural gas demand by applying a fixed-effects panel regression to monthly, state level data from 2001 to 2015. The results indicate that natural gas demand is price inelastic across the sectors at national, regional and state levels. That is, the impacts concerning the changes in natural gas prices across and within the sectors coupled with weather variation measured by heating degree days (HDD) and cooling degree days (CDD) are also not substantially high. Despite this, substantial variations in consumption in response to changes in prices, heating degree days, and cooling degree days are observed across sectors, regions, and states. Thus, the results imply efficacy of relevant price based policies in the natural gas sector (e.g., changing prices of natural gas through a policy either to reduce natural gas consumption or create market incentives for renewable energy sector) also changes across local and regional levels. Most importantly, provided the economic and environmental significance of natural gas in the contemporary energy system, inelastic price responses in the natural gas sector indicate that natural gas can serve a reliable transitional fuel source in scaling up the renewable energy sector. Thus, these findings offer insightful information to the energy industry and policymakers for the purpose of navigating energy sector challenges (e.g., achieving energy efficiency or developing supporting policies to shift the energy uses from fossil fuels to renewable energy) at the regional and national levels.

[redacted] Contributions and Limitations

Covering the topics in applied energy economics that are of critical significance to the economic and environment issues at the local and national scales in the US, this dissertation makes several contributions: (1) in an attempt to better understand the linkage of state level policies in achieving the goals of sustainable energy futures, the dissertation empirically evaluates the effectiveness of the RPS, (ii) in the context of proper dairy manure management needs, the dissertation conducts an empirical study on the economic and environmental evaluations for using dairy manure in bioenergy production, and (iii) in the existing opportunities and challenges in the renewable energy sector, coupled with contribution of the fossil fuel services in today's economic well-being, a blend of national and regional frameworks for sectoral natural gas demand is evaluated empirically in the US.

Exploration of typical energy market characteristics (supply diversity, demand heterogeneity and wide ranges of policies and regulations) in the context of advancing renewable or alternative clean energy can be attributed as a unifying theme of the dissertation. Addressing the issues of critical significance in the energy system at state, regional, and national scales is also an interesting aspect of the dissertation. Each empirical chapter of the dissertation relies on its modeling assumptions and data limitations. Such assumptions, caveats and future directions are discussed in each chapter of this dissertation. The empirical chapters also address their unique contributions with comprehensive discussions on policy relevance. Thus, readers are advised to refer to each empirical chapter to examine its unique contributions and recognized limitations. Moreover, the concluding chapter summarizes contributions, policy implications and limitations of each empirical chapter. The chapters collectively make significant contributions to the applied energy economics literature by covering the most relevant issues of the time in the energy market structure context, by empirically distilling range of supply, demand, technology and policies aspects across the regional and national scales.

Following the comprehensive background in this section, chapters 2-4 of this dissertation cover discussion on empirically distinct topics with interconnectedness in core motivations. Chapter 5 concludes the dissertation with policy relevance.

Chapter 2: Do Energy Policies Increase Renewable Energy Capacity? A Quasi-Experimental Evaluation of the Renewable Portfolio Standard in the United States

[redacted] Introduction

The growing consumption of fossil fuels is the major cause of anthropogenic pollution, including greenhouse gases (GHGs) emission and other forms of air pollution, in the United States (US) and around the world. The major components of the GHGs emitted by the generation of fossil fuel based electricity are carbon dioxide (CO_2), nitrogen oxides (NO_x), methane (CH_4) and nitrous oxide (N_2O) (US Environmental Protection Agency, 2016a). In addition to driving global climate change, GHGs are also precursors of local environmental pollution (e.g., GHGs contribute to the formation of $PM_{2.5}$, ozone, smog, and acid rain). In 2017, 63% of the electricity generation in the US was from fossil fuels, 20% was from nuclear energy and the remaining 17% was from various renewable sources (US Energy Information Administration, 2018e). Indeed, this predominance of fossil fuels is difficult to overstate: The electricity sector is the second largest GHG emitter, account for 28.4% of emissions and thus only marginally behind the transportation sector (28.5%) in the US (Environmental Protection Agency, 2018; US Energy Information Administration, 2018c).

Renewable electricity can help to offset negative externalities and natural resource sustainability concerns associated with fossil fuel electricity (e.g., air pollution, GHGs, and fossil fuel resource depletion). The development of renewable electricity also contributes to the diversification of local energy mixes to help minimize the energy security risks (e.g., risks associated with supply disruptions due to natural disasters or policy changes). However, the renewable energy sector lacks cost competitiveness in the energy market due to relatively higher upfront capital and transaction costs compared to conventional fossil fuel electricity. This is because; (i) the fossil fuel industry often receives financial subsidies (Berry and Jaccard, 2001; US Energy Information Administration, 2018b), (ii) the current electricity market does not adequately factor in fossil fuel externalities (Berry and Jaccard, 2001; Palmer et al., 2017), (iii) the renewable sector relies on newer and relatively expensive technologies (Berry and Jaccard, 2001) and (iv) current renewable technologies are only capable of intermittent generation with limited storage possibilities (Berry and Jaccard, 2001; del Río et al., 2018; Verbruggen et al., 2010). Examples of subsidies or tax deduction benefits in the fossil fuel production sectors in the US include the percentage depletion for oil and natural gas wells, domestic manufacturing deductions for oil and natural gas, and a two year amortization period for geological and geophysical expenditures associated with oil, natural gas, coal and lignite. Despite the current lack of a fully developed market system to account for fossil fuel based externalities (because, trading of such externalities are often subsidized), it should be noted that efforts to institutionalize markets for some components of the GHGs (e.g., carbon dioxide, methane, nitrogen and phosphorus) are underway in some countries at the regional or national level (e.g., the Regional Greenhouse Gas Initiatives in the US, the California Cap and Trade Program and the EU Emissions Trading System).

The growing awareness of such economic and technological barriers in the energy sector, the time criticality of climate change combined with energy security imperatives, and the increasing public support for environmentally benign development pathways have led to increased interest in experimenting and institutionalizing various renewable energy policies (such as, regulatory mandates or financial incentives across the production, investment and consumption sectors) for the purpose of securing a sustainable energy transition (Allcott and Mullainathan, 2010; Delmas and Montes-Sancho, 2011; Dincer, 2000; Stern et al., 2006). The renewable portfolio standard (RPS) is one such policy that is designed to promote the renewable electricity sector. The RPS, a state level renewable electricity policy in the US, mandates that electricity suppliers include a specified fraction or quantity of electricity from renewable sources in their retail sales. To date, this policy has been adopted by 29 states and it covers 54% of the total electricity generation in the US electricity market (Barbose, 2017). Although the RPS is a command-and-control policy, it is often configured to accommodate features of the functioning competitive market system. Such configuration is important because electricity market stability can be impacted by RPS regulation due to its potential impact on electricity and natural gas prices (Palmer and Burtraw, 2005). Thus, RPS mandates are often met by; (i) self-production, (ii) power purchase agreements, or (iii) renewable energy certificates. That is, states that have mandated RPS policy have created several alternative provisions to facilitate compliance by electricity producers, including flexible penalty payments for failure to comply with the mandates.

Since states in the US have independent authority to adopt and adapt this policy, the design and stringency of RPS attributes (e.g., adoption year, nominal obligations, eligible technologies) varies across the country. For example, California has set RPS mandates to reach 50% by 2030. In Hawaii, the mandate is set to be 100% by 2045. In contrast, 21 states have no mandatory RPS legislation at all. Despite the geographical and temporal differences in RPS attributes, the goals of minimizing the impacts of environmental externalities, ensuring a path to energy security and promoting fuel diversity characterize the intersecting motives across states for adopting RPS (Lyon and Yin, 2010; Rabe, 2006, 2004).

The primary objective of this research is to differentiate the impacts of the RPS on renewable electricity capacity in the US. As the significance of public policies are rising as the cornerstone of renewable energy development, understanding and exploring the efficacy of such policies (i.e., an evaluation for policy success) is equally important. Doing so not only provides policy guidance in developing the renewable energy sector in a most efficient way, but the potential economic costs of such policies (economic costs to consumers and other market participants) also warrant the evaluation of the policy effectiveness. Among different policy effectiveness indicators (e.g., cost-effectiveness and changes in consumer preferences), evaluating the impacts of specific targets of the policy on renewable electricity capacity provides more comprehensive and nuanced gauge of policy success.

The extant empirical literature on evaluation of RPS effectiveness is thin. Although some relevant studies exist (e.g., Berry and Jaccard, 2001; Delmas and Montes-Sancho, 2011; Yin and Powers, 2010), the efficacy of this policy intervention in terms of stimulating and sustaining renewable energy capacity is not currently well understood. More precisely, while a few studies (e.g., Shrimali and Kniefel, 2011; Yin and Powers, 2010) are linked to the key objectives of this research, their conclusions demonstrate substantial inconsistencies. Yin and Powers (2010), using data from 1990 to 2006, illustrate a positive contribution of the RPS to the percentage of non-hydro renewable electricity generation capacity, but their results are based on an imputed RPS stringency index (they define RPS design as aggressive or weak based on regulatory stringency) rather than incorporating policy heterogeneity from actual annual RPS mandates. Moreover, their sampling frame only spans 1990 to 2006, where only 16 states had binding RPS standards (i.e., regulatory mandates) in this period, and most of those states were in their early years of RPS adoption (limiting the policy heterogeneity to be accounted for in the estimation). They also do not differentiate the RPS impacts by renewable technologies.

Moreover, Shrimali and Kniefel (2011), using data from 1990 to 2007, conclude negative impacts of RPS on the share of non-hydro renewable generation capacity (MW) of total generation (MWh). This outcome variable (defined as the share of generation capacity (MW) in total generation (MWh)) of their study does not capture a meaningful construct regarding renewable energy development. This is because dividing MW by MWh, does not result in a well-defined outcome variable, making it difficult to interpret the predicted outcomes due to a lack of meaningful reference. Their RPS measurement is also based on linear interpolation, so that a constant number is imputed for each year, derived by dividing the stated long-term targets of the RPS by the numbers of years between RPS adoption and target year (i.e., not a time variant RPS obligation is used). Thus, the inconclusive findings of previous studies, plausibly, associated with the data limitation (exhibiting limited variation in the RPS spatially and temporally) coupled with assumptions on data and estimations, the question of whether the RPS is contributing to the renewable electricity capacity development remains poorly understood.

This investigation endeavors to fill such gaps in the literature, by reducing the number of implicit and explicit assumptions introduced in the data and methodologies employed in previous studies and by incorporating subtle identification of consistent estimates. The examples of such assumptions in previous studies include t imputed incremental RPS mandates rather than actually mandated obligations and ambiguous RPS adoption date due to a lack of clarity in defining whether the variable represents policy enactment date or the actual policy effective date. These assumptions are omitted by incorporating the years that represent the actual RPS effective dates, and actual annual variation in the RPS mandates (i.e., annual nominal obligations): The uses of RPS effective date and actually mandated annual RPS obligations are the unique differentiation of current investigation in the literature.

This study also makes a unique contribution by estimating the spatial spillover effects (application of spatial econometric methods by incorporating a spatial weights matrix to examine spatial structure of both the RPS and renewable electricity) from RPS. The spatial diagnostics, based on the estimations from both the spatial lag and spatial error models, allow to observe the presence of spatial spillover as well as quantify the extent to which states with high renewables potential are economically incentivized to develop renewable electricity capacity to export to other states. The application of a multi-method approach, combining spatial econometric tools with linear regression analysis not only contributes to examine the estimation precisions, but guides with additional robustness checks of the estimates. The distribution of sample data used herein, from 1990 to 2014 and covering 47 states, with a binding RPS in effect in more than 50% of those states, provides a relatively ample frame in terms of spatial and temporal coverage, as well as policy heterogeneity, from which robust conclusions can be drawn.

This study econometrically differentiates the impacts of the RPS on non-hydro renewable electricity capacity, the share of non-hydroelectricity capacity in total electricity capacity and the specific shares of renewable electricity capacity from four sources (wind, solar, biomass, and geothermal) in total electricity capacity. Distributions of annual RPS mandates across states are often skewed to the future periods; and thus, it is noteworthy that while states may be fully complying to the RPS mandates, the estimated average impacts the RPS on generation capacity may not reflect RPS potentials in its entirety during the observed sample frame (1990-2014). The significance of examining the impacts on the capacity development also pertains to the fact that existing renewable electricity capacity infrastructures may not be generating electricity at full capacity, (e.g., due to the intermittent nature of current renewable energy technologies and electric load balancing constraints). However, such capacity infrastructures are indicative of how effectively the RPS is contributing to the renewable electricity generation at present or in the coming years.

The sample consists of annual state-level data from 1990 through 2014. Data for Texas, Iowa and Alaska are removed from the analysis as outliers. Texas (one of the largest renewable electricity producing states) is already exceeding its RPS target for 2025 (renewable electricity capacity of 10,000 MW). An abundant supply of economically viable wind resources (90% of non-hydro renewable electricity in Texas is derived from wind sources) and declining petroleum production are attributed as crucial drivers of renewable energy development in Texas (Zarnikau, 2011). Because of these attributes, and the designation of non-wind renewable sources as goals (rather than mandates), the inclusion of Texas in the analysis is likely to result in biased estimation (these features make it difficult to identify whether Texas falls within a treated or control group). Iowa, the first state in the US to adopt a RPS has not had percentage obligations associated with that RPS in recent years. Finally, Alaska doesn’t have RPS targets or significant publically available data on renewable energy.

Panel econometric modeling approaches with nuanced identification strategies are used for empirical analysis. The Difference-in-Difference (DID) method is used to transform observational data into a quasi-experimental randomization setting to mitigate against potentially inconsistent estimator or selection bias concerns vis-à-vis the adoption of RPS across states. As a robustness check, sensitivity analyses with various model specifications and estimation techniques are conducted (including estimations across various randomized subsamples). Following finite sample properties (e.g., spatial and temporal dependencies), generalized least squares with panel corrected standard errors (GLSPCSE) is selected as an estimation method. Spatial econometric methods, specifically a spatial autoregressive model (SAR) and spatial Durbin model (SDM), are used to examine the spatial aspects of RPS impacts and to explore the robustness of the GLSPCSE estimates.

The results illustrate that the increase in average renewable electricity capacity attributable to RPS is 194 megawatts (MW). Put differently, this is the policy treatment effect, denoting the RPS driven increase in renewable electricity capacity in states that have adopted the RPS against those that have not adopted the RPS in the US. This accounts for more than one-third of average electricity capacity from 1990 to 2014 across the 47 states in the sample. External validation of this RPS impact can also be derived from Lawrence Berkeley Lab reports (Barbose, 2017, 2015) which determined that62%

of the growth in renewable energy capacity in the US since 2001 is attributable to RPS compliance. Results with respect to various RPS attributes (annual nominal mandates for renewable electricity, RPS age, REC provision and provision of energy efficiency) also illustrate positive impacts on renewable electricity capacity or the shares of renewable electricity capacity in total electricity capacity.

RPS impacts are found to change across renewable electricity sources. The results show that RPS significantly promotes renewable electricity capacity in terms of solar and wind technologies, with the greatest impacts being in terms of the latter. The results are mixed for biomass and geothermal resources: the impacts for biomass are significantly negative with no significant impacts in terms of geothermal. The technology specific (i.e., renewable source specific) results are consistent with the increasing share of solar and wind based electricity capacity built since 2000. Declining shares of biomass and geothermal electricity capacity in recent years and the predominant focus of RPS legislation across states on wind and solar as eligible technologies, testify to the robustness of the estimates.

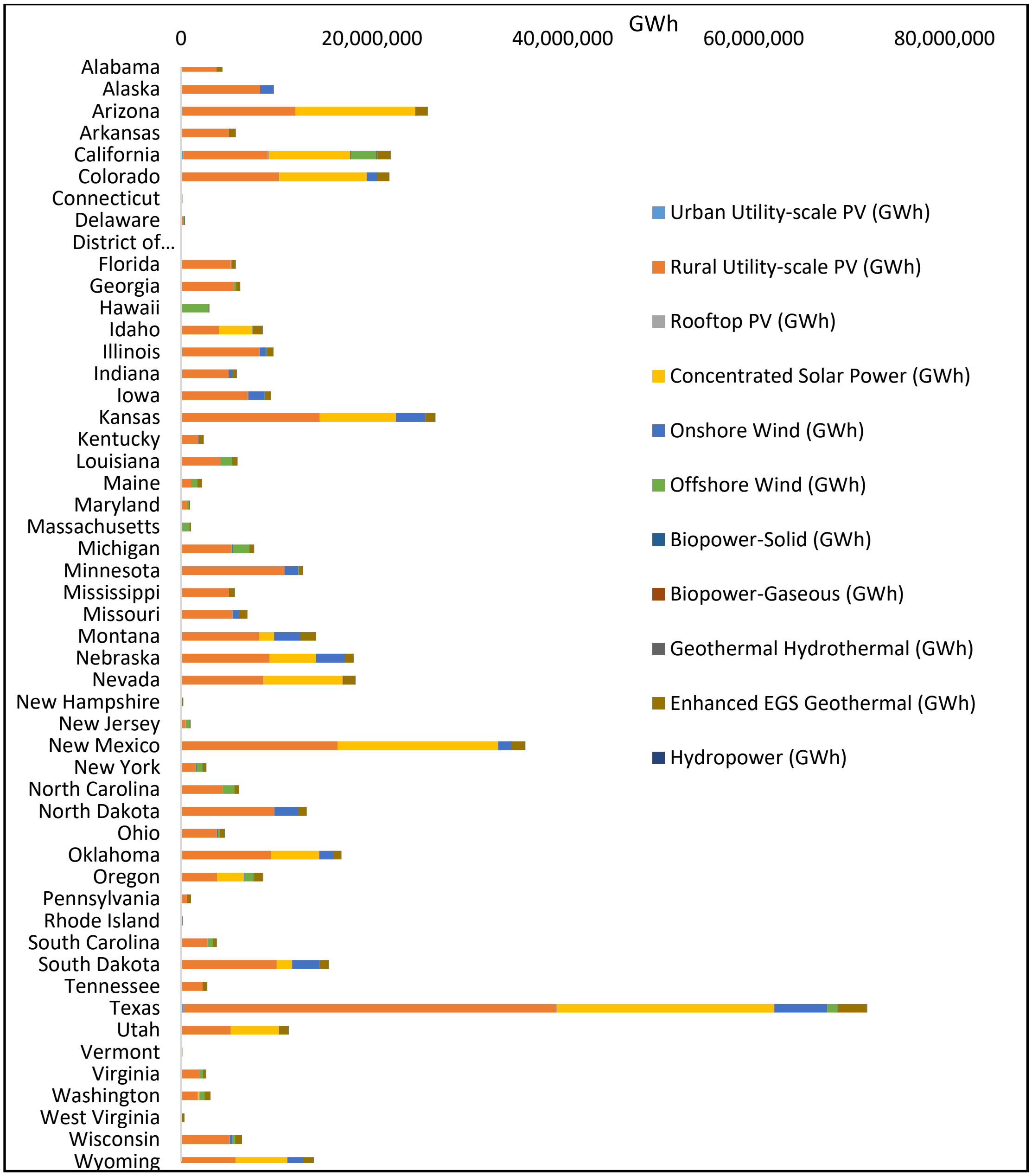
The significantly positive results for wind and solar in the SAR specification suggest the existence of the spatial spillover effects of the RPS, implying that RPS impacts are enhanced if the policy is adopted in a state and its neighbors. As results by sources of renewable energy are significantly positive only for solar and wind (which often receive greater attention in the RPS targets across states), RPS policies may also become more successful if the RPS mandates are tailored with bespoke policy specifications for each renewable source. However, to adequately contextualize these broader implications, it should be noted that the technology specific (i.e., renewable energy source) estimates in this study are based on aggregate RPS attributes for individual states (since RPS mandates by each renewable source were not available). Nevertheless, the results across the specifications can provide insights into the challenges of implementing renewable energy technologies into efficient energy production system.

[redacted] Background

Multi-dimensional challenges facing the present-day energy sector, namely climate change, energy security, energy resource sustainability and market stability have contributed to increased interest in renewable energy (Dincer, 2000; Jacobson, 2009; MacKay, 2009; Zerta et al., 2008). Renewable resources that translate into renewable electricity potentials in the US are substantial, to accommodate the growing demand for energy services. For example, Mai et al. (2014) estimate that existing renewable energy technologies could supply 80% of total electricity demand in the US by 2050. Figure 2.1 illustrates the technical potential of renewable electricity across states: utility-scale photovoltaics (urban and rural), concentrating solar power, onshore wind power, offshore wind power, biopower, and enhanced geothermal systems. Despite this high technical potential, the renewable energy sector is in its early stages of maturity regarding commercialization (e.g., cost competitiveness) in competitive energy markets. While the renewable energy sector has been expanding in recent years (see Figure 2.2), the market share of non-hydro renewable electricity generation was only 7% in 2015 (EIA, 2016). Still, it is important to note that social preferences for (and the economic prospects of) renewables, which are critical for their penetration in energy markets (Wüstenhagen et al., 2007), continue to increase (Borchers et al. 2007; Hansla et al. 2008; Roe et al. 2001;

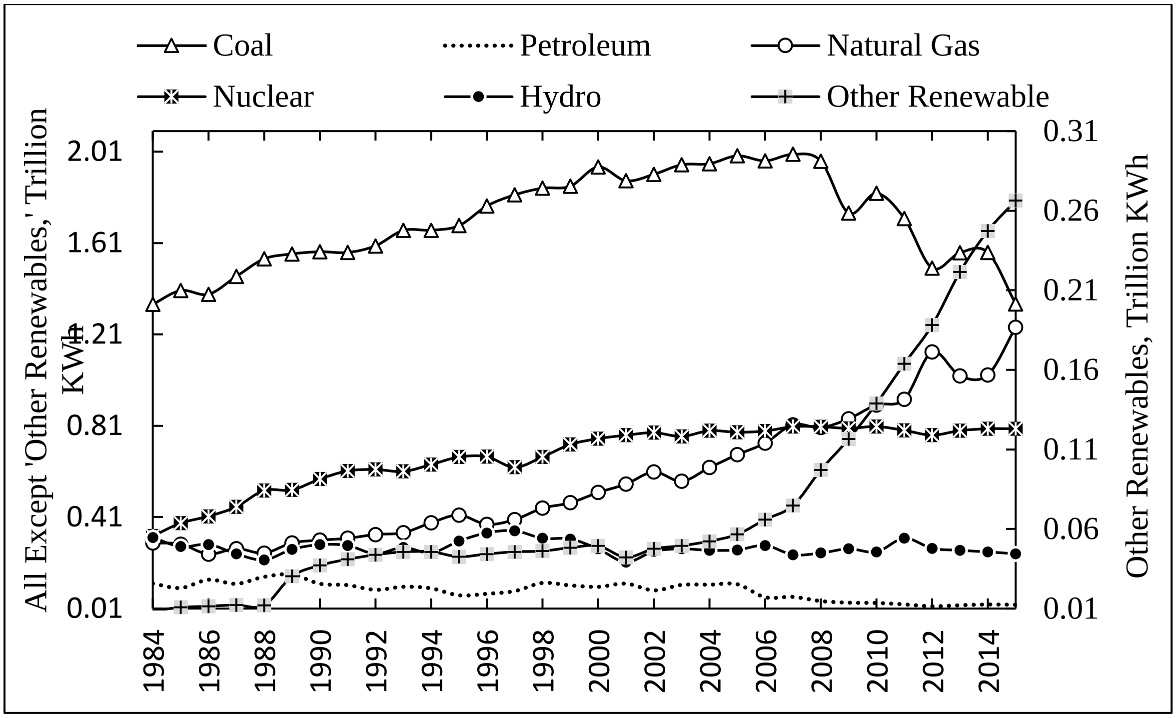
Sundt and Rehdanz 2015). This can be exemplified by the fact that non-hydro renewable generation (7%) has recently surpassed traditional hydroelectricity (6%) (EIA, 2016).

Figure 2.1: Renewable energy technical potential distribution by state



Data Source: National Renewable Energy Laboratory (NREL): Lopez et al., (2012)

Figure 2.2: Electricity generation by different source in the US:1984-2015



Data Source: US Energy Information Administration (2018b)

Despite the recognized potential of renewable energy services in addressing myriad environmental and energy security concerns, the renewable energy sector faces various barriers to its advancement. High production (upfront costs) and distribution costs (transmission infrastructures), coupled with technological challenges are among the primary obstacles to accelerating the growth of renewable energy (Menanteau et al., 2003; Painuly, 2001). The lack of a fully developed market for environmental goods and services (e.g., markets for air quality) also acts as an institutional constraint on the renewables sector. The absence of market institutions for environmental commodities has contributed to the negative externalities associated with fossil fuels to proliferate, which, in turn, impedes bringing down the high upfront costs of the newer renewable technologies. That is, technological innovations to advance the transformation of the renewable industry require substantive financial incentives. Thus, the market failures created by prevalent negative externalities in the energy sector justify the significance of appropriate policy interventions (e.g., adoption and execution of precisely engineered policies) in the energy market (Gillingham and Sweeney, 2010).

These contexts of changing energy sector challenges have led to extensive discussions, at both the research and policy level, from different perspectives (e.g., advancing cost competitiveness of renewable energy technologies or leveraging supporting policies) to generate financial incentives to attract investment in renewable energy projects. Several federal and state policies have been adopted to promote the renewable energy sector in the US and around the world. Such policies can be broadly categorized as; (i) command and control, (ii) market based incentives, (iii) voluntary goals and (iv) hybrid policies(US Environmental Protection Agency, 2010). Federal and state level governmental entities in the US continue to experiment and advance policies to incentivize the expansion of renewable energy capacity through taxes, subsidies, grants, loans and other market safety provisions (e.g., federal renewable energy production tax credits, federal solar investment tax credits, feed-in-tariffs, and other several state-sponsored incentives, including guidelines from the Federal Energy Management Program).

Various policies have been adopted by individual states to promote the renewable energy sector. For example, 12 states have adopted Mandatory Green Power Options (MPGO) that mandates electric utilities to provide options to consumers to purchase electricity generated from eligible renewable sources. In 41 states, net metering policies allow consumers to sell back surplus electricity to the electric grid. Among the range of such policies, RPS is one of the most crucial state level renewable energy policies in the US (Stauffer, 2017). The policy requires that utilities operating within a state supply a specified fraction of electricity from renewable sources over a specified time period. The RPS can also be voluntary in some states (voluntary RPS goals). Its mandated targets can be met through in-state, out-of-state renewable energy credits, or both.

The RPS is not federal legislation, and thus, states can act independently whether they adopt this policy or not. However, the RPS is gaining considerable interest across the US amid ongoing debates on national energy security, global warming potential and environmental damage mitigation (Rabe, 2006). In 1983, Iowa became the first state to adopt the RPS. To date, 29 states, Washington D.C., and three territories have adopted binding RPS policy. Additionally, eight states and one territory have adopted voluntary renewable energy goals.

Table 2.1 illustrates RPS attributes across states. The ‘Enactment Year’ column denotes the year when the states adopted the policy through state legislation. The third column, ‘Effective Year’ denotes the year in which binding RPS mandates went into effect. The last two columns in the table concern key RPS provisions that also vary across states: whether RPS legislation incorporates REC trading provision and whether it includes the energy conservation objectives (e.g., through the use of energy efficient appliances). As Table 2.1 shows, RPS features vary substantially across states and over time, including with respect to embedded compliance provisions.

Table 2.1: Features of renewable portfolio standard in the US

State	**Enactment Year**	**Effective Year**	**Requirement**	**REC Trading Provision**	**Energy Efficiency Included**
Arizona	2006	2006	15% by 2025	Yes	No
California	2002	2002	33% by 2020 40% by 2024 45% by 2027 50% by 2030	Yes	No
Colorado	2004	2004	30% by 2020	Yes	No
Connecticut	1998	2004	27% by 2020	Yes	Yes
Delaware	2005	2007	25% by 2025-2026	Yes	No
Hawaii	2001	2001	30% by 2020 40% by 2030 70% by 2040 100% by 2045	No	Yes
Illinois	2007	2008	25% by 2025-2026	Yes	No
Iowa	1983	1983	105 MW	Yes (since 2007)	No
Maine	1999	2000	40% by 2017	Yes	Yes
Maryland	2004	2006	20% by 2022	Yes	No
Massachusetts	1997	2003	15% by 2020 and an additional 1% each year after	Yes	No
Michigan	2008	2012	10% by 2015	Yes	Yes
Minnesota	2007	2007	26.5% by 2025	Yes	No
Missouri	2007	2011	15% by 2021	Yes	No
Montana	2005	2008	15% by 2015	Yes	No
Nevada	1997	2003	25% by 2025	Yes	Yes

State	**Enactment Year**	**Effective Year**	**Requirement**	**REC Trading Provision**	**Energy Efficiency Included**
New Hampshire	2007	2009	24.8% by 2025	Yes	No
New Jersey	1999	2001	24.5% by 2020	Yes	No
New Mexico	2002	2005	20% by 2020	Yes	No
New York	2004	2006	50% by 2030	No	No
North Carolina	2007	2008	12.5% by 2021	Yes	Yes
Ohio	2008	2009	25% by 2026	Yes	Yes
Oklahoma	2010	2010	15% by 2015	No	No
Oregon	2007	2011	25% by 2025	Yes	No
Pennsylvania	2004	2006	18% by 2020-2021	Yes	Yes
Rhode Island	2004	2007	14.5% by 2019	Yes	No
Texas	1999	2000	10,000 MW by 2025	Yes	No
Washington	2006	2012	15% by 2020	Yes	No
Wisconsin	1998	2000	10% by 2015	Yes	No

Note: Only states that have adopted mandatory RPS (excluding states that have not adopted the policy and have only adopted non-binding/voluntary renewable portfolio goals, as well as Washington D.C., and US territories).

Data Source: Database of State Incentives for Renewables & Efficiency (DSIRE) [1]

The most widely perceived benefits of RPS adoption are (i) diversifying energy portfolios, (ii) reducing fossil fuel dependence, (iii) minimizing externalities attributable to fossil fuels (e.g. GHG emissions, other air pollution and therm effluent), (iv) creating economies of scale that help mitigate the cost of renewable technologies, and (v) promoting the social acceptance of renewable energy through information spillovers (e.g., promotion of social education about the negative externalities and economic costs

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[1] http://www.dsireusa.org; accessed: 05/20/2018

of fossil fuels). The extant literature explores various determinants of RPS adoption. In the context of the environmental and economic benefits of renewable energy over fossil fuels, Rabe, (2006, 2004) points out that the economic development with employment creation via the renewable energy is a core motive for RPS adoption. Huang et al. (2007) highlight the positive roles of education, population growth, gross state product and the share of coal in electricity generation. Lyon and Yin (2010) elaborate on factors influencing RPS adoption in various aspects, for example, wind, solar and biomass potential, emissions, electricity prices, unemployment rates, farmers interests, environmental preferences, natural gas generation, and coal industry influence.

The RPS is primarily a quantity-based policy instrument (although its embedded features may also demonstrate aspects of influencing the price of renewable and other energy services) intended to increase the share of renewable electricity (i.e., changing supply) in the market. Theoretically, policy instruments based on either prices or quantities can correct market failures with the same outcome, if they are designed by appropriately accommodating the magnitude and scale of such externality driven market inefficiencies. However, the RPS is only expected to partially offset the negative externalities associated with the energy sector (Espey, 2001). The reasons for this are twofold: (i) the RPS only targets electricity sector of a broader energy economy, and (ii) the RPS often mandates a certain percentage (i.e., not 100%) of renewable electricity.

Nevertheless, the RPS continues to proliferate in terms of both its coverage and targets across states and those states which were early adopters have been revising RPS designs, often by increasing the mandates. Consequently, the twofold aspects (with respect to the partial RPS contributions in abating negative externalities of the fossil fuels), again, results in the twofold implications. First, renewable electricity, which is expected to minimize the environmental externalities and energy security risks, takes time to mature. In this way, the complete transition is considered long-run feasibility. Second, it helps to minimize the pre-existing energy sector externalities in the near term, with the subsequent efforts of increasing the share of renewable electricity in the market.

[redacted] Electricity Market and RPS

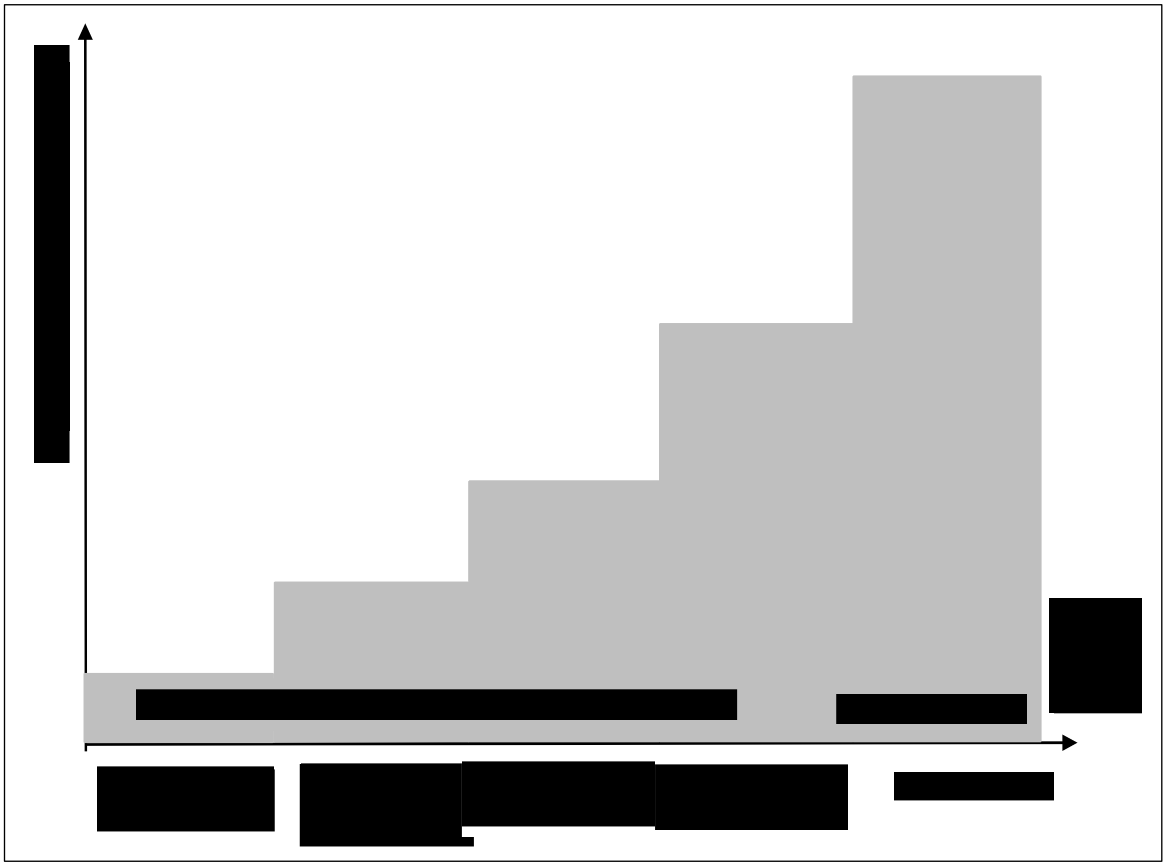
Electricity suppliers aim at maximizing profits (or minimizing costs) while maintaining reliable supply to meet real-time demands for electricity. The reliable supply contributes to both securing consumer interest and maintaining electric infrastructure stability. Electricity generation cost (e.g., average operating cost or fuel cost) and estimated demand at each point in time (e.g., peak hours) influence the choice of the fuels by the electric firms to dispatch the electricity. More specifically, fuel choice is guided by consideration of average costs and the reliability of such sources to meet consumer demand. Electric firms should be able to predict the demand structure at a given point in time, where demand fluctuates across the hours in a day (e.g., peak hours) and over different seasons in a year). Electric firms also remain cautious to dispatch electricity for unexpected demand shocks (i.e., a reserve margin).

Thus, the firm’s dispatch decision is a complex cost minimization or profit maximization problem, where additional decision making complexities stem from the fact firms may not be able to change supply as quickly as they would like even when the average cost of production is high. Types of fuel source along with heat content determine the cost of electricity production. Following cost minimization objectives, the electric firm dispatches the power plant with the lowest available average cost fuels to supply electricity. Collectively the lowest cost facilities may not be able to meet peak demand, and plants with relatively high average costs are dispatched in such periods.

Dispatch decisions (i.e., dispatch order) are primarily a function of operating costs of the power plants (average variable costs), where operating costs vary by the types of fuels that power plants use to generate electricity. The dispatch order of the power plants selected to supply electricity for base, intermediate and peak load hours of electricity demand through 24 hours in a day. That is, power plants with lowest operating costs are operated first (supplies baseload demand), and then as demand increases through different hours in a day (i.e., peak hours), power plants with sequentially higher operating costs are added in operation to meet the increased demand. Baseload electricity generators typically operate throughout 24 hours (provided that such plants have technological capability to generate electricity throughout hours in a single day). Other than the operating costs influencing the dispatch order of fossil fuel and renewable based power plants, technological constraint of intermittent generation capacity associated with renewable electricity generators and regulatory mandates of supplying a specific fraction of renewable electricity also interact in decision making system of deciding the dispatch order of the power plants.

A simplified illustration of typical electricity supply curve as a function of operating cost is illustrated in Figure 2.2. The left side of the supply curve reflects the baseload power plants, and intermediate and peak load hours appear on the right side of the curve. Solar, wind, nuclear and hydroelectric plants primarily operated to supply baseload needs. Solar and wind plants have lowest operating costs, and nuclear plants are operated as a baseload provider because of the technical and economic reasons. Coal fired power plants have been the reliable provider of baseload demand, with natural gas as intermediate and peak load provider in the past. But due to declining prices of natural gas and increasing efficiency of gas fired plants, natural gas power plants are emerging as reliable baseload providers. Power plants with higher operating costs (e.g., petroleum based power plants) are operated to meet the peak demand (right part of the supply curve).

Figure 2.3: Electricity Dispatch Curve

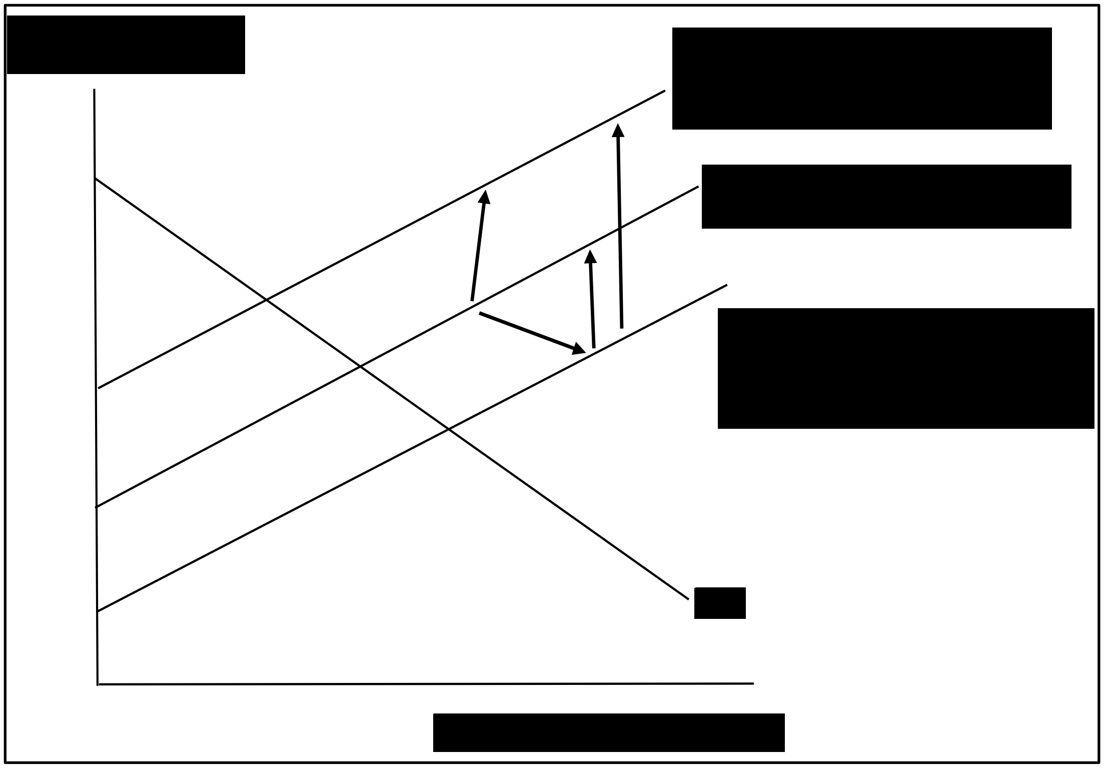


Provided the variation in supply for electricity by sources through different hours in a single day, changes in the technical capacity of renewable electricity will change the share of operational renewable electricity to meet the baseload demand, and then there will be subsequent impacts on electricity prices. Thus, there are dynamics in supply and demand of electricity in a single day. However, the objective of this research is to assess whether the RPS is contributing to the renewable electricity capacity, as whole, in the US, an illustration of change in the supply curve is analyzed due to RPS adoption below.

The North American interconnected electric grid system consists of the Eastern Interconnection, Western Interconnection, Texas Interconnection, and Quebec Interconnections. Southeast, Southwest, and Northwest represent the regional wholesale electricity market systems in the US, where several utilities operate within each region under the Independent System Operator (ISO) jurisdiction. Partial deregulation and liberalization of the electricity market have led the utilities to own the generation, transmission and distribution infrastructures, where the electric firms are vertically integrated. The electricity market attributes as represented by the synchronous interconnection systems illustrates regional structure of the electricity market (e.g., electricity produced anywhere by using any fuel sources are likely to be connected in the interstate transmission systems). The electricity generation and installed nameplate capacity are expected to move in the similar direction where higher nameplate capacity allows to generate more electricity.

Based on the foregoing discussion on the economic and environmental layers as the diversifying features of RPS policy across states and time, the question arises to whether and how the RPS contributes to renewable electricity capacity. Following Fell et al. (2012), Figure 2.3 illustrates theoretical potentials of RPS impacts as exogenous policy shock on electricity supply within a simplified electricity market conceptualization.

Figure 2.4: Supply of electricity and RPS

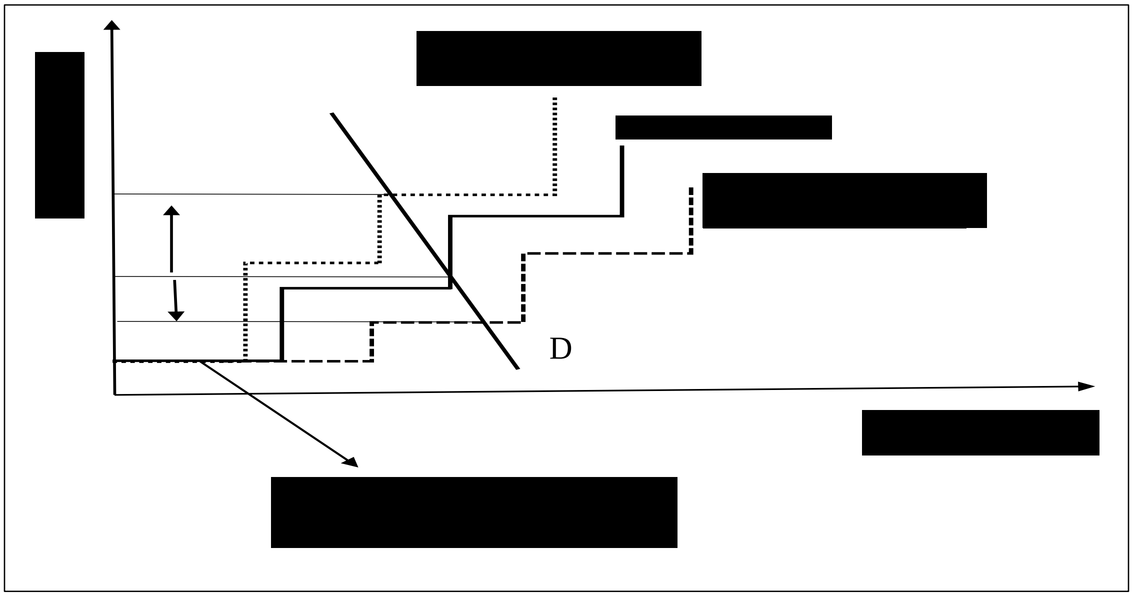


Therein, assume that there is no RPS policy and that the electricity market is in initial equilibrium at the intersection of D (demand for electricity) and S_1 (supply of electricity). If an RPS enters into effect, then the electricity producer needs to supply mandated fraction of renewable electricity in its total retail sales. Following the theory of producer behavior, the supply curve (exogenous shock) shifts left, (say, to S_3 level), *ceteris paribus,* when RPS is simply considered a command and control policy instrument (equivalent to implicit tax to electricity suppliers). The electricity supplier may meet the required fraction of renewable electricity through self-production, REC purchase or purchase from independent producers, and the resulting economic burdens are equivalent to the concept of an implicit tax to the fossil fuel based electricity producer (Fell et al., 2012). This is because fossil fuel based electricity generation (due to implicit tax, resulting from complying with RPS mandates) becomes expensive, thereby producers may follow declined economic incentives (i.e., implicit tax provision discourages investment in fossil fuel based electricity capacity) by reducing production.

However, RPS represents more than just a command and control policy instrument: embedded features of the RPS also include REC provision, mimicking features of the incentive based policy instruments. The renewable electricity producer (renewable electricity producers can be either an independent producer or the utilities themselves or both) receives credits for each MWh generation of renewable electricity (equivalent to an implicit subsidy for renewable energy projects). Because of such financial incentives (i.e., implicit subsidy), *ceteris paribus*, renewable electricity generation increases and this will shift the electricity supply curve to the right (even when fossil fuel electricity generation remains constant), where a new market equilibrium may occur at the initial equilibrium level (D and S_1) or even farther at the intersection of D and S_2 (the magnitude of these changes in supply depends on the economic costs of implicit tax provision, economic benefits of implicit subsidy provision or both).

Following the preceding discussion on dispatch order (Figure 2.3) and shifts in linear electricity supply curve due to RPS effects (Figure 2.4) can be mapped through the merit order effect as illustrated in Figure 2.5. Explanation on shifts in the supply curve is analogous to the preceding discussion. RPS may generate different dynamics to shift the supply curve in different directions (as discussed before), simplistic analysis of the merit order effect is provided in the context of shifts in the supply curve from S_1 to S_2 or S_1 to S_3. If dispatch of renewable electricity capacity increases due to the RPS effects, the supply curve shifts right (increased share of renewables in the baseload reduces the share of fuels in electricity supply) and market clearing price of electricity will decline (declined price due to shifts from S_1 to S_2). Similarly, if RPS disincentives renewable energy projects, the baseload share of renewable electricity will decline and the supply curve will shifts if S_1 to S_3 (indicating an increase in market clearing price of electricity). Regardless of changes in market clearing electricity prices, Figure 2.5 shows the marginal costs advantage of renewable power plants, which can help offset their high fixed costs.

Figure 2.5: Electricity market and RPS with merit order effect



[redacted] Related Literature

The related literature can be discussed under two broad categories: factors motivating RPS adoption by states and impacts of the RPS on renewable electricity development. In terms of the former, there are few studies pointing out the determinants of the adoption of state-level renewable energy policies. In the context of the environmental and economic benefits of renewable energy over fossil fuels, qualitative work by Rabe (2006, 2004) illustrates that economic development in general and employment creation more specifically are the key drivers of RPS adoption by states.

Based on the case studies by Rabe (2006, 2004), Huang et al. (2007) conducts a quantitative analysis, configuring a logit model to explain the probability of a state adopting RPS as a function of state specific social, economic and environmental characteristics. Their results suggest that education, population growth, gross state product, political beliefs and share of coal in electricity generation are significant determinants of RPS adoption. Lyon and Yin (2010) extend such previous studies more comprehensively by incorporating additional explanatory variables namely wind, solar and biomass potential, emissions from electricity generation, electricity price, unemployment rate, farmers interests, environmental preferences, natural gas generation and coal industry influence. Consumers' consciousness to a range of environmental concerns (e.g., local issues, such as air pollution and water contamination) are also among the significant factors of affecting RPS enactment at the state level (Matisoff, 2008; Stauffer, 2017).

The extant literature is exceptionally thin in specifically evaluating RPS policy effectiveness with robust estimation techniques. Some studies explain, in part, that the

RPS impacts a diverse number of areas (e.g., impact on prices of electricity and natural gas) (Beck and Martinot, 2004; Delmas and Montes-Sancho, 2011; Lyon and Yin, 2010; Palmer and Burtraw, 2005; Upton and Snyder, 2015). The previous focus of RPS studies has either in terms of evaluating a range of the policies (e.g., see Palmer and Burtraw, 2005) or policy impacts vis-à-vis single renewable energy source (e.g., wind in Adelaja et al., 2010 and Menz and Vachon, 2006). The literature also lacks a nuanced comparative analysis of the impacts of RPS policy attributes on different types of renewable technologies. While such studies remain scant, variations across the closely related studies regarding the data, methods, coverage of study region and results exist. Moreover, the primary focus of much of the extant studies appears to examine the impact of the RPS on electricity generation from alternative fossil fuels (e.g., Palmer and Burtraw, 2005; Palmer et al., 2011 and Upton and Snyder, 2017) or renewable sources (e.g., Carley, 2009; Carley et al., 2016 ; and Yin and Powers, 2010), and on installed renewable electricity capacity (e.g., Kneifel, 2008; Shrimali and Kniefel, 2011;). The following paragraphs elaborate the closely related literature in the filed in detail, and summary of these studies are presented in Table 2.2.

Table 2.2: A survey of previous empirical studies

Authors	**Objectives**	**Data**	**Methods**	**Results**
Upton and Snyder, 2017	Effectiveness of RPS on renewable energy generation.	Panel data for 49 states in the US.	Panel model	RPS is not effective in increasing renewable electricity generation.
Carley et al., 2016	Effectiveness of RPS and feed-in tariff (FIT) on renewable energy.	Panel data for 164 countries.	Unbalanced Panel model	RPS and FIT are effective in increasing renewable power generation. They also find that increasing renewable energy generation doesn’t always imply shifting away from fossil fuels.

Authors	**Objectives**	**Data**	**Methods**	**Results**
Shrimali and Kniefel, 2011	Effectiveness of RPS and other renewable energy policies in the US	Panel data (1991-2007) from different sources, (e.g., EIA, union of concerned scientist, DSIRE, etc.)	Panel model	RPS has negative impact of renewable electricity capacity.
Dong, 2012	Relative impact of FIT vs. RPS on wind power development.	Panel data for 53 countries.	Panel model with various scenarios.	FIT is relatively more effective than RPS.
Yin and Powers, 2010	Impact of RPS design on in-state renewable electricity investment.	Panel data from different sources, (e.g., EIA, union of concerned scientist, DSIRE, etc.)	Panel fixed effect model controlling for state and year heterogeneity:	Aggressive RPS creates weak incentives while moderate RPS creates strong incentives for in-state renewable power generation. Overall effectiveness of RPS for in-state green power generation is found positive and significant, but renewable energy credit program can weaken RPS effectiveness.
Lyon and Yin, 2010	Empirical analysis of the political and economic factors that drive state governments to adopt an RPS, and the factors that lead to the inclusion of in-state requirements given the adoption of an RPS.	Panel data from different sources (e.g., EPA, EIA, US, Census of Agriculture, etc.) in the US	Binomial (RPS=1 OR 0) and multinomial probit model (no RPS, an RPS with in-state requirements, or an RPS without in-state-requirements)	State attributes such as political ideology and private interests are major reasons for the adoption of RPS than the reasons of local environmental and economic benefits.
Adelaja et al., 2010	Impacts of RPS on state wind power development.	Various sources such as EIA, NREL, American Wind Energy Association, US Census etc.	Cross-section OLS method	RPS adoption significantly increases state wind power development.
Carley, 2009	Effectiveness of RPS to promote renewable power.	Various sources	Panel fixed effect model- fixed effect vector decomposition method.	RPS does not increase the percentage share of renewable power out of total power generation, but it contributes to total renewable power development.
Kneifel, 2008	Impacts of multiple state policies such as RPS and mandatory green power options on renewable electricity.	Various sources such as EIA, League of Conservation Voters, Clean	Panel fixed effect model	Multiple state policies are found to have significant impact on renewable power development.

Authors	**Objectives**	**Data**	**Methods**	**Results**
		Energy States Alliance etc.		
Menz and Vachon, 2006	Impact of state level policies such as RPS, mandatory green power option (MGPO) and public benefit funds (PBF) on wind power development.	Various sources (e.g., American wind association, DSIRE, etc.)	Cross-section OLS method:	Positive impact of RPS, and MGPO while PBF and RET have negative impacts on wind power development.

A study by Menz and Vachon (2006) is one example to illustrate the focus of previous studies on one specific renewable technology for the range of energy policies. This study illustrates the impact of state level policies, (e.g., RPS, mandatory green power option (MGPO), public benefits funds (PBF) and retail choice (RET)) on wind power development by using a cross-sectional OLS method. Their sample contains data from 37 states in the US and A wind development index (WDI) is constructed as the dependent variable. With these modeling strategies, Menz and Vachon (2006) conclude that RPS and MGPO (PBF and RET) contribute positively (negatively to wind power development. Following empirical framework of Menz and Vachon (2006), Adelaja et al. (2010) provide an extension on the empirical model with the inclusion of broad state-specific socio-economic characteristics along with RPS stringency. They find the similar results. More specifically, the RPS is effective in increasing the share of installed wind capacity. However, Adelaja et al. (2010) conclude that the impact of the RPS percentage mandates is insignificant and the mandates with longer time periods have a negative impact on wind power development.

Another example representing the diversity in methods and objectives is Palmer and Burtraw (2005). Palmer and Burtraw (2005) use a Haiku electricity market model (i.e., a simulation of regional electricity markets and inter-regional electricity trade) to assess the cost effectiveness of RPS, and other energy policies in the US. They find that RPS adoption raises electricity prices, reduces generation, and reduces emissions. These trends become more pronounced as RPS stringency increases. The results of Palmer et al., (2011) concur with the findings in Palmer and Burtraw (2005).

Few studies show a link to the evaluation of the RPS impact on renewable energy generation. Delmas et al. (2007), with the core objective of studying the impacts of economic deregulation on firm strategy and environmental quality using a pooled OLS method to utility level data spanning 1998-2000, controls the RPS as one of the exogenous variables. Their results suggest an insignificant impact of the RPS on annual changes in the percentage of renewable electricity generation.

Kneifel (2008) and Carley (2009) exemplify the case where the focus is on several energy policies. Kneifel (2008) evaluates the effectiveness of different state level policies (e.g., RPS, MGPO, clean energy fund) on renewable electricity generation capacity using a panel fixed effect model at the state level for the period 1996-2003. The results reveal that the RPS, and other state level policies (e.g., MGPO, clean power fund) contribute positively to non-hydro renewable generation. In a similar study, Carley (2009) analyzes data from 1998-2008 in the US and finds that the RPS increases the total generation of renewable electricity, but its impact on the share of renewable electricity generation is not significant. Thus, differences in the data, methods, and coverage of the study regions appear to lead to differences in estimates of RPS impacts, as seen in Palmer and Burtraw (2005), Delmas et al. (2007), Kneifel (2008), Carley (2009) and Bowen et al. (2015). Delmas and Montes-Sancho (2011) provide another variation in the data, methods and results. Delmas and Montes-Sancho (2011) evaluate the effectiveness of the RPS and the MGPO at the utility level in the US from 1997-2007, using a two-stage Heckman selection model. They conclude that the RPS has not stimulated renewable energy investments.

Thus, together, these preceding studies, can be summed up in two respects: (i) The extant body of literature is limited and (ii) those studies which are available suggest that differences in data, methods, and scope appear to lead to different, potentially artefactual, estimates of RPS impacts. Even the most closely related studies to the current investigation are found to focus primarily on examining the role of the RPS in affecting renewable electricity generation, where the intermittent nature of renewable electricity may not adequately capture actual advances occurring in the renewable electricity sector. Most of the existing research in the context of the US uses time series or panel econometric methods to data exhibiting limited heterogeneity in terms of policy attributes and electricity metrics. Furthermore, thus far there has been insufficient attention to robustness, i.e., the methodological, identification and empirical strategies necessary to valid estimates. As such, this study makes several contributions in terms of (i) adding important empirical evidence by using the most recent data, in the context of a lack of uniform estimates in the previous studies, (ii) incorporating real RPS obligations over time and across states as an advance on previous studies which have interpolated such data, (iii) evaluating the comparative effectiveness of RPS designs for a variety of renewable technologies and (iv) adopting a nuanced identification strategy in empirical estimation, along with a suite of robustness checks.

[redacted] Estimation and Hypotheses

2.5.1 Empirical Identification Strategies

The first step in the identification process involves defining the unit of the individual data observations. This study selected state level data as the unit of the data observations, because: (i) plant level microdata could have been more ideal for the microeconomic analysis, but the RPS (which is the variable of primary interest in this study) is a state level variable; and (ii) the independent variables can only be observed at the state level, as the study aims to examine the state attributes (e.g., whether the state adopts the RPS and state level socioeconomic attributes) on renewable energy development.

A selection of the appropriate methods of estimation that fit the data distribution is critically important. The fixed effect model is selected to account for the potential endogeneity running from the specification side. To deal with the cross-sectional dependencies (i.e., the heteroskedasticity and autocorrelation problems), the Generalized Least Squares Fixed Effect Model with Panel Corrected Standard Errors (GLSGLSPCSE) Method is applied. The GLSPCSE relaxes the assumption of independent and identically distributed disturbances by allowing the heteroskedasticity and contemporaneous correlations across the panels and autocorrelation within the panel (Beck and Katz, 1995; Hoechle and others, 2007). The strong finite sample properties of the GLSPCSE estimator for the panel with large time dimension (Hoechle and others, 2007) also justifies its fit in this research.

The GLSPCSE estimates are compared with the estimates from the model using the spatial Durbin model (SDM) and spatial autoregressive model (SAR) (Belotti et al.,

2016) for additional robustness check[2]. The spatial econometric models simultaneously estimate the model parameters by controlling for spatial dependencies (with a spatially weighted lag of the endogenous variable and spatial weighted exogenous variables as covariates) and the unobserved heterogeneity (Lee and Yu, 2010). The standard errors in the spatial estimation are clustered at the state level to account for the potential correlations of observations within and across the states. In addition to the robustness checks, the SDM estimates also illustrate the spillover effects in the neighboring states on the dependent variable of the exogenous shocks, with respect to the covariates. If the coefficients in the SAR and SDM are positively significant, they are interpreted as having positive spillover effects in promoting renewable energy development, (while negatively significant coefficients imply declined spatial effects).

Endogeneity caused by potential reverse causality can pose a potential problem to the estimate's efficiency (e.g., simultaneity bias). The primary variable of interest in this study is the RPS attribute across the states. Provided that the environmental concern often drives the adoption of the renewable energy policy, the variables representing the RPS attributes are exogenously determined. Other covariates specified in this study include the median household income, number of electricity consumers and the attributes representing the League of Conservative Voters (LCV) scores, all of which are exogenous to the renewable electricity production. For instance, the median household

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[2] I also performed a robustness check using the two-part model. As the dependent variable is semi-continuous in nature, with non-negative values, the dynamic two-part model estimates both the dynamic discrete choice model (e.g., logit model) and the generalized linear model (GLM) simultaneously. The logit model defines the dependent variable as one if the variable observations are greater than zero. All zero observations have zero output. The GLM is only performed for the observations which are greater than zero. The estimates from the dynamic two-part model were consistent with the findings from the GLSPCSE and the SAR.

income may drive the variation in renewable energy production, but the opposite situation may not occur. The LCV scores may also reflect the variation in renewable energy production, but the renewable electricity generation may not change public attitudes itself. This investigation also uses these estimation techniques under various randomized sub-samples to examine additional robustness of the estimates. More precisely, the states are separated into treatment (states that have adopted RPS) and control (states that have not adopted the RPS policy) groups to generate a rigorous quasi-experimental inferential design to apply the difference-in-difference (DID) econometric techniques to evaluate the policy effectiveness. The treatment and control groups are also allowed to vary across states and time (this setting allows to apply generalized DID techniques for inference).

2.5.2 Econometric Specifications and Hypotheses

2.5.2.1 Dependent Variable

Renewable energy development can be represented by two variables: (i) installed nameplate capacity, representing the investment trends in renewable electricity, or (ii) actual generation, which is a subset of the nameplate capacity (e.g., actual generation cannot exceed the nameplate capacity). From the empirical point of view, the two variables can be adjusted in a variety of ways to better examine the research objectives: annual total, annual change, annual ratio of renewable electricity capacity to total electricity capacity and annual ratio of renewable electricity capacity to conventional electricity capacity. As the RPS mandates the electricity suppliers to mix a certain percentage of renewable electricity in the market, the variable representing the annual ratio of the installed capacity of renewable electricity (known as the installed nameplate capacity) to the total installed electricity capacity, best fits in the case of the primary research objectives of this research. This is because the RPS often mandates renewable generation from new facilities (Yin and Powers, 2010), reflecting newer investment in the renewable capacity development.

2.5.2.2 Defining RPS Design

As RPS is a mandatory policy, the policy instrument is expected to contribute to investment in the renewable electricity production from a mix of renewable sources. The structure of the policy is mandatory. However, some states also offer financial incentives to minimize market constraints (e.g., high prices of renewable electricity), while others do not. The policy sets a specific percentage of renewable electricity to be supplied to the consumers over the specified periods of time.

The states act independently from the federal government, in terms of whether they adopt an RPS. Hence, the different RPS adoption date terminologies require explicit distinction in the empirical work. If any state chooses to adopt an RPS, it starts with the enactment of the RPS legislation, including information on the effective date of the implementation of the policy. Thus, there can be a gap between the date of the RPS enactment as law in the state and its actual implementation date (i.e., RPS effective date). The literature lacks a well-defined discussion on these issues in the empirical analyses. As a result, it is likely that some (if not all) of the previous studies may have accounted for the RPS enactment date, rather than the actual effective date. As such, the estimated results for policy effectiveness are likely to be biased (e.g., due to measurement errors). To avoid the effects of this ambiguity, this study considers the actual compliance dates (i.e., effective dates) of the RPS. The binary variable, RPS is defined as: (i) ‘1’ when it represents the years where RPS compliance went into effect in the state, (which varies spatially across the states, and temporally within and across the states), and (ii) ‘0,’ else.

Annual or incremental obligations (say, nominal obligations), the age of the policy and the provisions of renewable energy certificates are important features of the RPS (Shrimali and Kniefel, 2011; Yin and Powers, 2010). The weak market power (reflecting the economic competitiveness in the energy market), due to the relatively high production costs of the renewable energy, cannot attract autonomous investment in the nameplate capacity installment in the absence of proper policy intervention. The nominal obligations to be met annually plays a vital role in meeting the overall RPS targets over a specified time period. The nominal RPS obligations (MWh) are defined as annual RPS compliance to be met by the electricity industry before the application of alternative compliance payments, credit multipliers and compliance waivers. As a continuous variable, the variable, OBL is defined to represent the nominal RPS obligation in MWh.

Different states have designed some alternative provisions that allow the utilities to have some flexibility to meet the RPS compliance. Provision of a renewable energy certificate (REC), as an alternative method of complying with the RPS goal, is popular in most of the RPS states. Each MWh of renewable electricity generated by a qualified technology receives one REC. The electricity supplier can purchase the required amount of REC from the market to meet the RPS compliance. RPS policy design also differs by states in terms of the nature of the REC provisions (e.g., REC must be generated within the state border or generated in any state). The market-based REC can help boost renewable generations, as the incentives allow the technically potential capacity to optimally be exploited. The binary variable, REC is defined as: ‘1 if REC is part of the

RPS and 0 otherwise'. REC may also deter the in-state production of renewable electricity if the RPS allows the utilities within the state to purchase the REC that is generated anywhere (i.e., in other states). Some states (e.g., Hawaii, Iowa, California) do not have REC provisions in the RPS, while others who have REC provisions may require the REC to be generated within state borders or provide financial incentives to the in-state generated REC. Following Yin and Powers, (2010), the binary variable, say REC_DEGREE, is defined as (i) '1' if the time varying restrictions indicate the scenario where REC either is generated within the state borders or is not allowed as the alternative compliance, and (ii) '0' for all other states which do not discriminate between in-state and out-of-state generation. Thus, REC_DEGREE is designed to motivate the in-state generation of renewable electricity, while the restrictions may reverse such expectations.

Some states (e.g., North Carolina, Connecticut, Maine) also allow energy efficiency achieved from the fossil fuel based electricity to fulfill some RPS requirements. Such provisions help meet the goals of achieving energy security and minimizing environmental externalities (e.g., air pollution, GHGs emissions). However, the efficiency provisions are not expected to contribute to renewable energy development. The binary variable EFF is defined as: '1' if it is representing those states that have energy efficiency as a part of RPS, and '0' if it is representing states that exclusively disassociate an energy efficiency policy from the RPS design. The variable AGE denotes the number of years since each state implemented the RPS. It is expected that the older RPS will positively contribute to renewable electricity development.

2.5.2.3 Other Control Variables

RPS policy design and the additional variables, representing the state specific socioeconomic and environmental attributes, can be considered the primary drivers of renewable energy development in the state. Environmental preferences and the earnings of the consumers, along with the number of electricity consumers in the state, are likely to influence the state's investment in renewable energy.

To control for state environmental preferences, this study uses the League of Conservative Voter (LCV) index, represented by two categories: Senate and House of Representatives members. The LCV is an index with a value ranging from 0 to 100 for both the Senate and House of Representatives members, representing the environmental preferences of each. If the LCV is closer to 0, there is a lower preference for a clean environment in the state, while the LCV closer to 100 represents the scenario where the preferences for a clean environment are higher (0 represents no preference and 100 highest preference for the green economy). HOUSE denotes the LCV scores of the House of Representatives, while SENATE denotes the LCV scores of the senators.

The number of total electricity consumers in each state is taken into account in the CONSUMER variable. It is expected that CONSUMER explains the variation in the renewable energy development in the state. The prior expectation about the sign of such impacts cannot be made, based on the number of electricity consumers in the state. This is because there can be a scenario where the increased electricity from the additional consumers may come from fossil fuel fired generators (either fully or in a larger proportion).

To capture the economic attributes of the states, the median income (in 2014 US dollars) of the households in each state was used (denoted by INCOME). INCOME data were compiled from the US Census. Previous studies also controlled for the emissions of CO_2 (carbon dioxide), SO_2 (sulfur dioxide) and NO_x (Nitrogen Oxide). These are the major pollutants emitted in the electricity generation process from the fossil fuel based power plants. These variables are omitted in this study, because reverse causality (i.e., endogeneity) exists between environmental emissions and electricity production (or the electricity production explains the variation in emissions rather the emissions driving the production).

Other important regulatory and financially incentivizing policies in the renewable energy sector in each state may also play a vital role in driving renewable energy development. Several of these policies are available at the state level. The two that were considered the most important include: Mandatory green power options (MGPO) and net metering (NETMET).

2.5.2.4 Econometric Specifications

Equation (1) shows a generic econometric specification to estimate the impact of RPS attributes on the share of renewable electricity capacity of total electricity capacity:

$$Y_{it} = \varphi + \gamma_j POLICY_{ijt} + \delta_k X_{ikt} + \mu_t + \sigma_i + \epsilon_{it} \dots\dots\dots\dots..(1)$$

where, $Y_{it}$is the share of non-hydro renewable electricity capacity of total electricity capacity, $POLICY_{ijt}$ (j=1,2, 3, 4, 5 and 6, is the index, respectively denoting RPS, OBL, AGE, REC, REC_DEGREE, EFF) is a vector of RPS attributes, X_{ikt} (k=1,2,3,4,5 and 6, is the index, respectively denoting, $MGPO$, $NETMET$, $INCOME$, $HOUSE$, $SENATE$, $CONSUMER$) is the vector of control variables, φ is the intercept term, $\gamma_j$and δ_k are the vectors coefficients for $POLICY_{it}$ and X_{ikt} respectively. μ_t is the set of time dummies (representing year fixed effect), σ_i is time invariant state fixed effect (representing unobserved heterogeneity across states), and $\epsilon_{it}$is the idiosyncratic random component.

Four alternative hypotheses are proposed to reach the robust conclusion regarding the impacts of RPS attributes on each renewable technology. They are presented below.

Hypothesis I: The RPS adoption increases the renewable electricity capacity. The econometric specification is specified in equation (2) to test this hypothesis.

$$Y_{it}^{RE} = \varphi + \gamma_1 RPS_{it} + \delta_k X_{ikt} + \mu_t + \sigma_i + \epsilon_{it} \dots\dots\dots\dots..(2)$$

Where, Y_{it}^{RE}denotes total installed renewable electricity capacity across states over time and hypothesis I states that $\gamma_1 > 0$.

Hypothesis II: The RPS adoption increases the share of renewable electricity capacity of total electricity capacity. Equation (3) is the econometric specification to test the hypothesis II.

$$Y_{it} = \varphi + \gamma_1' RPS_{it} + \delta_k X_{ikt} + \mu_t + \sigma_i + \epsilon_{it} \dots\dots\dots\dots..(3)$$

Hypothesis II states that $\gamma_1' > 0$.

Hypothesis III: The RPS policy attributes positively contribute to the shares of renewable electricity capacity of total electricity capacity for each renewable technology (wind, solar, biomass and geothermal). The econometric specification is specified in equation (4) to test the hypothesis III.

$$Y_{ist} = \varphi + \gamma_{js} POLICY_{ijst} + \delta_{ks} X_{ikt} + \mu_t + \sigma_i + \epsilon_{it} \dots\dots\dots\dots..(4)$$

Where, index ‘s’ denotes the installed electricity capacity from solar, wind, biomass and geothermal, and Y_{ist} is the share of each ‘s’ of total installed electricity capacity. The vector, $POLICY_{ijst}$ denotes the heterogeneous RPS attributes across states over time, which are OBL, AGE, REC, REC_DEGREE, EFF. Hypothesis III states that $\gamma_{js} > 0 \; \forall \; s$.

Hypothesis IV: hypotheses III hold when spatial effects are included. That is, the combined effects of RPS in a state and neighboring states exert positive impacts on the shares of renewable electricity capacity of total installed electricity capacity of the state. The SDM specifications for each scenario are defined as:

$$\left.\begin{array}{l} Y_{it}^{RE} = \varphi_1 + \rho\omega Y_{it}^{RE} + \gamma_{11} RPS_{it} + \delta_{1k} X_{ikt} + \emptyset_{1k}\omega(RPS_{it} + X_{ikt}) + \mu_t \\ Y_{it} = \varphi_2 + \rho\omega Y_{it} + \gamma_{21} RPS_{it} + \delta_{2k} X_{ikt} + \emptyset_{2k}\omega(RPS_{it} + X_{ikt}) + \mu_t \\ Y_{ist} = \varphi_j + \rho\omega Y_{ist} + \gamma_{js} POLICY_{ijst} + \delta_{ks} X_{ikt} + \emptyset_{jk}\omega(RPS_{it} + X_{ikt}) + \mu_t \end{array}\right\} \ldots\ldots\ldots (5)$$

Where, $\mu_t = \lambda\omega\mu_t + \varepsilon_t$, ω is $N \times N$ spatial non-stochastic weighting matrix representing the distances between the neighboring states, μ are spatially correlated disturbances, and ε are independent and identically distributed (i.i.d.) errors. ρ and λ are scalers measuring the dependence of the dependent variable on the observations of the dependent variable of the neighboring states and spatial autocorrelation respectively. The specification corresponds to the SAR when the $\emptyset_{1k} = 0$, $\emptyset_{2k} = 0$, and $\emptyset_{jk} = 0$.

The first two hypotheses (i.e., Hypothesis I and Hypothesis II) are used to select the model specification following the consistency of the estimates. They also provide information about the contribution of RPS adoption on total renewable capacity or share of renewable capacity. This is done by only controlling the RPS adoption along with other control variables, while leaving the other RPS attributes (the Akaike information criterion (AIC) is also used to detect best-fitted specification). After confirming the specification, hypothesis III is introduced to break down the RPS attribute impacts by the renewable sources. The impacts of the RPS attributes are examined separately due to the potential multicollinearity bias running from the high correlations among different attributes of the RPS. Finally, hypothesis IV is designed to examine the potential spillover effects in a sense that the impacts of RPS in a state and neighboring states can have different impacts on the renewable energy development in the same state. The Result section provides estimates, coupled with interpretations of all of these hypotheses.

[redacted] Data Sources

Publicly available data were compiled from a variety of sources in this research. The sample contains the annual data for the 47 States in the US from 1990-2014. The data on the installed nameplate capacity, representing the total installed nameplate capacity from the utilities and independent producers, are obtained from the US Energy Information Administration (EIA) at the state level over the period of 1990-2014 (US Energy Information Administration, 2018e). These data do not include distributed generations. During this period, if the states did not have an installed nameplate capacity (e.g., no installed nameplate capacity for a renewable technology), such observations were instrumented by zero.

Data on RPS attributes for each state were collected from the Database of State Incentives for Renewables & Efficiency (DSIRE) (DSIRE, 2018). The supporting information (e.g., the nuances of RPS attributes) was obtained from the National Conference for State Legislators (NCSL, 2018) and the Berkeley Lab (Berkeley Lab, 2018). The LCV scores were compiled from the website of the League of Conservative Voters[3]. The CONSUMER (number of electricity consumers) data were collected from the EIA (US Energy Information Administration, 2018e). Information on MGPO and NETMET were extracted from DSIRE (DSIRE, 2018).

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[3] https://www.lcv.org/mission/, accessed 13/04/2018.

Tables 2.3 and 2.4 illustrate the definitions and descriptive statistics of RPS attributes and control variables. In the given sample, average installed renewable electricity capacity of renewable electricity (RE) is 577 MW, with standard deviations of 1,201 MW. Similar skewness in the sample exists in the variables representing the shares of renewable electricity (including the share of renewable electricity sources) of total electricity. The heterogeneity in the distributions also exists among the independent variables. For instance, when accounted for the different time periods for the effective dates of the RPS for individual states between 1990 and 2014, The RPS appears in effect in about 19% of the 47 states.

Table 2.3: Descriptive statistics for dependent variables

VARIABLE	**DEFINITION**	**MEAN***	**S.D.***
RE	Total renewable electricity installed capacity (MW).	576.788	1201.21
RE_SHARE	The share of installed nameplate capacity of renewable electricity in total electric nameplate capacity (in proportion).	0.0359	0.0498
BIO_SHARE	The share of biomass nameplate capacity in total electric nameplate capacity (in proportion).	0.0181	0.0303
SOLAR_SHARE	The share of solar nameplate capacity in total electric nameplate capacity (in proportion).	0.0008	0.0044
WIND_SHARE	The share of wind nameplate capacity in total electric nameplate capacity (in proportion).	0.0148	0.0374
GEO_SHARE	The share of geothermal nameplate capacity in total electric nameplate capacity (in proportion).	0.00211	0.0084

[*] The mean and standard deviations (S.D.) in the table represent the weighted statistics over 1990-2014 at annual interval across 47 US states. After adjusting data for outliers and missing information, the sample contains 1175 observations (OBS).

Table 2.4: Descriptive statistics for independent variables

VARIABLE	DEFINITION	MEAN	S.D.
RPS	1 if state ‘i’ has complied with RPS in time t, 0 else.	0.19	0.39
OBL	Annual nominal RPS obligations, the amount of renewable electricity, electric industries in the state are mandated to supply in total sales (in MWh).	860864	3748294
AGE	Age of the RPS since the date of compliance in state ‘i’.	0.94	2.41
REC	1 if renewable energy certificate provisions are included in the RPS, 0 else.	0.17	0.38
REC_DEGREE	1 if renewable energy certificates (REC) are restitutive to incentivize in-state REC generation, 0 else.	0.043	0.20
EFF	1 if energy efficiency is part of RPS standard, 0 else.	0.06	0.24
CONSUMER	Total number of electric customers across states.	2540371	2505029
MGPO	1 if state ‘i’ has mandatory green power options at time ‘t’, 0 else.	0.06	0.23
NETMET	1 if state ‘i’ has net metering options at time ‘t’, 0 else.	0.45	0.50
INCOME	Median household income across states over time (in 2014 US dollars).	541780	21943
SENATE	League of conservative voters representing the environmental preferences of senators in each state over time, indexed from 0-100.	50.02	33.52
HOUSE	League of conservative voters representing the environmental preferences of the house members in each state over time, indexed from 0-100.	47.40	26.940

[redacted] Results

2.7.1 Evaluating Hypotheses

Results with respect to Hypothesis , are presented in column (1) of Table 2.5. The coefficient of the RPS in the GLSPCSE model is 194, which is positive and statistically significant at the 1% level. This means that, on an average, renewable nameplate capacity is higher in RPS states by 194 MW compared to that in non-RPS states (the non-RPS states means the states in the US that have not adopted the RPS). Accordingly, Hypothesis I is accepted, stating positive contributions of the RPS on non-hydro renewable capacity.

The RPS coefficients are also positively significant at the 1% level, under SDM and SAR (see column (1) in Table 2.5), signifying the robustness of the GLSPCSE estimates and implying positive spillover effects of the RPS on the renewable electricity capacity, coupled with spatial structure of the renewable electricity capacity. That is, RPS adoption by a state (say, state ‘i’) and adjacent states (say, ‘j’ ≠ ‘i’) influences the growth of renewable electricity capacity. The existence of a positive spatial spillover effect in the case of total renewable electricity capacity leads to the acceptance of Hypothesis IV. Results concerning the impacts of the RPS on the share of renewable electricity capacity (RE_SHARE), as shown in column (2) of Table 2.5, are similar to those evaluated with respect to Hypothesis I. The RPS coefficients are positive and significant at the 1% level according to GLSPCSE, SAR and SDM. Thus, these estimates support Hypotheses II and IV.

Table 2.5: Impact of RPS on total renewable capacity and share of renewable capacity

	(1)			(2)		
	GLSPCSE	SAR	SDM	GLSPCSE	SAR	SDM
VARIABLES		RE			RE_SHARE	
RPS	193.8***	446.2***	1,715***	0.00755***	0.00755**	0.124***
	(56.76)	(54.71)	(213.5)	(0.00259)	(0.00306)	(0.0116)
MGPO	309.5***	532.5***	-1,609***	0.0308***	0.0452***	-0.0643***
	(68.85)	(88.85)	(418.4)	(0.00572)	(0.00491)	(0.0230)
NETMET	45.69	13.60	-399.9**	0.00333	0.00714***	-0.00636
	(66.88)	(45.57)	(163.7)	(0.00404)	(0.00251)	(0.00883)
INCOME	-0.000303	-0.00384	-0.0705***	1.10e-07	1.43e-06***	-4.26e-06***
	(0.00254)	(0.00436)	(0.0136)	(1.96e-07)	(2.42e-07)	(7.29e-07)
HOUSE	-0.562	-3.404***	-13.13***	-4.50e-05	-0.000320***	-0.000502**
	(0.719)	(1.129)	(3.580)	(6.47e-05)	(6.24e-05)	(0.000196)
SENATE	-0.0130	0.889	-4.527	1.22e-06	0.000104**	-0.000408**
	(0.300)	(0.793)	(2.945)	(2.18e-05)	(4.39e-05)	(0.000159)
CONSUMER	0.000649**	0.000468***	9.08e-05	1.32e-08***	-9.56e-09***	7.77e-09
	(0.000254)	(5.67e-05)	(0.000210)	(4.52e-09)	(3.13e-09)	(1.12e-08)
CONSTANT	-855.1	-	-	-0.0126	-	-
	(587.2)	-	-	(0.0150)	-	-
FIXED EFFECT	YES	YES	YES	YES	YES	YES
SPATIAL ρ	-	0.354***	0.0347	-	0.744***	0.307***
	-	(0.0601)	(0.0767)	-	(0.0591)	(0.0778)

Note: 'STATE FE' denotes state fixed effect, 'TIME FE' represents time fixed effect and 'SPATIAL ρ' denotes spatial dependencies of the residuals (or coefficient of the weighted lagged dependent variable). The TIME FE incorporated time-dummies with a five-year interval between 1990 and 2014, because the annual time effects showed the presence of multicollinearity (the estimate were also consistent with only inclusion of linear time trend). The results for SDM represent only for the spatially weighted covariates. The decimal places are not adjusted for consistency because most of the causal inferences are very small. 'YES' denotes the control of the respective variables (e.g., control for the state fixed effects), while the controlled coefficients may remain statistically significant, insignificant or both. This note applies to the relevant tables, hereafter. Standard errors are in parentheses: *** $p<0.01$, ** $p<0.05$, * $p<0.1$

The next objective of this research pertains to investigating how the nature and stringency of RPS attributes affect the shares of renewable electricity capacity by renewable sources. These sources are categorized as solar, wind, geothermal and biomass. The empirical results relevant to Hypothesis III are summarized in Table 2.6 (see the Appendix for Chapter 2, Tables A.1-A.8, for all estimated coefficients from GLSPCSE and SAR).

The results in Table 2.6 show the positively significant impacts of RPS attributes on the shares of solar and wind capacity. The results illustrate that the impact of the RPS on the share of solar electricity capacity in total electricity capacity (0.00103 MW) is about 1.3 times higher than the average share of solar electricity capacity in total electricity capacity (0.0008 MW) built between 1990 and 2014. Similarly, the impact of the RPS on wind electricity capacity in total electricity capacity (0.00975 MW) is nearly two thirds of the average share of wind electricity capacity in total electricity capacity (0.0148) between 1990 and 2014. Thus, while the impacts of the RPS on wind capacity are greater than on solar capacity, RPS driven change represents higher proportional growth in solar capacity with reference to their respective average built capacity from 1990 to 2014. The impacts with respect to the variables, OBL, AGE, REC and REC_DEGREE are also positively significant and consistent with the RPS impacts on solar and wind capacity

Table 2.6: Technology specific impacts of RPS attributes using GLSPCSE

VARIABLE	(1)	(2)	(3)	(4)
	SOLAR_SHARE	WIND_SHARE	GEO_SHARE	BIO_SHARE
RPS	0.00103*	0.00975***	-2.00e-05	-0.00229**
	(0.000622)	(0.00202)	(0.000212)	(0.000926)
OBL	4.17e-10**	1.17e-09***	-9.78e-11***	-1.70e-10**
	(2.07e-10)	(2.26e-10)	(0)	(7.20e-11)
AGE	0.00131***	0.00355***	0.000123*	0.000358***
	(0.000204)	(0.000429)	(6.76e-05)	(0.000125)
REC	0.00124*	0.00853***	-0.000139	-0.00255***
	(0.000706)	(0.00172)	(0.000189)	(0.000966)
REC_DEGREE	0.000186	0.00680**	9.44e-05	0.000185
	(0.000327)	(0.00316)	(6.31e-05)	(0.000823)
EFF	0.00105	0.00249	0.000376	-0.00968***
	(0.000822)	(0.00166)	(0.000625)	(0.00282)
CONTROL VARIABLES	YES	YES	YES	YES
FIXED EFFECT	YES	YES	YES	YES

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

Impacts of each of the RPS attributes are mixed with respect to geothermal and biomass. These results are consistent with the RPS mandates which primarily target renewable electricity capacity from solar and wind across states (RPS legislation across states have not identified specific targets with respect to biomass and geothermal as eligible renewable electricity sources). However, the impacts regarding AGE are positively significant for both biomass and geothermal, indicating positive contributions to biomass and geothermal capacity as the amount of time an RPS has been operational increases. The key point in the line of these patterns, in terms of varying PRS design and impacts across different renewable sources, is that the wind and solar sectors have several advantages over geothermal and biomass: widespread market power (e.g., advantage over marginal cost of production or operational costs), freely available natural resource as a primary input, and relatively advanced technology. These attributes lead to the solar and wind sectors outperforming biomass and geothermal sectors. The use of geothermal for electricity generation is limited; it is mostly used for space heating. Biomass based energy is relatively expensive with regard to its resource-based (e.g., croplands and forests) and sector-based (e.g., food sector) competition.

The results with respect to the control variables are mixed across the modeling scenarios (see Table 2.5). For instance, the coefficient of MGPO is positively significant for total renewable capacity and share of total renewable capacity, but positively insignificant in the context of solar capacity. Similarly, renewable electricity capacity increases with the number of electricity consumers in the case of total renewable electricity capacity, the share of total renewable electricity capacity, and the shares of solar and wind capacity, while negative impacts are seen in the case of geothermal and biomass. Clearly, therefore, relationships or the causal impacts with respect to the control variables are also found to change when the outcome variable changes. For example, the negative impact of an increase in the number of consumers in the case of biomass and geothermal indicates that, regardless of exogenous shocks (e.g., demand increase), there is a limited scope to increase the production capacity from biomass and geothermal.

To conclude this hypotheses evaluation section, it should be emphasized that the results of this study show inconsistency with respect to the findings of past literature in the field. The results contradict Shrimali and Kniefel (2011) who revealed a negative impact of the RPS. This divergence is a function of the identification strategies used vis-à-vis data, variables and estimation methods. For instance, in contrast to the approach taken here, Shrimali and Kniefel (2011) adopted RPS enactment dates (rather than the actual effective dates) and linearly extrapolated RPS mandates (rather than using actual nominal obligations). Among the identification issues and data availability, the primary reasons of the RPS effectiveness estimates in the previous studies seem to be driven by lack of enough RPS heterogeneity in terms of enforcement (or mandatory implementation)[4]. For example, Yin and Powers (2010) provide a plausible explanation of finding the insignificant impact of the RPS stringency index on the share of renewable electricity capacity as electric utilities would rather pay penalties than install new capacity or purchase the REC (because of technological barriers coupled with high economic costs of installing renewable electricity capacity). However, such issues have changed in recent years with the ongoing advances in the renewable electricity sector; the RPS mandates are generally met across RPS states (Barbose, 2017).

2.7.2 Discussions and Policy Implications

The RPS is widely recognized as one of the most feasible policy tools for opening the door to a long-term low carbon energy transition while promoting fuel diversity in the short-run (Stauffer, 2017). This is primarily because the RPS, as a policy instrument to

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[4] The models were re-estimated for a sub-sample spanning 1990 and 2006 to determine whether results are consistent with cognate studies (e.g., Shrimali and Kniefel, 2011).

manage energy sector externalities and other challenges, embodies features of both command and control instrument and incentives instrument. Heterogenous RPS attributes closely mimic the properties of the incentives instrument (creating economic incentives to change responses, for example, similar incentives as being created by changing taxes and subsidies). Since RPS is a state level policy (allowing states to make choices about whether to adopt and adapt the RPS), the states are not mandated to adopt the policy. Among the states that choose to adopt the policy also consider economic viability and consumers' and producers' trust in RPS legislation. Incentives aspects of the RPS are also related with multiple compliance provisions (e.g., self-production, REC, power purchase agreement or lenient enforcement of penalty payments for choosing not to comply with the policy), making the policy instrument as a hybrid in nature. Provided the time criticality of addressing the climate challenges (which largely stem from energy sector activities) and relevance of the RPS as flexible policy instrument, the RPS can be expected to further proliferate across space and time in the US. Consistent with such expectations and features of the RPS, the results of this investigation delineate multifold policy implications, which are discussed below.

The first finding of this study is that RPS adoption promotes renewable electricity capacity development. RPS adoption, on average, has increased installed renewables capacity by 194 MW, representing more than one third of the average renewable electricity capacity (577 MW) built nationally between 1990 and 2014. Since the effective date of RPSs in the sample start from 2000 (see Figure 2.4), RPS impacts are evaluated for different sub-samples to examine if those impacts have changed in recent years. Specifically, data are split on the basis of 1990-2014, 1995-2014, 2000-2014, 2005-2014, and 2000-2014. The results show that RPS impacts on renewable electricity capacity have indeed increased in recent years (see Figure 2.5). The relevance of these findings based on past observations across different sub-samples can also be connected to the fact that the RPS goals are often skewed to the future reflecting the realization of potentially enhanced RPS contributions in accelerating renewable electricity capacity in the long-run. This is clearly interesting and encouraging from a public policy perspective. However, in spatial terms, some states have experienced attempts at repealing or weakening RPS legislation; for instance, Kansas amended its RPS legislation in 2015 by changing standard mandates (i.e., 20% of peak demand capacity from renewable sources) to voluntary goals (Gallucci, 2013; Maguire and Munasib, 2016; Plumer, 2013). Unsurprisingly, changes in legislation can enhance or dampen the promotion of the renewable electricity sector (Maguire and Munasib, 2016). Stauffer (2017) highlights the significance of state level RPSs in addressing a wide range of market efficiency and environmental issues in the context that federal policies remain volatile and uncertain, not least because of electoral cycles.

Figure 2.6: RPS effective dates in states in the US

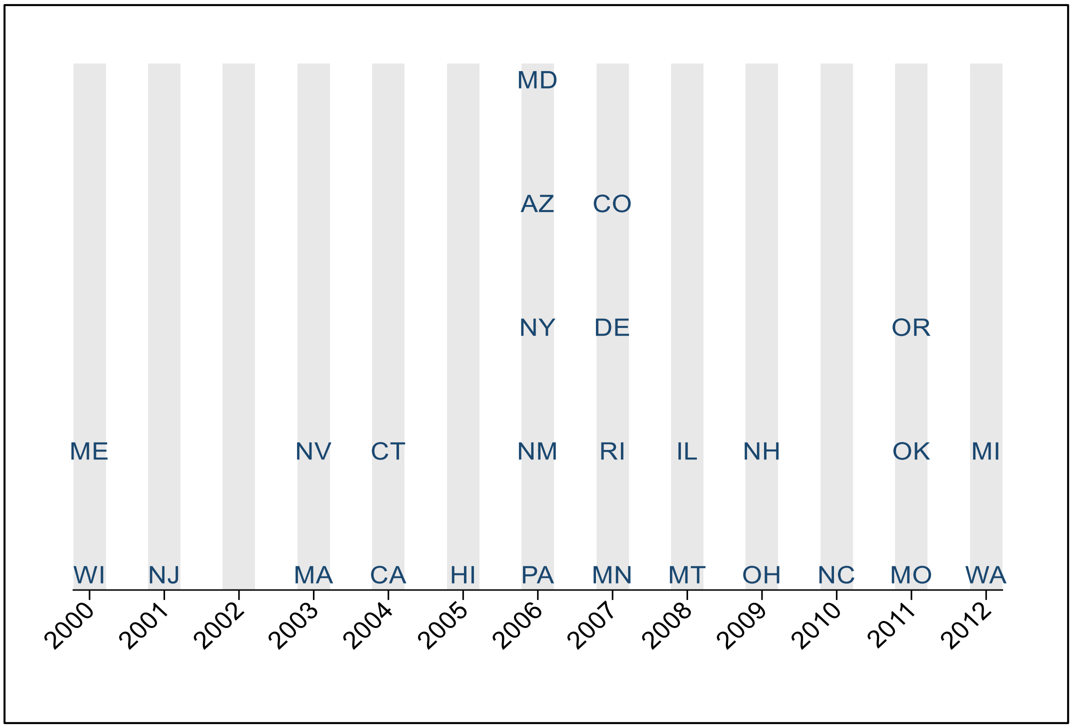
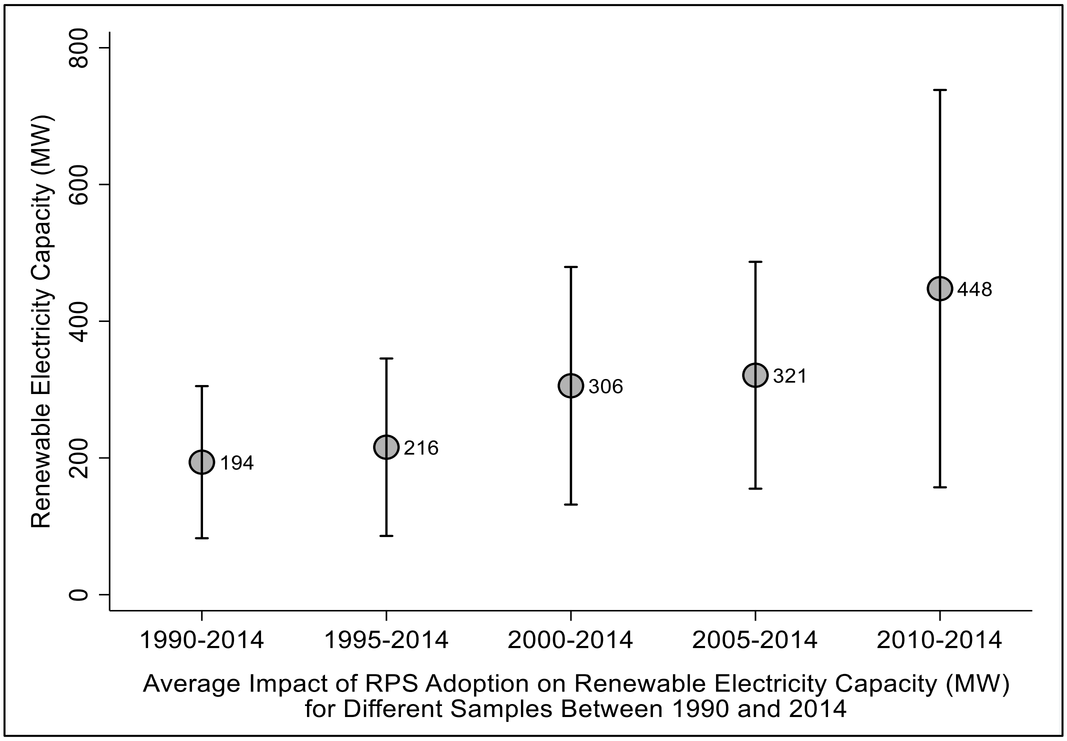


Figure 2.7: RPS impacts across different sub-samples



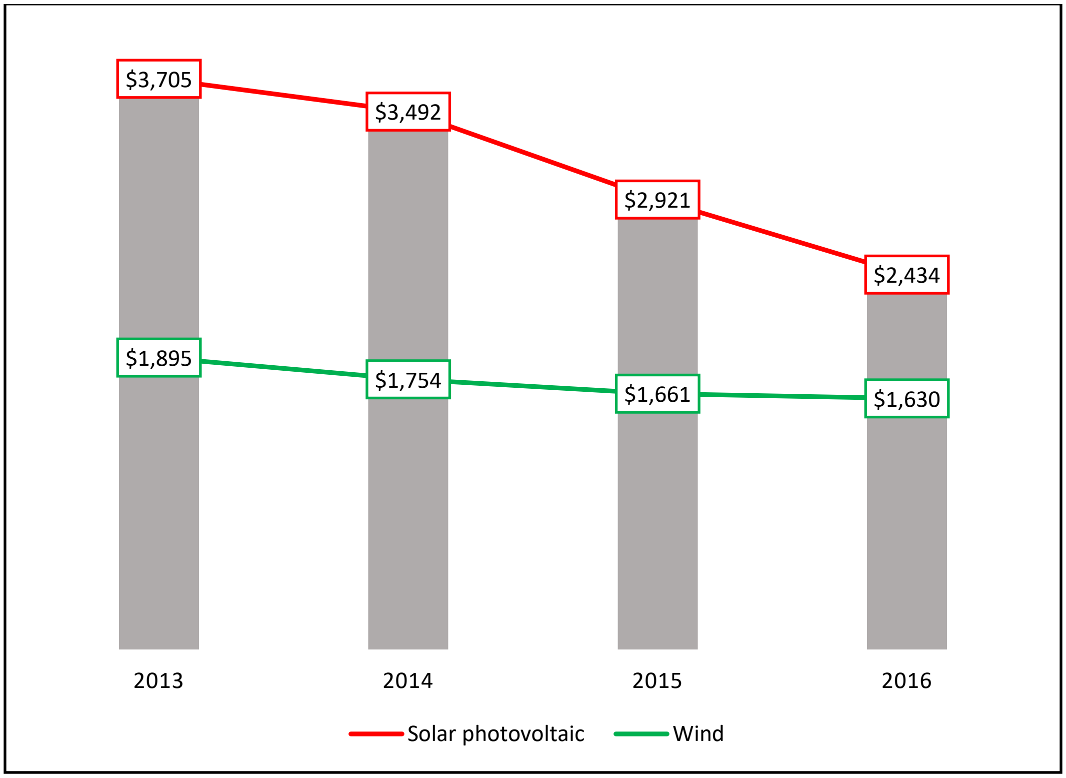
As the RPS impact on the aggregate renewable electricity capacity at the state level is positively significant, it is important to determine if the RPS contributes to the total supply (i.e., built renewable electricity capacity) and its share (i.e., the share of renewable electricity capacity in total electricity capacity). The increased demand for electricity may be met by increasing the production from both fossil fuels and renewable sources in different proportions. For example, the total renewable electricity production capacity may appear to be increasing for the increased demand for electricity, but its share may decline if the higher proportion of the additional capacity derives from the fossil fuels. The relevance of this proposition also indicates that the RPS often mandates the electricity suppliers in proportion, (rather than in quantity). As a result, the actual RPS effectiveness is attributed to its success to promote the share of renewable electricity capacity in the market. This specification leads to the second finding; RPS adoption increases the proportion of aggregate renewable electricity capacity in total electricity capacity, as confirmed by Hypothesis II. This further validates the confirmation of Hypothesis I (i.e., RPS exerts positive impacts on renewable electricity capacity).

The third finding sheds light on the contribution of the RPS attributes to the share of renewable electricity from each source. This is an important proposition, because impacts of the RPS on renewable electricity capacity by source may appear diverse (in terms of statistical significance and magnitude of the estimates) aggregate renewable, in the context that RPS is found to have a positive impact on total renewable electricity capacity and shares of total renewable electricity capacity (results with respect to hypothesis I and hypothesis II). Hypothesis III examines this scenario by separating the

RPS impacts for each renewable source and the findings suggest that the impacts of the RPS attributes for each renewable source are heterogeneous.

The RPS adoption impacts are positively significant for solar and wind capacity, while the impacts are mixed (positive, negative, significant or insignificant) for biomass and geothermal (see Table 2.6). The highest impact of the RPS adoption is for wind capacity, while the second highest is for solar. The relatively higher RPS contributions to wind than solar are justified by the fact that solar technologies remain relatively expensive compared to wind technologies across the US (Wiser et al., 2011). Figure 2.6 shows relatively higher average capital costs for constructing a solar power plant than the wind power plant. But, the trends in the per unit costs shows that they are declining more rapidly in the solar sector. The results of the investigation, consistent with such trends in construction cost parameters, also illustrate that while the magnitude of the PRS impacts is smaller on solar capacity compared to the wind capacity, the impacts become larger for the solar when the estimated coefficients are compared with the mean of the shares of solar and wind capacity in total electricity capacity. While comparing the findings with the trends in the construction costs in the renewable energy sector, it is important to note that marginal cost of renewable electricity generation (typically derived from the operational and maintenance activities) rather remain complex and volatile phenomena due to the intermittent structure of renewable electricity generation: while the marginal costs in the renewable electricity sector are expected to be lower compared to the fossil fuel sector, the magnitudes of marginal cost can change across seasons and locations. For instance, status of solar radiation and wind speed, which vary across seasons and geographies, can affect electricity generation capability of a plant (among primary reasons of intermittent generation structure), and accordingly, the marginal cost of renewable electricity generation changes across these dimensions.

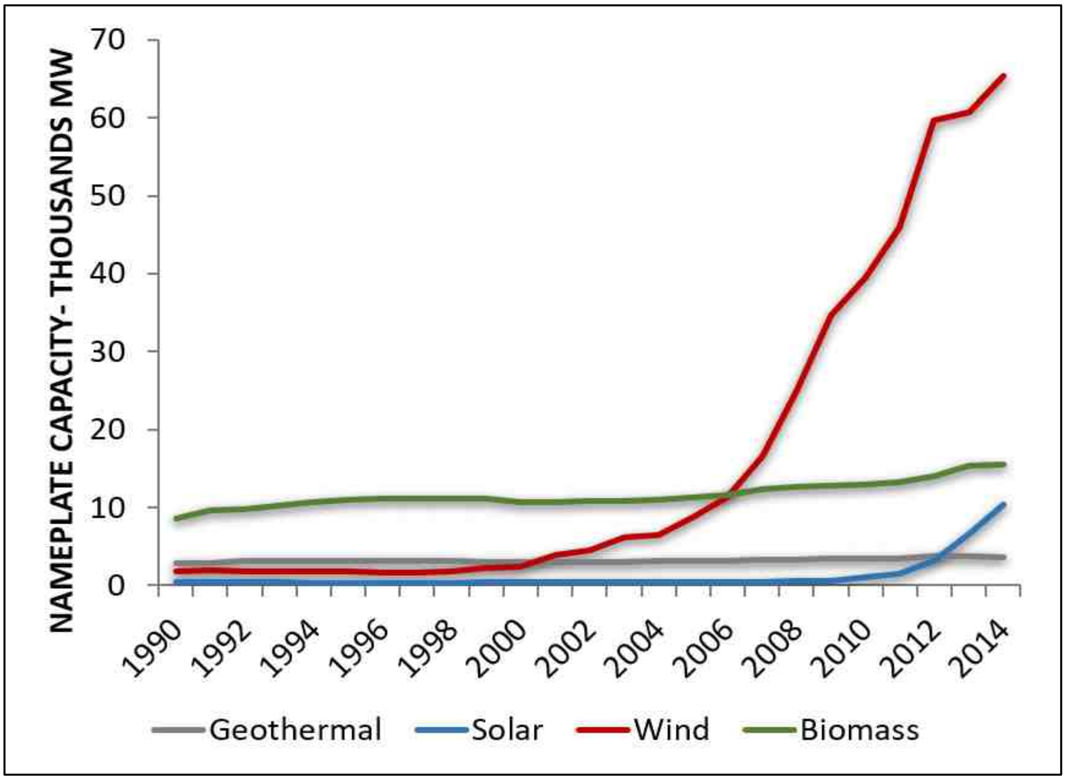
Figure 2.8: Average construction cost ($/kilowatt of installed nameplate capacity) for solar and wind



Data Source: US Energy Information Administration (2018b)

The impact of RPS adoption is negatively insignificant for geothermal and negatively significant for biomass. This finding signifies the magnitude of constraints that run from resource availability (e.g., availability of geothermal and biomass potential in individual RPS states, coupled with associated economic cost of utilization), technology and infrastructure costs, and the competition of inputs of biomass and geothermal sectors with inputs of other sectors of the economy (e.g., trade-offs for land use). The negative impact of RPS adoption on biomass and geothermal implies that if the electricity capacity from biomass and geothermal sources remains constant (or decline), while the RPS driven solar and wind capacity grows, the shares of biomass and geothermal capacity in total renewable electricity capacity declines. These results are consistent with the fact that the shares of geothermal and biomass capacities continue to decline over the time period, while the shares of wind and solar capacity are accelerating rapidly, particularly in the recent years (see Figure 2.7).

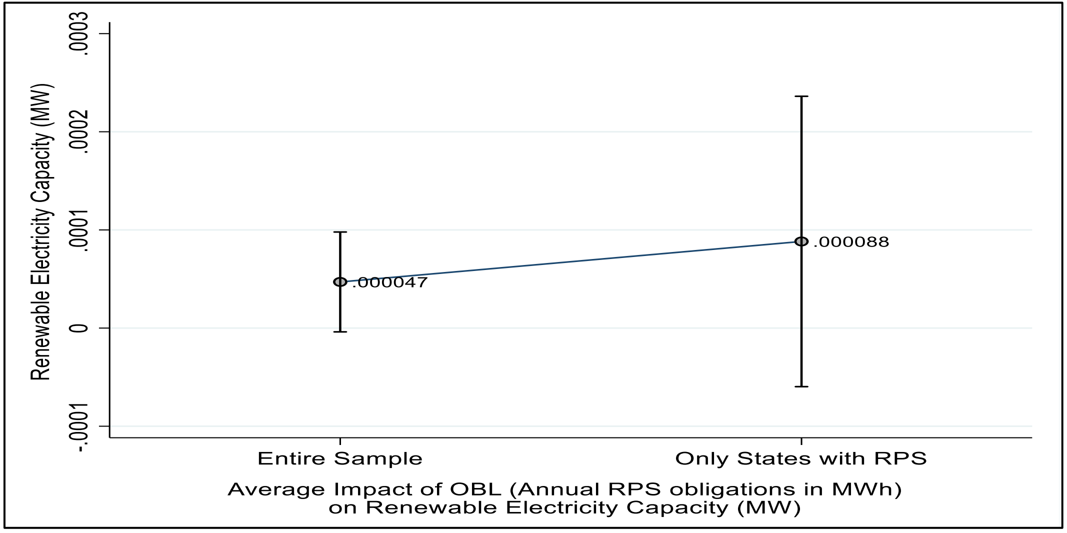
Figure 2.9: Renewable electricity nameplate capacity by renewable sources in the US



Data Source: US Energy Information Administration (2018b)

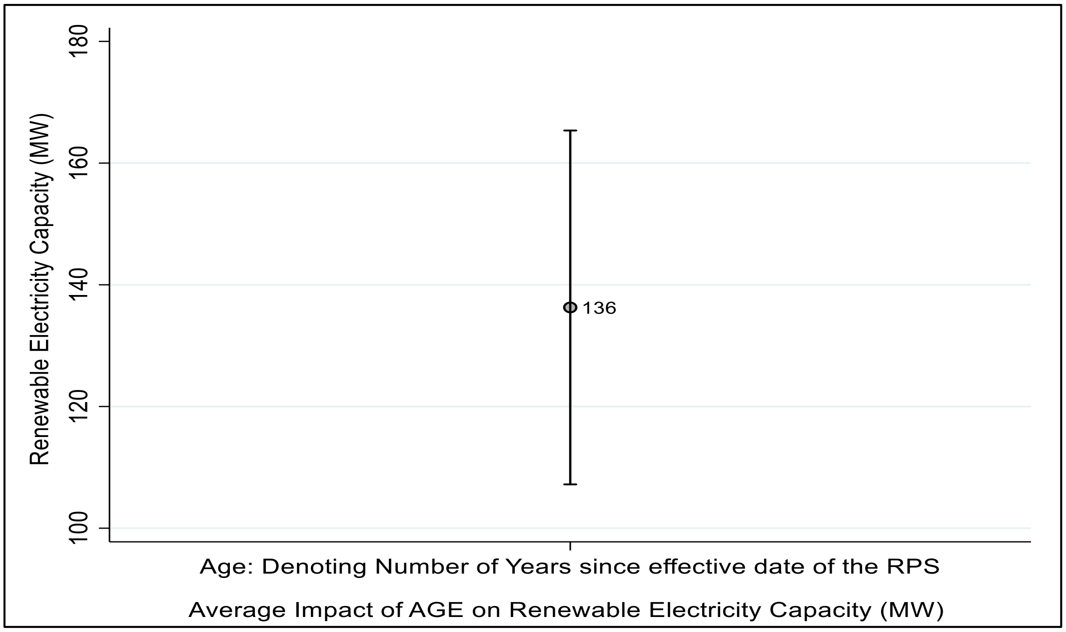
The results, with respect to the annual nominal RPS obligation (indicated by variable OBL), are also consistent with the RPS adoption impacts across the proposed hypotheses. The average impact of annual nominal RPS obligation on renewable electricity is nearly one third of average renewable electricity capacity. Figure 2.8 illustrates coefficients of annual nominal RPS obligation estimated by using the entire sample (sample containing data between 1990 and 2014 across treatment and control groups) and sub-sample (the sub-sample excludes the control group observations; states and years where RPS is not adopted). Under entire sample, the coefficient is 0.000047 (significant at 1%), implying that if annual nominal RPS mandate is 1MWh of renewable electricity, renewable electricity capacity increases by 0.000047 MW (which translates into nearly one third of average renewable electricity capacity built between 1990 and 2014 in 47 states). When the impact of annual nominal RPS obligation is estimated under the sub-sample (only treatment group observation), the coefficient (0.000088) increases by more than 50% compared to the coefficient estimated under the entire sample.

Figure 2.10: Impact of OBL on renewable electricity capacity under the entire sample and a sub-sample of only treatment groups



Similarly, the coefficients on AGE and REC are positively significant, while the impacts are insignificant for REC_DEGREE and EFF, in the case of solar and wind. On an average, if age increases by one year, the renewable electricity increases by 136 MW (see Figure 2.9). The findings, with respect to the RPS attributes, reflect the RPS stringency impacts. The longer the RPS is in effect, the larger the impacts will be on solar and wind capacity (as represented by AGE variable). Similarly, the positive REC impacts indicate that the greater flexibility of meeting the RPS mandates translates into higher capacity development.

Figure 2.11: Impact of AGE on renewable electricity capacity



The REC denotes the inclusion of the renewable energy certificates in the RPS design and the REC inclusion reflects the risk diversification for the producers to meet the mandates. That is, the additional choices created by the REC help minimize the risks for producers to comply with the regulatory mandates (Espey, 2001). The average contribution of REC on the renewable electricity is also nearly one third of average electricity capacity (reflecting REC as an important embedded feature of RPS). The REC_DEGREE represents the scenarios where REC is restricted to be generated within the state. The restriction of choices reduces the flexibility, compared to the REC (the REC allows the renewable energy certificates to generate anywhere inside and outside the state). This justifies the positively insignificant coefficients (with an exception for wind capacity) of the REC_DEGREE (i.e., reflecting the significance of the impact with respect to embedded economic incentives in flexible REC). Although, the coefficient of REC_DEGREE (0.007) is significant for wind capacity, its magnitude is smaller than the coefficient of REC for wind capacity (0.009).

The EFF denotes if the RPS allows its mandates to be met partially or fully by the energy conservation from the energy efficiency measures. The energy efficiency measures typically apply to fossil fuel based electricity, and thus, minimizing the consumption of fossil fuel energy may not necessarily promote the renewable energy capacity. This is because the efficiency targets are obtained by adopting energy efficient technologies, not by increasing the renewable energy technologies. This justifies the positively insignificant coefficient of the EFF in solar and wind. The impacts of the RPS attributes are consistent in the case of geothermal and biomass. It is observed that the increase in the age of the RPS adoption promotes the biomass capacity, indicating that the biomass sector can increase the capacity in the long-run if the incentives exist. Geothermal is the exceptional case, as it primarily supplies direct energy for space heating, where the techno-economic difficulties (e.g., transmission infrastructures) deter the geothermal based capacity development.

Table 2.7: Technology specific impacts of RPS attributes using SAR

VARIABLE	(1)	(2)	(3)	(4)
	SOLAR_SHARE	WIND_SHARE	GEO_SHARE	BIO_SHARE
RPS	0.00239***	0.00760***	2.52e-05	-0.00122
	(0.000389)	(0.00289)	(0.000143)	(0.000752)
OBL	4.08e-10***	1.17e-09***	-1.66e-10***	-8.63e-11
	(0)	(2.97e-10)	(0)	(8.13e-11)
AGE	0.000906***	0.000593	7.83e-05***	0.000386***
	(5.50e-05)	(0.000461)	(2.18e-05)	(0.000115)
REC	0.00256***	0.00436	-0.000176	-0.00111
	(0.000405)	(0.00297)	(0.000149)	(0.000786)
REC_DEGREE	-9.31e-06	0.00648	0.000238	0.000221
	(0.000671)	(0.00475)	(0.000244)	(0.00129)
EFF	0.00206***	-0.0155***	0.000728***	-0.00802***
	(0.000608)	(0.00439)	(0.000222)	(0.00115)
CONTROL VARIABLES	YES	YES	YES	YES
FIXED EFFECT	YES	YES	YES	YES

Standard errors are in parentheses: *** $p<0.01$, ** $p<0.05$, * $p<0.1$

The final highlight of this research pertains to hypothesis IV, which postulates positive spatial spillover effects of the RPS. Table 2.7 summarizes estimates for this scenario (See Appendix for Chapter 2, Table A.1-A.8 for detailed estimates). The relevance of the spatial dependencies lies with the spatial distribution of the renewable energy potentials within and across the states. The results of spatial effects across the technology (i.e., renewable source such as wind, solar, biomass and geothermal) specific scenarios are consistent with estimates regarding hypotheses I, II and III. When the spatial effects are incorporated in econometric estimation, the proportion of solar electricity of total electricity is higher by 0.00136 than in the estimation excluding the spatial effect. This increment as estimated by the SAR specification represents nearly 43% higher of the GLSPCSE estimation for Solar. Similarly, RPS impact on wind capacity is also positively significant, but it smaller than the RPS impacts without spatial effects by 0.001 (share of wind capacity of total electricity capacity).

The spatial effect with respect to the solar is also consistent with its estimates in Hypothesis III, where RPS impacts were found to be highest for the wind capacity. The estimates for geothermal and biomass insignificant. The consistency of the estimates across the modeling scenarios contributes to the validation and precision of the estimations (i.e., partially confirms hypotheses IV). Moreover, positively significant RPS impacts for wind and solar illustrate if the RPS is in effect in a state, as well as in its neighboring states, then the RPS contributions to the renewable electricity capacity increase further.

The results are consistent to the fact the RPS adopted by neighboring states have contributed to the increase in the renewable electricity capacity even in the states without RPS (e.g., Wyoming, North Dakota, South Dakota and West Virginia) by more than 10% (Barbose, 2017). This finding also validates the positively significant contribution of the flexible REC (that allows the renewable energy certificates to generate anywhere inside and outside the state) against the REC_DEGREE (REC_DEGREE represent the scenario where the RPS either doesn’t have REC provision or REC is restricted as to be generated within the border of the state). Thus, the positively significant spatial spillover, illustrating the RPS impacts beyond the state border, signifies interstate trading opportunities of renewable energy (market driven economic incentives to the non-RPS states from the states have the RPS into effect). Of course, building reliable infrastructures to allow the interstate transmission of renewable electricity should also be addressed to further accelerate renewable electricity capacity across the US.

The empirical and observational discussions has extensively shown the link of the rising temperature (i.e., changing climate) to the myriad natural disasters across the globe (e.g., frequency and severity of drought, wildfires, flooding, and coastal region’s livelihood and ecosystem challenges) (Grinsted et al., 2013; Pachauri et al., 2014; US Environmental Protection Agency, 2016b). In the context that burning fossil fuels is a leading contributor (more than 75% of GHGs in the US are emitted from burning fossil fuels) to environmental emission and climate change challenges, the federal government often appears on the front line for setting GHGs emission reduction targets or negotiating such targets with international governments (to obtain temperature stabilization goals at the global level). Transforming the energy market structure with substitution of fossil fuels by renewable energy is a primary solution to meet such climate targets. The results of this research suggest that state governments can be important partners of the federal government to meet such emission reduction targets (or to transition the energy market with proliferation of renewable energy capacity through state level legislation).

Results of this study imply that, since the RPS contributions are found to change across the spatial and temporal dimensions (stronger impacts in recent years, coupled with spatial spillover effects). The economic incentives (created by the opportunities to sell renewable electricity or REC) transferred to the non-RPS states from states that have adopted the RPS are the primary cause of significant spatial spillover effect. Thus, expanding RPS coverage across the regional scales and over different time periods can contribute to further minimize the portfolio of renewable energy sector challenges (e.g., economies of scales or average production costs). The relevance of the regionalization (e.g., coordination and cooperation among the neighboring states on the policy design) of the RPS targets also pertains to the regional structure of the electricity market, and growing importance of developing regional market for renewable electricity to optimize efficiency gains from the uses of intermitted renewable electricity generation. Moreover, the results across types of the renewable sources imply that specifying the RPS targets to the economically viable renewable sources can make significant contribution in increasing renewable energy capacity.

[redacted] Conclusion

This research investigates the effectiveness of the RPS using annual data for 47 states in the US, compiled from variety of sources (e.g., EIA, US Census and DOE) between 1990 and 2014. The primary conclusion of this research is that the RPS plays a critical role in the development of the renewable energy sector. The results suggest that the nature and stringency of the RPS attributes as characterized by the heterogeneous RPS design across spatial and temporal scales is important part of the policy in reshaping the energy market structure. RPS impacts vary by types of renewable energy sources, where the impacts are positively significant for solar and wind whilst they are either insignificant or significantly negative for biomass and geothermal. Spatial dependencies of the RPS indicate enhanced policy strength when coverage expands across larger areas (reflecting economic incentives of interstate trading possibilities or regional structure of the electricity market).

Contextual relevance of this research pertains to the rising interest and discussions on issues of leading transformative changes in the renewable energy sector. Policy choices guided by nuanced evaluation of policy efficacy is important part of generating momentum or economies of scales in the renewable energy sector since there may not be a single solution (cost-effective and carbon free) to lead a complete transition to renewables. The pervasive risks and uncertainties (e.g., market safety and the policy changes) of the renewable sector keep it at the crossroads for its acceleration. The implications concerning the comparative impacts of the RPS across the renewable sources signifies that the specification of RPS targets for each renewable source, by following the economic and technological viability of the state, can contribute to diversify non-hydro renewable electricity capacity portfilio. The hybrid nature of the RPS that maintains flexibility to comply with it makes the policy more effective. The hybrid RPS incorporates both market based incentives (e.g., renewable energy certificates) and regulatory mandates (e.g., annual nominal obligations). These results can also have broader implications for other countries (particularly developed countries as the developing countries require different sets of policies) around the world to mitigate the risks of climate change and energy security.

Notwithstanding the policy-relevant implications of the findings of this study, there is plenty of scope for future research in this domain. Disaggregating state level data to the plant level (or utility level) coupled with plant (utility) specific attributes is desirable for the purposes of providing microscale assessments of the hypotheses considered in this study as well as additional hypotheses depending on the availability of relevant data.

Chapter 3: Manure Management Coupled with Bioenergy Production: An Environmental and Economic Assessment of Large Dairies in New Mexico

[redacted] Introduction

The livestock sector is a prominent component of the agricultural economy. It can make a significant contribution to addressing food security concerns for the growing world population through the direct supply of nutrient enriched food. The importance of the livestock sector is also reflected in its additional indirect economic contributions, such as employment and supply of valuable co-products like fiber, fertilizer, and renewable energy (Idel and Reichert, 2013). The livestock industry in the United States (US) has been going through structural changes since the late eighties. The industry has experienced a massive consolidation marked by a decline in the number of farms and an increase in the number of dairy cows per farm (MacDonald and McBride, 2009). Such dynamics create both opportunities and risks to the industry. The consolidation helps generate higher farm revenue with the reduction in the average cost of the livestock production due to economies of scale. This pattern also increases external costs of livestock farms. These farms produce various waste elements including manure, the management of which has remained a complicated issue. The excreted manure constitutes a significant amount of nitrates, the improper management of which can produce adverse environmental and health effects. The manure-borne pollutants, including pathogen and odor, can affect water quality, air quality, and welfare of the surrounding communities. Furthermore, the livestock sector is an important source of greenhouse gases (GHGs), with manure decomposition emitting globally about 1.5% of all human-induced GHGs emissions per year (Gerber et al., 2013).

Among the major components of the livestock sector is the dairy industry (USDA, 2012). The state of New Mexico ranks number one in the US in terms of dairy cows per farm. Considering the arid climate and water scarcity in New Mexico, the issue of dairy manure management through the direct land application can be a challenging one (e.g., trade-offs associated with allocation of limited water resources in different uses in the arid region). Alternative dairy manure management considerations, backed by economic viability and environmental sustainability, can serve in conserving limited water sources and protecting water quality. Moreover, water and energy are interlinked scarce natural resources, the consumption of both of which is increasing rapidly with escalating socio-economic activities and the improved quality of life. Fossil fuels such as coal, oil, and natural gas occupy dominant share over renewable energy sources in the energy market due to several advantages, including low price, high efficiency, and attributes of mobility and storability (Ellabban et al., 2014; US Energy Information Administration, 2013). New Mexico, while also being a leading fossil fuel producer in the US, relies on fossil fuel for more than 90% of its energy consumption (US Energy Information Administration, 2016). Excessive reliance on such traditional fossil fuels further exacerbates the negative impacts on the environment, ecosystem, energy security, and energy sustainability (Cantrell et al., 2008; Goldemberg, 2006; Nakicenovic and Nordhaus, 2011; Shafiee and Topal, 2009; Tuladhar et al., 2009). Development of clean alternative energy that co-exists with food production without a trade-off and that work as substitutes for fossil fuels is crucial for sustainable management of the livestock and energy sector in arid-land regions like New Mexico (Arent et al., 2011).

The direct land application is the traditional dairy manure management method. Consolidation in livestock production generates higher average net farm incomes due to economies of scale, which has sustained a trend toward larger and more concentrated animal feeding operations (CAFOs) (for more details on current practices, trends and policies in New Mexico's dairy sector, see Wang and Joshi, 2015). However, the common practice of livestock operators continues to be (over-) application of manure on adjacent agricultural land, because consolidation combined with the decreasing acreage for field crops lead to less land available for manure disposal, and manure (especially dairy and swine manure) is costly to move relative to its nutrient value. Over-application of manure results in nutrient losses to aquatic ecosystems, which disrupt nutrient cycles and cause eutrophication. Excessive concentration of nitrogen in groundwater is also a potential threat to public health (e.g., blue-baby syndrome in infants and stomach cancer in adults).

The large dairy CAFOs lead to challenges in proper waste management. Livestock waste is a good source of nutrients and applying it to cropland has been a traditional way of waste management. When properly managed, livestock waste makes an excellent fertilizer promoting crop growth and improving overall soil quality. Consolidation in livestock production generates higher farm incomes, but it also brings waste disposal problems when consolidation combined with limited acreages for field crops leads to less land suitable for waste spreading. Relative to wastes from other livestock species, dairy (and swine) waste is costly to move relative to its nutrient value due to high liquid contents. Therefore, the common practice of dairy operators continues to be over-application of dairy waste on land adjacent to the facility.

Excess nutrients transported off the farm through volatilization, run-off or leaching can produce adverse environmental and health effects. For surface water, either nitrogen or phosphorus can lead to potentially large algal blooms in receiving aquatic ecosystems and a variety of problems including clogged pipelines, fish kills, and reduced recreational opportunities (USEPA 2000). An example is the toxic algae bloom occurred in Lake Erie in early August 2014 that provoked a tap water ban in Toledo, Ohio where nearly half a million people were told not to use water for drinking, cooking, or bathing for two days.[5] Although this algae bloom is in part due to climate change, agricultural nutrients runoff from the watershed plays an important role in feeding the algae bloom. For groundwater, nitrate-nitrogen is a potential threat to public health. Excessive concentration of nitrates in drinking water can lead to blue-baby syndrome in infants and stomach cancer in adults (Addiscott 1996; Powlson et al. 2008).

According to the New Mexico Environment Department, two-thirds of the state’s dairies were contaminating groundwater in 2009 with excess nitrogen from lagoon leaking or over-applying manure to crop fields. Groundwater nitrate pollution from large dairies in New Mexico was featured on National Public Radio in 2009.[6] Approximately 90% of the total population in New Mexico depends on groundwater as drinking water and about 10% of the population depends on private wells for drinking water without any

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[5] Jane J. Lee, National Geographic, August 06, 2014. *Driven by Climate Change, Algae Blooms Behind Ohio Water Scare Are New Normal*. URL: http://news.nationalgeographic.com/news/2014/08/140804-harmful-algal-bloom-lake-erie-climate-change-science/.

[6] John Burnett, December 09, 2009. *New Mexico Dairy Pollution Sparks 'Manure War.'* URL: http://www.npr.org/templates/story/story.php?storyId=121173780.

treatment (NMED, 1998). Given New Mexico's leading trend in dairy consolidation and a severe scarcity of water resources, proper waste management is one of the greatest challenges to the dairy industry as well as the state. We thus investigate alternative approaches to control nitrate emissions from the state's large dairy CAFOs in this project.

The use of an alternative dairy manure management strategy may assist in achieving the dual goals of minimizing environmental pollution risks and producing renewable energy without affecting food production. Manure-to-bioenergy treatments can provide livestock operators with renewable energy that can meet heating and power needs or serve as transportation fuels (Cantrell et al., 2008). Among the existing manure-to-bioenergy processes, anaerobic digestion is an established technology capable of biogas production, while other biological and thermal-based conversion technologies are still in early research stages (Cantrell et al., 2008). Potential benefits of anaerobic digestion include generation of renewable energy, reduction in odor and GHG emissions, by-product sales (e.g., solid manure can be sold off farm), and potential pathogen reduction in manure (Beddoes et al., 2007; Demirer and Chen, 2005).

The anaerobic digestion system of manure management has received considerable attention, particularly in developing countries due to cheap labor costs and a shortage of traditional fossil fuels. However, it has not gained much popularity among US dairy farmers, primarily because of high labor and capital costs coupled with low relative energy efficiency. For instance, despite being one of the leading states in the US in dairy farming, New Mexico has only one anaerobic digester; that is still under construction (US Environmental Protection Agency, 2015). Beddoes et al. (2007) find that the capital cost of digester installation, machinery maintenance, operational costs, and costs of power plant installation for electricity generation are major obstacles to commercializing anaerobic digestion in the US. Despite these economic hurdles, the number of operational anaerobic digesters is increasing in the US. For instance, the number of operational digesters in the US rose to 247 in 2014 from 171 in 2011, a 45% increase over three years (Klavon, 2011; US Environmental Protection Agency, 2015). Various factors such as odor and pathogen control, improved efficiency of digester technology, and increased regulatory restrictions have led to the increment in the number of digesters. Over 80% of the 247 operational digesters (202 digesters) operating in 2014 were dairy-manure based (Klavon, 2011; US Environmental Protection Agency, 2015). Dairy-manure based digesters have been relatively popular for several reasons: suitable biochemical properties (e.g., solid content in dairy manure for digester), free-stall farming, and relatively low average cost (Balsam and Ryan, 2006; Lazarus, 2008). Thus, given the different economic and environmental benefits, the promising prospects of increasing anaerobic digestion of dairy manure are gradually being recognized.

Several studies on co-digestion of dairy manure with subsequent microalgae biomass production have found significantly higher bioenergy productivity to single digestion systems (Higgins and Kendall, 2012; Mulbry et al., 2008b; Pizarro et al., 2006; Zhang et al., 2013). Microalgae are a type of unicellular photosynthetic microorganisms that grow in aquatic environments. The photosynthetic conversion efficiency of microalgae is very high compared to other photosynthetic species, and its biomass volume can double within a few days (Brennan and Owende, 2010). Microalgae can be cultivated on non-arable or marginal-quality lands using low-quality water (e.g., wastewater from municipal, agricultural, industrial, or energy sectors). As nutrients are major inputs for microalgae growth, integrating dairy manure management with microalgae cultivation to co-produce bioenergy can be an advantageous approach of dairy manure management from both environmental and economic perspectives. New Mexico has abundant non-arable land resources, and its arid and sunny climate is suitable for microalgae production (Durvasula et al., 2015).

Arid-land regions (i.e., arid, semi-arid, and dry sub-humid) that support more than one-third of the global population and almost half of the world's livestock and cultivated land are facing multiple challenges that call for integrated approaches for optimal management of its food, water, and energy resources. (Mortensen et al., 2016). The environmental and economic impacts of alternative animal manure management for bioenergy production in these regions are not well understood due to the lack of literature in the context of the consolidating livestock industry with the growing supply of manure as a potential source of bioenergy. Given the supportive geographic and climatic attributes for microalgae cultivation in New Mexico (Durvasula et al., 2015) and the importance of proper dairy manure management (Cabrera et al., 2009), this study seeks to integrate the twofold aspects through a case study of large dairies in New Mexico. The primary objective of this study is to assess the relative environmental and economic impacts of alternative dairy manure management methods coupled with bioenergy production potentials. The findings of this study also offer a window into the future of other dairy states in arid-land regions. The empirical analysis is conducted using a combination of life cycle assessment (LCA) and cost-benefit analysis (CBA) supplemented by robustness checks with sensitivity analysis.

In the context of widely acknowledged economic and environmental challenges associated with dairy current waste management practices, we seek to understand best alternative manure management possibilities. We examine three cases of dairy manure management: direct land application (DLA), anaerobic digestion (AD), and anaerobic digestion coupled with microalgae cultivation (ADMC). In DLA case across different modeling scenarios, agronomic nitrogen application rates that are prescribed to be safer are incorporated in the analysis. It should be noted that the environmental challenges (e.g., methane pollution, nitrate pollution and air pollution) will not be entirely eliminated even when the standard agronomic application rates are adopted.

The LCA consists of inventory analysis of energy balance, water balance, eutrophication potential and global warming potential for each alternative case. The CBA is used to estimate the economic profitability of all cases under a baseline scenario of agronomic nitrogen application rate (with new Dairy Rule being under implementation, New Mexico's dairies will be required to apply manure on crop field by following crop specific nitrogen application rates[7]) and other several policy scenarios of current and prospective policies relevant to sustainable dairy waste management sector. Hereafter, baseline scenario will be referred to represent the scenario where land application of dairy manure is assumed to follow agronomic nitrogen application rates. The LCA imply that the DLA case is found least favorable. The AD case is most favorable concerning energy balance, and the ADMC case demonstrates the relative favorability regarding water balance, eutrophication potential, and global warming potential. The present values of net benefits under the baseline scenario, a current policy scenario, and scenarios with

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[7] McDuffy, N. (2018, December 13). Ground Water Quality Bureau, New Mexico Environment Department, Phone call.

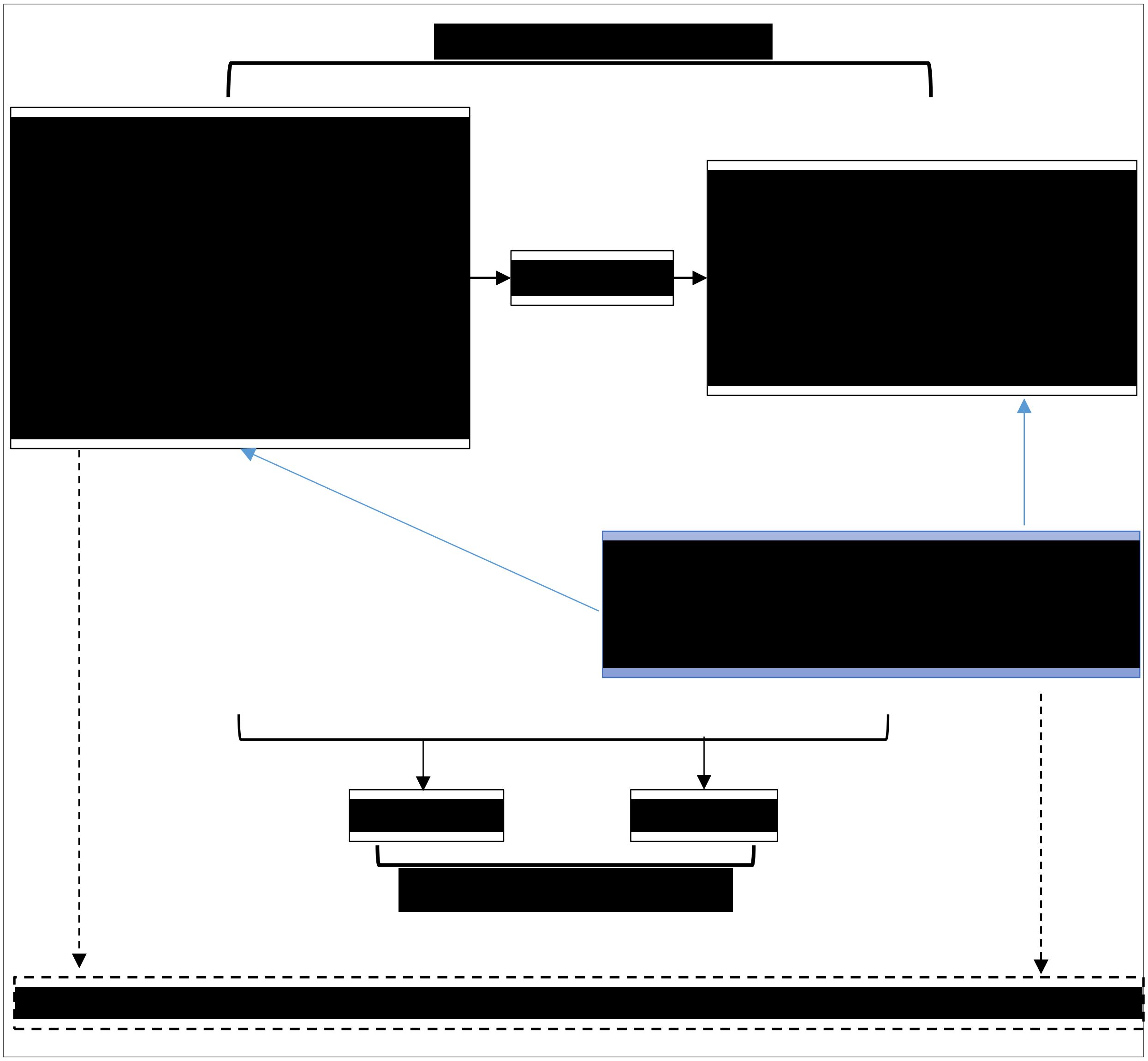
more available cropland or rangeland suggest DLA as the least profitable and AD as the most profitable. The ADMC case is found to be most cost-effective in prospective policy scenarios where markets for environmental credit trading exist. The following sections discuss the methodology, data, and results with policy implications.

Methodology and Data

3.2.1 Modeling Framework

Our conceptual modeling framework is presented in Figure 3.1. Using a typical large dairy farm as a function unit, we employ a combination of life cycle assessment (LCA), cost-benefit analysis (CBA), and sensitivity analysis for three cases of dairy manure management. In the DLA case, dairy manure is stored during the off-season and applied to agricultural lands during cultivation periods. In the AD case, an anaerobic digester co-produces digested manure and biogas. The digested manure effluent is separated into liquid and solid parts. Both parts can be directly applied to adjacent cropland, and the digested solid can also be sold off-farm. The biogas is used to produce electricity. In the ADMC case, the digested liquid generated from the anaerobic digestion system is used as nutrient supplements to cultivate microalgae, which is then fed back into the digester to produce more biogas and electricity. The DLA case is used as a reference case so that the environmental and economic impacts of alternative cases can be compared to it.

Figure 3.1: A conceptual framework of a combination of life cycle assessment, cost-benefit analysis, and sensitivity analysis



The major output from our LCA analysis is a comprehensive assessment of four environmental impacts including energy balance, water balance, eutrophication potential, and global warming potential of dairy manure management. Regulations and policies implemented to reduce these environmental impacts can either impose costs or create benefits to dairy farms. The CBA analysis is used to evaluate economic impacts of alternative policies, i.e., net economic benefits of each manure management case under a baseline scenario and alternative policy scenarios. The CBA analysis incorporates sensitivity analysis under varying scenarios of cropland availability, rangeland availability, and policy strength to deal with uncertainties and risks in the model. Details of each of these model components are provided in Appendix for Chapter 3; here we provide a general overview.

Since the study focuses on alternative proper dairy manure management methods, the pre-processes (e.g., dairy manure production and collection process, and milk cow diets) and post-processes (e.g., consumption of produced biofuels and crops) of manure management are excluded in the LCA and CBA analyses. Thus, the system boundary of the study is "cradle to gate" (see Appendix for Chapter 3, Figures B.1, B.2, and B.3 for boundaries of DLA, AD, and ADMC). The measurement units of energy balance, water balance, eutrophication potential, and global warming potential are respectively gigajoule (gj), gallons, kilograms of phosphate equivalent (kg PO_4-eq), and megagrams of carbon dioxide equivalent (Mg CO_2-eq).[8] All dollar values in the CBA analysis are adjusted for inflation using 2014 US dollars. Other units of measurements, if used, are defined in the relevant sections, tables, and figures.

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[8] Gigajoule is the derived unit of energy and equivalent to 278 kilowatt hours. Megagram is the derived unit of weight and equivalent to 1,000 kg.

3.2.2 Dairy Data

In this study, we focus on an important category of animal feeding operations – concentrated animal feeding operations (CAFOs). CAFOs are the largest of the animal operations and the one that poses the greatest risk to environmental quality and public health. By definition, a large CAFO in the US is a facility with 1,000 or more animal units, which is the equivalent of 700 dairy cattle(US Environmental Protection Agency, 2003). There is little information available on dairy operations with 700 or more milk cows, but the US Census of Agriculture provides statistics for dairy farms with 500 or more milk cows. We thus use this category of dairy farms (with 500 or more milk cows) as a proxy for large dairy CAFOs and hereafter define it as "large dairy farms." In our LCA and CBA analyses, the functional unit is defined as a typical large dairy farm in New Mexico with an average number of 2,892 milk cows.[9]

With the fast-growing dairy industry in New Mexico since the 1980s, the challenge of properly managing dairy manure to prevent nitrate pollution of scarce water resources has been emerging as a serious issue in the state. Various environmental rules and policies regulate livestock manure management, especially for large dairy farms. The major federal environmental law currently affecting animal feeding operations is the Clean Water Act (CWA).[10] The CWA prohibits the discharge of pollutants from a point source to waters of the US except as authorized through a National Pollutant Discharge

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[9] According to the latest US Census of Agriculture (USDA, 2012), there are 410 dairy farms in New Mexico with 318,878 milk cows. However, the total number of milk cows in 109 large dairy farms (with 500 or more cows) is 315,183. This implies that about 99% of all the milk cows in New Mexico are concentrated in the large dairy farms. Diving 315,183 cows by 109 large dairy farms gives the size of a typical dairy farm, which contains 2,892 milk cows.

[10] Atmospheric pollutants are regulated under the Clean Air Act (CAA), but CAA currently does not recognize CAFOs for regulatory purposes. Although air pollution from CAFOs is receiving increasing attention in the academic literature (Sneeringer, 2009, 2010; Tosiano, 2012), there is little or slow progress on regulatory change in practice.

Elimination System (NPDES) permit. The Act requires the US Environmental Protection Agency (EPA) to establish national technology-based effluent limitations guidelines and standards (ELGs) for different categories of sources. Although agriculture has long been recognized as a nonpoint pollution source and exempted from NPDES requirements, animal production facilities (not including the adjacent lands) are easily identified and more similar to point sources. Therefore, large CAFOs with more than 1000 animal units have been historically defined as "point sources" by CWA (section 502, CWA). In the mid-1970s, EPA established ELGs and permitting regulations for CAFOs under the NPDES program, under which CAFOs are required to install acceptable technologies to improve farmstead structures and control runoff (US Environmental Protection Agency, 2003). Waste application to crop fields was exempted from the requirements because the regulations presumed that livestock manure removed from the farmstead area was handled appropriately through land application.

Despite more than four decades of CAFOs regulation, reports of discharge and runoff of animal waste from these large operations persist. A high correlation was found between areas with impaired surface and groundwater due to nutrient enrichment and areas where dense livestock exist (US Environmental Protection Agency, 2003). Although this is in part due to inadequate compliance with existing regulations in the livestock sector, the recent trend of concentrating more animals within smaller geographic units contributes more to the persisting waste discharge (Wang, 2012). In response to these concerns, the US Department of Agriculture (USDA) and EPA have attempted to control emissions from CAFOs since the late 1990s. In 1999, the two agencies jointly announced the Unified National Strategy for Animal Feeding Operations (hereafter Strategy), which establishes the goal that “all AFO owners and operators should develop and implement technically sound, economically feasible, and site-specific comprehensive nutrient management plans (CNMPs) to minimize impacts on water quality and public health” (US Environmental Protection Agency and US Department of Agriculture, 1999).

The Strategy calls for both voluntary and regulatory programs, but voluntary ones (e.g., locally led conservation, environmental education, partnerships, financial assistance, and technical assistance) were mainly used at the early stages of implementing the strategy to address the vast majority of AFOs (US Environmental Protection Agency and US Department of Agriculture, 1999). Most of the voluntary programs are executed by the USDA’s Natural Resources Conservation Service (NRCS), the primary federal agency that works with private landowners to help them conserve, maintain, and improve their natural resources. For example, NRCS provides technical and economic assistance to dairy farmers for secure manure management (e.g., construction of synthetic lined lagoons, nutrient management, and prescribed grazing) to help them meet the mandatory requirements of NPDES and to protect environmental quality (NRCS, 2014).

In response to the increasingly severe problem of nutrient pollution, EPA published a new rule for CAFOs in 2003 to target high-risk operations (US Environmental Protection Agency, 2003). This rule can be seen as a part of the regulatory program proposed by the 1999 Strategy. It expanded the number of CAFOs required to seek NPDES permit coverage. One important change was that large CAFOs were required to prepare and implement site-specific nutrient management plans (NMPs) for animal waste applied to land. The guidelines for NMPs included land application rates, setbacks, and other land application best management practices (US Environmental Protection Agency, 2003). EPA finalized the rule in 2008 in response to the order issued by the US Court of Appeals for the Second Circuit in Waterkeeper Alliance et al. *v.* EPA. There are two changes relative to the 2003 rule, but the fundamental restrictions in NMPs remain the same for large CAFOs (US Environmental Protection Agency, 2008).[11] For a thorough review of federal and state regulations for water pollution from land application of animal waste, refer to Centner (2012).

EPA Region 6 directly implements the CAFO rule under the NPDES program in New Mexico.[12] The NPDES General Permit for Discharges from Concentrated Animal Feeding Operations in New Mexico (hereafter New Mexico CAFO general permit) covers any operation that meets the definition of a CAFO and discharges or proposes to discharge pollutants to waters of the country. The New Mexico CAFO general permit first became effective on September 3, 2009, and lasted for five years until September 2, 2014 (EPA, 2009). EPA is currently proposing to reissue the New Mexico CAFO 5-year general permit, and the NMPs that are required to be submitted along with the permit application are currently available for public review and comment.[13] If effectively implemented, NMPs can significantly decrease nitrogen run-off and leaching. However, without better methods for manure disposal other than the land application, NMPs increase competition for land capable of receiving animal manure and create additional

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[11] There were two changes in the 2008 final rule relative to the 2003 rule. First, only those CAFOs that discharge or propose to discharge were required to apply for permits; second, CAFOs were required to submit the NMPs along with their NPDES permits applications, which will then be reviewed by both permitting authorities and the public.

[12] This is different from how the CAFO program is implemented in the other states in EPA Region 6. The states of Arkansas, Louisiana, Oklahoma and Texas are authorized by EPA to implement the CAFO program in their respective states. EPA acts in an oversight and technical assistance role for these state programs.

[13] For details, refer to the EPA Region 6 CAFO program: http://www.epa.gov/region6/water/npdes/cafo/.

costs for farm operators (Wang and Baerenklau, 2015). Developing and implementing such a plan may substantially increase operating costs for dairy producers and thus economically impact the dairy industry in New Mexico.

The New Mexico Water Quality Act (NMWQA) is the primary authority for water quality management in New Mexico (NMAC, 2015)(WQCC, 2015). The New Mexico Water Quality Control Commission (WQCC) has been created by NMWQA under the New Mexico Environmental Department (NMED) for various duties of water quality management. WQCC establishes guidelines for the certification of federal water resources regulations and provides technical assistance to the farmers in compliance with federal regulations (WQCC, 2015).

As discussed previously, EPA directly administers the NPDES permits for CAFOs in New Mexico. NMED supervises surface water quality programs in the state but does not have the power to issue NPDES permits to CAFOs (EPA, 2009). It helps EPA review the NPDES CAFO permits and make modifications as appropriate. NMED regulates dairies mainly through state groundwater regulations for dairies. According to NMED regulations, all the large dairy farms of New Mexico are required to obtain Ground Water Discharge Permits (NMAC, 2015, 20.6.2.3000 through 20.6.2.3114). NMED has maintained standard requirements and guidelines to issue groundwater discharge permits and monitor dairy farm manure disposal activities. The requirements include the proper application of liquid and solid dairy manures to agricultural lands, tracking off-site manure applications, soil and plant tissue sampling, monitoring well installation and groundwater sampling, provision for penalties, and enforcement actions (Lazarus et al., 2010).

Due to potential contamination of groundwater from some dairy facilities, the WQCC adopted a Dairy Rule in response to a 2009 amendment to the Water Quality Act. The objective was to set forth specific rules for the dairy industry to monitor groundwater quality and to prevent groundwater pollution (NMED, 2011). WQCC passed New Mexico's first industry-specific regulations for the dairy industry in December 2010 (NMED, 2011). The proposed regulations mandated various provisions in order to control water pollution from the dairy sector: a plastic liner for manure filled wastewater impoundments, minimum setbacks from important water resources such as drinking water wells, and notice to property owners within a mile radius of a proposed dairy that includes a map so the public can see where the dairy will be located in relation to residences and natural resources (NMAC, 2011, 20.6.6). The Dairy Industry Group for a Clean Environment (DIGCE) filed a Notice of Appeal to the Court of Appeals in January 2011 to seek judicial review of the Dairy Rule. A settlement was reached in July 2011, and the amended Dairy Rule went into effect at the end of that year. DIGCE filed two additional petitions with the WQCC, one in 2012 and one in 2013, to amend the Dairy Rule (NMELC, 2015).

The most recent amended Dairy Rule went into effect in August 2015, which deals primarily with how dairies manage wastewater and monitor groundwater. Large dairies in the state are required to line wastewater lagoons with two feet of compacted clay to catch manure runoff, the clay must be installed according to EPA guidelines, and the liners need to be regularly monitored to detect nitrate contamination above the state standard (NMAC, 2015, 20.6.6). If the clay liners fail to provide adequate protection, the state could require the addition of synthetic liners (NMAC, 2015, 20.6.6). Another main rule concerns the installation, on a case-by-case basis, of groundwater monitoring wells depending on the hydrogeology beneath the dairy (NMAC, 2015, 20.6.6). The new Dairy Rule is currently under implementation in New Mexico, and mandates of this policy on land application of manure are consistent our assumption of nitrogen application rates.

The discussion and result section of this chapter develops various sensitivity analyses (e.g., assumptions that the average sized large dairy farm contains sufficient on-site croplands to manage the manure by following the agronomic nitrogen application rates or the assumption that willingness to accept manure by the off-site farmers is 100% as illustrated by the rangeland case). This section provides analytical approaches on data construction by following the defined set of assumptions and justification for such assumptions. The unifying motivation in construction these various analytical approaches pertains to the context that the current practices of dairy waste management follow the traditional land application (or over application of manure on adjacent on-site croplands), which translates into various environmental and economic challenges (e.g., atmospheric and terrestrial pollutions, such as methane and nitrate emissions, and odor and pathogen problems).

The estimated quantities of total nitrogen (TN) and total phosphorus (TP) excreted from the typical large dairy farm are 312,336 kgN/yr and 57,840 kgP/yr, respectively (see Appendix for Chapter 3, section B.2). Manure is applied to croplands during the cropping season and is stored during other periods. During the collection, storage and land application processes, some of the inorganic nitrogen losses occur through volatilization. Available nitrogen for the direct land application (i.e., inorganic nitrogen available after volatilization plus 25% of organic nitrogen) in the DLA case is

27.1 kgN/cow-yr and in the AD case, it is 11.4 kgN/cow-yr (Zhang et al., 2013). Therefore, for the typical large dairy farm in New Mexico, TN available for land application in the DLA case (TN_{land}^{DLA}) is 78,373 kgN/yr and in the AD case (TN_{land}^{AD}) is 32,997 kgN/yr.

Since our unit of analysis is the average sized typical large dairy farm, we assume that this typical dairy farm is responsible for properly managing the dairy manure. In the context of the land application cases, land constraint (i.e., the average land size owned by the defined typical large dairy farm to apply dairy manure by following agronomic nitrogen application rates) in relation to the quantities of produced manure-based nitrogen by that farm is taken into account in the analysis. The size of land owned by the typical large dairy farm (A) is calculated by using equation (1).

$$A = \frac{\sum_{i=1}^{I} L_i^{MV} \aleph_i}{\sum_{i=1}^{I} \aleph_i} \dots\dots\dots\dots..(1)$$

where i is the index for land size categories, $\aleph_i$ is the number of large dairy farms in each land size category, and L_i^{MV} is the median value of land area in each land size category. Over 60% of the large dairy farms in New Mexico contain at least 202 ha (i.e., 500 acres) of land and around 45% contain at least 405 ha (i.e., 1,000 acres)[14] (USDA, 2012) (see Appendix for Chapter 3, Table B.2). By using equation (1), the typical large dairy farm in New Mexico contains 391 ha of land.

The basic proposition adopted in this research is that the dairy farmers follow the standard agronomic nitrogen application rates specific to the field crops to ensure that

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[14] According to McDuffy, N. (2018, December 21) with regard to current dairy waste management practices, Dairy farm of size containing 3000 cows may roughly require 500 acres of cropland. McDuffy, N. (2018, December 21). Ground Water Quality Bureau, New Mexico Environment Department, Phone call. This clearly indicates continued challenges (over application of manure on croplands) with proper nitrate management in the sector.

manure is not applied more than the absorption capacity of field crops in adjacent croplands (or that land application is one of the economically and environmentally plausible options to properly manage the manure). While analyzing each case within the context of proper waste management practices, it should be noted that environmental impacts (e.g., eutrophication and global warming potentials) associated with the land application approach (or even in the cases of AD and ADMC) will not be entirely eliminated (see section '3.3.1 LCA results' for more details on environmental aspects of each case). Being consistent with New Mexico's cropping pattern (year-around alfalfa or summer corn and winter wheat), we assume that alfalfa is grown on 80% of the land while summer corn and winter wheat are grown on 20% of the land (see Appendix for Chapter 3, Section B.4 and Table B.3). The offsite croplands suitable for receiving dairy manure are also assumed to follow the same cropping pattern.

Average nitrogen requirement per unit of field cropland ($\overline{N}_{crop}$) is then estimated using Equation (2), where $N_{alfalfa}$, N_{wheat}, and N_{corn} are respectively the nitrogen requirement rate of alfalfa, wheat, and corn, and α is the share of field crop land growing alfalfa. The three field crops have different nitrogen requirements. Alfalfa can obtain all the required nitrogen from its own nitrogen-fixing nodules with the help of Rhizobium bacteria; however, it may require between 22-35 kgN/ha during the seeding period until the development of nitrogen-fixing nodules (Caddel et al., 2001; Lindemann and Glover, 2003). Therefore, the average nitrogen requirement for alfalfa is 28.5 kgN/ha. The recommended agronomic nitrogen application rate for wheat is 135 kgN/ha (Hossain et al., 2004). The agronomic nitrogen requirement that maximizes corn grain and silage yield ranges from 200-240 kgN/ha, so on average, it is 220 kgN/ha (Contreras-Govea et al., 2014; Cox and Cherney, 2001). By using equation (2), the average nitrogen requirement per unit of field cropland in New Mexico is 93.4 kgN/ha.

$$\bar{N}_{crop} = \alpha N_{alfalfa} + (1 - \alpha)(N_{wheat} + N_{corn}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(2)$$

Irrigation requirement depends on the crops' evapotranspiration (ET) rates. The average ET rates for alfalfa, wheat and corn ($ET_{alfalfa}$, ET_{wheat}, and ET_{corn}) in New Mexico are respectively 48, 25, and 30 inches (HCD-CWR, 2011). The average ET per unit of field cropland ($\overline{ET}_{crop}$) is calculated as in Equation (3).

$$\overline{ET}_{crop} = \alpha ET_{alfalfa} + (1 - \alpha)(ET_{wheat} + ET_{corn}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(3)$$

We assume that dairy manure is applied to croplands based on crops' agronomic nitrogen requirements. Given the land size of the typical large dairy farm and the average nitrogen requirement per unit of field cropland, total nitrogen that can be properly managed on the farm (TN_{onsite}^{DLA}) in the DLA case is calculated as in Equation (4).

$$TN_{onsite}^{DLA} = A\,\bar{N}_{crop} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(4)$$

To minimize the external environmental costs, excess manure that the on-site land cannot absorb by following the agronomic nitrogen requirements should be transported to off-site field croplands in the DLA case (and in the AD case, if any)[15]. The excess nitrogen that needs to be managed off-site ($TN_{offsite}$) is defined in Equation (5):

$$TN_{offsite}^{DLA} = TN_{land}^{DLA} - TN_{onsite}^{DLA} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

where TN_{land}^{DLA} is total nitrogen available for land application from the typical large dairy farm in the DLA case.

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[15] Only liquid parts of the digested manure are applicable to the cropland in the AD case. In our case study, AD does not have excess manure to be hauled off-site.

Some of the off-site lands may not be suitable to receive dairy manure as a fertilizer. Also, some off-site farmers may not be willing to accept dairy manure as a substitute for commercial fertilizer for various reasons. For instance, dairy manure may not fulfill the required nutrient requirements of a specific crop in proper proportion or might be subject to the problems of pathogens, salinity, and odors. Both the fraction of the off-site land that is suitable for receiving dairy manure (σ_1^{crop}) and the percentage of surrounding farmers who are willing to accept dairy manure (σ_2) are controlled to model the total land area to be searched for the disposal of excess manure. The total land area to be searched ($\tilde{A}$) is calculated as described in Equation (6). Around 90% of large dairy farms in New Mexico are concentrated in five southeastern counties (USDA, 2012) (see Appendix for Chapter 3, Table B.5 and Figure B.6). Thus, the fraction of surrounding land suitable for receiving dairy manure is calculated as the ratio of the total area of field crop lands in these five counties over the total area of the five counties: σ_1^{crop} =67,455 ha/4,692,022 ha=1.4%.

Ribaudo et al. (2003) examine over a willingness-to-accept-manure (WTAM) range between 10%-80% and find that crop producers' WTAM is a very important determinant of manure-spreading costs. Aillery et al. (2005) assume a WTAM of 30% in the Chesapeake Bay watershed to ensure that all the manure produced in the region can be land-applied at a rate based on the nitrogen needs of crops. Wang and Baerenklau (2015) use three levels of WTAM (20%, 60%, and 100%) for the Central Valley region to perform sensitivity analysis. Being consistent with the literature, we conduct sensitivity analysis allowing the impact of variation in WTAM of 10%, 30%, 50% and 80% on off-site hauling costs and net benefits in the baseline scenario (see the Appendix for Chapter 3, Figures B.10 and B.11). Following these developments in the literature and with known information that the willingness to accept manure by offsite farmers is low because of various economic and environmental reasons, we assume an off-site willingness to accept manure of 30% in the main analyses[16].

Again, since the unit of this analysis is the typical large dairy farm, equations (1) through (6) take into account the land restriction faced to the typical dairy farm, but the analysis has not restricted or defined the size and boundary of the off-site crop lands since such considerations are outside the scope of the study. Moreover, the analytical approach developed in equation (6) for $\tilde{A}$ should not be viewed as a fixed parameter, because depending on the level of willingness to accept manure by off-site farmers, the values for $\tilde{A}$ also changes (see section '3.3.3 Sensitivity Analysis' for different possible values for $\tilde{A}$ and associated hauling costs within different possible context and assumptions). While the land restriction to account for available on-site cropland that the typical dairy farm owns is taken into account, the land restriction for off-site land sizes has not been controlled to allow the land application as one of plausible proper manure management methods.

$$\tilde{A} = \frac{TN_{offsite}^{DLA}}{\sigma_1^{crop}\sigma_2\bar{N}_{crop}} \dots \dots \dots \dots \dots \dots (6)$$

The average hauling distance for excess manure determines off-site hauling costs and is calculated following Keplinger and Hauck (2006), Baerenklau et al. (2008), and Wang and Baerenklau (2015). We assume that both the land in the typical dairy farm and

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[16] WTAM is applicable only to the DLA case. WTAM is critical determinant of hauling cost of manure to off-site willing croplands. As illustrated in Appendix for Chapter 3, Figures B.10 and B.11, when WTAM increases from 30% to 80%, the hauling cost declines by about 5 times and the net present of benefits in the DLA case increases substantially. These patterns clearly indicate that if WTAM by offsite farmers increases, dairy farmers will bear declined burden on hauling cost part.

the total land required for manure management have the shape of a disk, with the dairy farm at the center of the two disks. The area of the inner disk is A (the land size that the typical large dairy farm contains), and the area of the outer disk is the sum of A and $\tilde{A}$. The radii of the outer and inner disks are ξ_1 and ξ_2, as calculated in equations (7)–(8). Assuming the average hauling distance of excess manure to off-site croplands ($\hbar_d$) as a straight line, Equation (9) is used to calculate the average hauling distance.

$$\xi_1 = \sqrt{(A + \tilde{A})/\pi} \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

$$\xi_2 = \sqrt{A/\pi} \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

$$\hbar_d = \frac{1}{\tilde{A}} \int_{\xi_2}^{\xi_1} (\xi * 2\pi\xi) dr = \frac{2(\xi_1^3 - \xi_2^3)}{3(\xi_1^2 - \xi_2^2)} . \ldots\ldots\ldots\ldots\ldots\ldots . (9)$$

Land requirement in the AD case for the crops to absorb all the available nitrogen ($A^{AD} = \frac{TN_{land}^{AD}}{\bar{N}_{crop}}$ =354 ha/yr) is smaller than the land owned by the typical dairy farm, indicating there is sufficient cropland on the farm to absorb manure and no off-site hauling is necessary. In the ADMC case, land is required for microalgae cultivation, and the information on land area is required to assess water balance of ADMC. Following Zhang et al., (2013), land requirement of ADMC (A^{ADMC}) is calculated as in Equation (10), where μ_1 is mass fraction of phosphorus in microalgae biomass, μ_2 is mass fraction of solid digestate, and θ is microalgae productivity (ash free dry weight) for open pond microalgae. The parameter values are P_{ADMC}= 63 kgP/day, μ_1 = 0.013 (Mulbry et al., 2008), μ_2 = 0.6, and θ = 0.0126 kg/day-m^2 (Clarens et al., 2010). The land required in the ADMC case to consume all liquid digestate phosphorus is 64 ha. Table 3.1 summarizes the characteristics of typical dairy farm in New Mexico.

$$A^{ADMC} = \frac{P_{ADMC}}{\mu_1 \mu_2 \theta} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(10)$$

Table 3.1: Characteristics of a typical large dairy farm in New Mexico

Variable	Definition	Unit	Value
H	Number of milk cows	Head	2892
A	Land area contained in the typical large dairy farm	Hectare	391
α	Share of field crop land growing alfalfa	Fraction	0.8
$\overline{ET}_{crop}$	Average evapotranspiration (ET) per unit of field cropland	inch	49.4
$\overline{N}_{crop}$	Average nitrogen requirement for all crops per unit of cropland	kgN/ha	93.4
σ_1^{crop}	Off-site crop land suitable for receiving dairy manure	Fraction	0.014
σ_2	Percentage of surrounding farmers that are willing to accept dairy manure	Fraction	0.3
TN_{land}^{DLA}	Total nitrogen available for land application from the typical large dairy farm	kgN/year	78,373
TN_{onsite}^{DLA}	Total nitrogen that can be properly managed on the typical dairy farm	kgN/year	36,746
$TN_{offsite}^{DLA}$	Excess nitrogen that needs to be managed off-site the typical large dairy farm	kgN/year	41,627
$\tilde{A}$	Off-site land area to be searched to haul the excess manure	hectare	106,400
ξ_1	Radius of the outer disk	km	18
ξ_2	Radius of the inner disk	km	1.2
$\hbar_d$	Average hauling distance of excess manure to off-site croplands	km	12
A^{AD}	Land requirement of the AD case	Hectare	354
A^{ADMC}	Land requirement of the ADMC case	Hectare	64

3.2.3 Data for Life Cycle Assessment

Energy balance denotes the difference between energy output and energy input, and energy ratio is the rate of energy produced per unit of energy invested (i.e., energy output divided by energy input). The higher the energy balance and energy ratio are, the greater the economic and technical favorability for energy production will be. Both are estimated to evaluate the relative favorability of each manure management case for energy production. The DLA case requires energy to spread manure to the on-site croplands and to transport excess manure off-site. The AD case requires electricity for the operation of the digester (e.g., dilution and infrastructure operation) and heat for the maintenance of temperature for optimal biogas production. The ADMC case requires a significant amount of energy in several of its stages. Water, CO_2, and nutrients are the major inputs in the microalgae cultivation system and pumping these inputs into the open pond consumes energy in large quantity. The open pond system requires continuous circulation of nutrients with the water so that photosynthetic efficiency of the biomass is optimized, and thus, electricity is continuously required to perform this operation. Energy is also needed to harvest and dewater the biomass. As the produced biomass is used for biogas production in the anaerobic digestion, the anaerobic digestion process in the ADMC case also requires energy as in the AD case. For this study, we adapted energy input and output data from (Lazarus, 2014), Zhang et al. (2013) and (Sanford et al., 2009) as reported in Table 3.4.

Water balance is another component of our LCA analysis and is an extension of the literature in the field. Water scarcity is expected to increase due to climate change, population growth, and economic development in New Mexico. Water conservation goals can be partially achieved by recycling and reuse of wastewater. Apart from dairy manure, wastewater generated on large dairy farms also contains pollutants that can harm the environment and public health (Ulery et al., 2004). Dairy wastewater reuse serves three goals of water conservation, water quality preservation and recovering the nutrient value in dairy waste. We examine potential reuse of wastewater on the typical large dairy farm under all the three cases. For each case, the volume of wastewater is compared to total on-site water requirement (within the system boundary) to investigate water balance.

Dairy farms require water for cow drinking, farmhouse cleaning, cow cleaning, manure collection, and other uses in the milking parlor (e.g., cleaning tanks, pipelines, house floor, and other equipment). Water requirements of a milking cow can vary widely, depending on the type of manure removal system and other factors. Guerrero et al. (2012) find a direct water use of 55 gallons per day per milk cow in the Texas High Plains. Longworth et al. (2013) pointed out that efforts have been made in past years by the dairy industry in New Mexico to reduce the amount of water used in facility sanitation and water use per day per milk cow in New Mexico was reduced from 100 to 65 gallons based upon information from area studies and experts. Total wastewater generated, including wastewater from the milk house, parlor, and cow holding area but excluding wet manure, is around 14.7 gallons per day per milk cow (Holmes and Struss, 2009). Thus, total wastewater generated on the typical dairy farm is 42,512 gallons per day (or 15.5 million gallons/yr).

For the DLA case, water is required for irrigating the three field crops (alfalfa, wheat, and corn) grown on-site. In addition to climate and soil quality, the efficiency of irrigation systems also influences irrigation water requirement. In New Mexico, the common method of irrigation is gravity (flood or furrow) followed by sprinklers, and the average irrigation efficiency (η) is 80% (Samani et al., 2005). The total irrigation water requirement of DLA (W_{irrig}^{DLA}) is calculated as in Equation (11) to be 1,620 million gallons/yr.

$$W_{irrig}^{DLA} = \frac{A \cdot \overline{ET}_{crop}}{\eta} \dots\dots\dots\dots\dots\dots\dots..(11)$$

In the AD case, over dilution of manure adversely affects biogas productivity and hydraulic retention time. Therefore, manure should be optimally diluted to maximize biogas production in the anaerobic digestion. Dairy manure as excreted contains 12% solids and 10.5% volatile solids, but digester efficiency is optimized at the concentration of 6-7% of total solids (Dennis and Burke, 2001). Generally, for every 5 kg of fresh manure, water required for manure dilution is approximately 4 gallons (An et al., 1997). The amount of water that is required to dilute the excreted manure for anaerobic digestion (W_{digest}^{AD}) in a typical dairy farm is then 48 million gallons/yr.[17] Using the same approach as in the DLA case, we estimate the irrigation requirement in the AD case (W_{irrig}^{AD}) to be 1,465 million gallons per year. Using Equation (12), the total water requirement of the AD case (W^{AD}) is 1,513 million gallons per year.

$$W^{AD} \; = \; W_{irrig}^{AD} + W_{digest}^{AD} \dots\dots\dots\dots\dots\dots..(12)$$

The total water requirement of the ADMC case consists of water required for the anaerobic digestion of dairy manure and microalgae cultivation. The former is the same as in the AD case, with W_{digest}^{ADMC} equal to 48 million gallons per year. Microalgae slurry

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[17] The total excretion wet manure is 56.7 kg/cow-day in New Mexico (see Appendix for Chapter 3, Table A.1) so the typical dairy farm excretes 59,851,386 kg wet manure per year.

contains about 6.05% of total solids (Olsson et al., 2014), which is within the range of optimal concentration of total solids for digester efficiency. Therefore, no dilution is needed for the microalgae slurry before it enters the digester. For the microalgae pond, water lost through evaporation needs to be replaced daily. The amount of water required for microalgae cultivation (W_{algae}^{ADMC}) is calculated using Equation (13), where A^{ADMC} is the land area of microalgae production pond (64 ha), D is the depth of microalgae production pond, E is evaporation loss of water from the microalgae production pond, and τ is the length of microalgae growth. Following Richardson et al. (2010), we have D=2 m, E=0.0127 m/day, and τ=365. Using Equation (14), the total water requirement of the ADMC case (W^{ADMC}) is estimated to be 1,170 million gallons/yr.

$$W_{algae}^{ADMC} = A^{ADMC}(D + \tau E) \dots\dots\dots\dots\dots(13)$$

$$W^{ADMC} = W_{digest}^{ADMC} + W_{algae}^{ADMC} \dots\dots\dots\dots\dots\dots(14)$$

Potential emissions of nitrogen and phosphorus occur through various mechanisms like volatilization, leaching, and runoff during different stages of the manure handling process (e.g., during manure collection, storage, and application). The eutrophication potential accounts for emissions of nutrients and other chemicals such as nitrogen monoxide, nitrogen oxides, ammonium, nitrogen, and phosphorus (Zhang et al., 2013a). The global warming potential consists of emissions of CO_2, nitrous oxide, and methane. In the DLA and AD cases, GHGs emit during the processes of manure storage, land application, and from the production of input materials. Energy consumption is the major source of global warming potential in all cases. AD and ADMC additionally co-produce GHGs from the bio-electricity production process. In the scenario of best data available in the absence of New Mexico-specific information, we adapted the eutrophication potential and global warming potential values from Zhang et al. (2013) to the large dairy farms of New Mexico: the per cow eutrophication potential values are respectively 30.24, 21.62 and 0 kg PO_4-eq/yr for DLA, AD and ADMC; the per cow global warming potential values for the three cases are respectively 4.37, 3.37 and 3.09 Mg CO_2-eq/yr.

3.2.4 Data for Cost-Benefit Analysis

We examine the life-cycle costs, revenue, and present value of net benefit of each case under two types of scenarios: a baseline scenario and alternative policy scenarios. In the baseline scenario, we conduct cost-benefit analysis without considering any incentive-based policies, by assuming agronomic nitrogen application rates for land application of manure (current dairy rule in New Mexico will require dairy farmers to follow crop specific nitrogen application rates for land application of manure). Therefore, in the context of DLA, the baseline scenario intends to provide a perspective on economic profitability of dairy farmers in relation to the profitability of AD and ADMC when the dairy farmers are required to follow crop specific nitrogen application rates. For the policy scenarios, we simulate existing and prospective policies that have been or will potentially be adopted to control nutrients and greenhouse gas emissions from the agricultural sector or to incentivize bioenergy production and reduction of these emissions. The present value of net benefit of each case under each scenario is calculated as in Equation (1), where NB is the sum of the present value of the net benefit in each year of the planning period, TR is total revenue, TC is total cost, τ is the tax rate, r is the discount rate, and t is the index of year.

$$NB = \sum_{t=1}^{T} \frac{(TR - TC)(1 - \tau)}{(1 + r)^t} \ldots\ldots\ldots\ldots.(1)$$

Since the common lifecycle of anaerobic digesters is 20 years with a steady stream of net income over the life span (Martin, 2005; Zhang et al., 2013), the net benefit of each case is calculated for a 20-year planning period. We assume that the beginning period of all the cases is the year 2015, the average tax rate is 28.6%, and the discount rate is 5%.[18] Total cost is the sum of initial outlays (i.e., capital costs) and operating and maintenance (O&M) costs.[19]

3.2.4.1 Baseline Scenario

In the DLA case, initial outlays and O&M costs are associated with manure collection, handling, off-site transportation and land application. Following (Pfost and Fulhage, 2003) and (Zhang et al., 2013a), we calculate the initial outlays of the DLA case using Equation (16), where I^{DLA} is the manure land application costs ($/cow) and H is the number of cows. Note that the initial outlay exhibits economies of scale with increased farm size. Given the size of the typical large dairy farm in New Mexico, the initial outlay of the DLA case is $692.7/cow, which is $704/cow in 2014-dollar value.

$$I^{DLA} = 1732.1H^{-0.115} \ldots\ldots\ldots\ldots\ldots..(16)$$

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[18] Tax rate is the sum of approximate current federal and state tax rates: federal tax rate is 21.6% (http://www.ers.usda.gov/media/997011/eib-107.pdf) and state gross receipt tax lies between 5.125% to 8.9375% with an average of 7%, taking the mid value of the lower and upper bound with equal weights (http://www.tax.newmexico.gov/gross-receipts-tax-historic-rates.aspx).

[19] Initial outlays are discounted by the seven years of Modified Accelerated Cost Recovery System (MACRS-Internal Revenue Service), which is a smart tax policy used to depreciate the current tax burden in the US. This policy of Internal Revenue Service (IRS) allows depreciation of capital investment on a percentage basis for a specific period from taxable income so that tax burdens could be reduced at the beginning of the long-term project. The depreciation period and rates differ by property types as defined by the IRS, but the total deprecation will be 100% of the capital investment. Agricultural equipment and machinery and anaerobic digesters fall into the seven-year depreciation category.

The O&M cost is the sum of costs of on-site manure land application and off-site manure hauling. The O&M costs for manure land application include the costs of labor, fertilizer, electricity, fuels, insurance, and other miscellaneous items and are approximately $93.5/cow-yr (Zhang et al., 2013a). We assume that dairy farmers solely bear all costs associated with hauling the excess manure to off-site farms.

Table 3.2: Initial outlay and operating and maintenance (O&M) costs for the typical large dairy farm in New Mexico in DLA, AD, and ADMC under all scenarios

Costs	Categories	Unit	DLA	AD	ADMC	Reference
Initial outlay	**Manure land application**					
	Manure on-farm application	$	2,036,667	1,914,468	0	Zhang et al. (2013)
	Anaerobic digestion					
	Digester system	$	0	2,560,008	3,303,459	Lazarus (2014)
	Post-digestion solids separation	$	0	229,617	271,157	Lazarus (2014)
	Hydrogen sulfide treatment	$	0	111,221	131,342	Lazarus (2014)
	Utility requirements	$	0	190,152	224,552	Lazarus (2014)
	Algae cultivation system					
	Infrastructure and equipment	$	0	0	5,400,267	Zhang et al. (2013)
	Algae homogenizer	$	0	0	687,472	Zhang et al. (2013)
	Miscellaneous	$	0	0	2,700,133	Zhang et al. (2013)
	Total	$	2,036,667	5,005,466	12,718,382	
O&M	**Manure land application**					
	Manure on-farm application	$/year	270,380	254,157	0	Zhang et al. (2013)
	Manure off-farm hauling	$/year	18,726,400	0	0	Estimated by author
	Anaerobic digestion					
	Engine overhaul & spare engine cost	$/year	0	80,850	80,850	Lazarus (2014)

Digester sludge cleanout	$/year	0	6,930	6,930	Lazarus (2014)
Labor cost for routine O&M	$/year	0	5,023	5,023	Lazarus (2014)
Oil changes & other routine O&M	$/year	0	11,550	11,550	Lazarus (2014)
Algae cultivation system	$/year	0	0	1,328,802	Lazarus (2014)
Total	$/year	18,996,780	358,510	1,433,155	

*All zero values reported in the table indicate 'not applicable.' Source: Lazarus (2014); Zhang et al. (2013)

The average hauling distance ($\hbar_d$) in the DLA case is 12 km with a corresponding hauling cost of $176/km-12ha (see Appendix for Chapter 3, Table B.6). Thus, the total hauling cost for the typical dairy farm (associated with hauling manure to off-site farms of size 106,400 hectares) is $18,726,400/yr. The hauling cost of the DLA case remains the same in all scenarios, except in the sensitivity analysis of manure application to rangeland. The initial outlay and O&M costs for the DLA case are reported in column (4) in Table 3.2.

Total revenue in the DLA case equals the sales value of produced crops on the farm, which depends on prices and quantities of produced crops during the planning period (see the Appendix for Chapter 3, Figures B.7 and B.8 for historical variations in field crop prices and yield rates in New Mexico). For simplicity, we use the 2012 yield rates (bushel/ha) and per unit prices ($/bushel) (see Appendix for Chapter 3, Table B.7). The impacts of crop price volatility are left for future research. Using the prices and yield rates of the major crops and the cropland area, total revenue per typical dairy farm in the DLA case is $2,684,231/yr.

In the AD case, the initial outlay refers to all initial costs incurred by the anaerobic digestion system (e.g., digester tank, boiler and heat exchanger, building, and other materials), post-digestion solid separation system (e.g., solid-liquid separator, composter, and dryer), and hydrogen sulfide treatment system. The initial outlay also accounts for utility charges, which includes the costs of the power generator and gridline connection. Similar to the DLA case, the initial outlay declines with the increase in the farm size due to economies of scale (see Appendix for Chapter 3, Figure B.9). As digested manure is applied to croplands, initial outlays also contain costs for manure collection and land application equipment. The procedure applied to calculate the cost of manure land application is the same as described in the DLA case. However, as only the digested liquid manure is applied to croplands, the typical dairy farm in DLA with 2,892 cows is equivalent to a farm in AD with 2,719 cows in terms of nitrogen content in the digested liquid (Zhang et al., 2013a). The off-farm hauling cost is zero here as the land requirement in the AD case is smaller than the land owned by the typical dairy farm. The initial outlays on the anaerobic digestion system is $3,090,998 per typical dairy farm, and initial outlays for manure land application are $1,914,468. Similarly, the O&M cost includes various operational costs such as maintenance, repairs, labor, fuel, and insurance. The O&M cost of the typical dairy farm in the AD case is $358,510/yr. The initial outlay and O&M costs for the AD case are reported in column (5) in Table 3.2.

Sale of bio-electricity is the major source of income in the AD case. As previously discussed, the annual net energy surplus per typical dairy farm in the AD case is 8,714,956 kilowatt hours. We assume that the bio-electricity generated on the dairy farm can be fully sold back to the electric grids under mandatory policies, and the sale price of electricity in the agricultural sector of New Mexico is $0.066 per kilowatt hours (Informa, 2013). The digested solid is also an important component for revenue generation in the AD case. The digested solid has a high use value for various reasons (US Environmental Protection Agency, 2013). Its low nutritive content attracts its use as a soil conditioner (i.e., soil amendment) because there is a low risk for nitrate pollution, gaseous pollution, and pathogen problems when applied to the land. The high value of digested solid manure also pertains to the organic bedding material. If no demand for digested solid manure exists in the local market, it can also be easily transported to other regions where demand is high. We assume that all the digested solids can be sold in the market and the value of digested solid manure (i.e., nutrients and fiber) is $259.14/cow-yr (US Environmental Protection Agency, 2013). The typical dairy farm generates additional income from the sale of crops as the digested liquid is directly applied to the cropland. Calculation of crop revenue is similar to that in the DLA case. Total annual revenue (aside from animal and milk sales) in the AD case is $3,750,771 per typical dairy farm.

The parameters for initial outlays and O&M costs in the anaerobic digestion process of ADMC are the same as in the AD case. However, as manure is co-digested with microalgae, the volume of post-digestion material is higher in ADMC than in AD and thus, the cost is higher in the digester system of ADMC. The typical dairy farm in DLA with 2,892 cows is equivalent to a large dairy farm in ADMC with 5,639 cows based on initial outlays (Zhang et al., 2013a). In addition to the costs introduced in the AD case, ADMC requires initial outlays and O&M costs in the microalgae cultivation system. The microalgae cultivation system contains various expenses such as pond construction, engineering designs, algal homogenizer, cultivation, and harvesting. The initial outlays for microalgae cultivation system in the ADMC case is about $13 million and the O&M costs are about $1.5 million per year for the typical dairy farm. The costs of ADMC are summarized in column (6) in Table 3.2. Similar to the AD case, the major sources of income in the ADMC case are the sale of bio-electricity and digested manure. Crop revenues are not applicable in this case as there is no need to dispose the digested liquid manure. The revenues are calculated by following the procedure as in the case of AD with the same assumptions. Total annual revenue (aside from animal and milk sales) in the ADMC case is $1,942,921 per typical dairy farm. The total revenue data of all cases under the baseline scenario are reported in the first five rows of Table 3.3.

Table 3.3: Annual revenues for the typical large dairy farm in New Mexico in DLA, AD, and ADMC under alternative scenarios

Scenarios	Revenues	Unit	DLA	AD	ADMC	References
Baseline	Sale of crops	$/year	2,684,231	2,430,224	0	Zhang et al. (2013)
	Sale of bioelectricity	$/year	0	571,125	818,787	Zhang et al. (2013)
	Sale of digestate	$/year	0	749,422	1,124,134	US Environmental Protection Agency (2013)
	Total	$/year	2,684,231	3,750,771	1,942,921	
Policy	*Additional revenues*					
	Sale of nutrients credits (N)	$/year	0	847,650	8,639,346	Zhang et al. (2013)
	Sale of nutrient credits (P)	$/year	0	2,182	4,400	Zhang et al. (2013)
	Sale of carbon credits (CO_2)	$/year	0	73,110	100,237	Zhang et al. (2013)
	Total	$/year	2,684,231	4,673,713	10,686,904	

* All zero values reported in the table indicate 'not applicable.'

Source: US Environmental Protection Agency (2013); Informa (2013); Zhang et al. (2013)

3.2.4.2 Policy Scenarios

Different state and federal policies have been adopted to control nutrients and GHG emissions in the agricultural sector, including bioenergy production incentives to reduce pollutions. We call these types of policies "green policies." Given the set of various incentive-based policies available in the renewable energy sector of New Mexico, we choose the Agricultural Biomass Income Tax Credit as the major current green policy as this is most relevant in our case study (see the Appendix for Chapter 3, section B1 for details). According to this policy, a dairy farmer gets a $5 credit per ton of dairy manure used for bioenergy production, and the total credit limit is $5 million. This policy expires at the end of December 2019. Thus, we include this credit from 2015-2019 in the current policy scenario (or the tax credit scenario). In our case study, the typical dairy farm receives $0.33 million credits per year for five years as the 'agricultural biomass income tax credit.' Other revenues and costs in the current policy scenario are the same as in the baseline scenario for all the manure management cases.

Carbon and nutrient credits are market-based incentives that can be earned by offsetting their emissions below the regulatory compliance. These credit markets are considered to be efficient tools to combat climate change, and to protect water quality and the ecosystem as the markets create incentives to reduce GHG emissions and nutrient loading (Avi-Yonah and Uhlmann, 2009; Hoag and Hughes-Popp, 1997). Currently, California and the Regional Greenhouse Gas Initiative in the US are regulating GHGs through cap-and-trade policies (NICC, 2015). Some states like Virginia, Maryland, and Pennsylvania are regulating nutrient loading through trading markets to preserve the water quality of the Chesapeake Bay (Branosky et al., 2011). These environmental credits markets have been adopted in the other states and are potentially available in the future to large dairy farms in New Mexico as prospective green policies.

The carbon and nutrient credits are applicable in the AD and ADMC cases because they both have lower global warming potential and eutrophication potential relative to the reference DLA case. Under this prospective policy scenario, the initial outlays and O&M costs of all cases also do not change from the baseline scenario, as reported in Table 3.2. The net benefits of the DLA case are the same as in the baseline scenario. For AD and ADMC, the only difference is the additional revenues generated from nutrients and/or carbon credits. In the AD case, the annual N, P and CO_2 credits per cow are respectively 13.33 kgN, 0.05kgP and 2,528 kg-CO_2 and in the ADMC case, they are 135.87 kgN, 0.09 kgP and 3,466 kg-CO_2 in the same order (Zhang et al., 2013a). Thus, the typical dairy farm in New Mexico generates a total of 84,995kgN, 136kgP, and 7,310,976kg- CO_2 credits in a year. The prices of N, P and CO_2 credits per kg are $9.07 (Jones et al., 2010), $12.5 (Greenhalgh et al., 2003) and $0.01, respectively (see the Appendix for Chapter 3, section B.1.5 for more information). We also conduct a sensitivity analysis with ±25% changes in the prices of N, P and CO_2 credits to examine the economic impacts of real market conditions with potentially fluctuating credit prices. The total revenue data of all cases under the policy scenarios are reported in the last five rows of Table 3.3.

[redacted] Results and Discussions

3.3.1 LCA Results

The input-output calculations of energy in the three cases are reported in Table 3.4. Energy balance in the DLA case is -3,380 gj/yr, which means the DLA case consumes 3,380 gj of net energy annually. In the AD and ADMC cases, energy balances are 31,374 gj/yr and 15,670 gj/yr, respectively. Although total energy production in the ADMC case is highest among all the cases, energy balance, in this case, is about 50% less than that of the AD case.

Table 3.4: Energy input, output and net surplus for the typical large dairy farm in New Mexico in alternative dairy manure management cases (in gj/year)

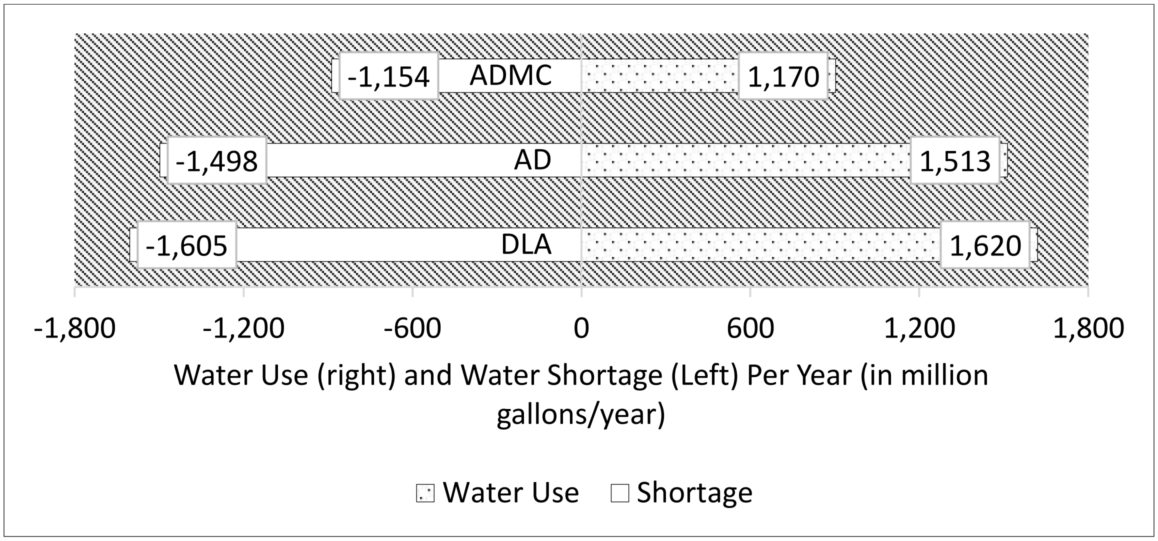
	DLA	AD	ADMC	Reference
Total energy input	**3,380**	**1,739**	**31,803**	
On-farm manure land application	629	265	0	Zhang et al. (2013)
Off-farm manure hauling	2,635	0	0	Estimated by author
Algae cultivation	0	0	6,976	Lazarus (2014)
Anaerobic digestion (electricity)	0	521	7,899	Lazarus (2014)
Anaerobic digestion (heat)	0	405	846	Lazarus (2014)
Infrastructure burden	116	549	16,081	Zhang et al. (2013)
Total energy output	**0**	**33,113**	**47,473**	
Energy Net Surplus	**-3,380**	**31,374**	**15,670**	
Energy Ratio	**0**	**19.0**	**1.5**	

Source: Lazarus (2014); Zhang et al. (2013)

A zero energy ratio of DLA indicates that DLA is completely infeasible from the energy production perspective. The energy ratio is 1.5 for ADMC, implying that 1.5 units of energy can be produced per 1 unit of energy invested. The energy ratio of ADMC would seem economically feasible if it is considered in isolation as it produces 0.5 unit of surplus energy. The energy ratio is 19 for the AD case, implying that it has a comparatively high energy efficiency. Therefore, AD is the most economically and technically feasible system from the energy balance perspective.

The water balance results are illustrated in Figure 3.2. The annual water requirements in DLA, AD and ADMC are 1,620, 1,513 and 1,170 million gallons respectively. ADMC is the least water consumptive case, followed by the AD case, which uses less water than the DLA case. Water shortage in each case is the total water collection in the typical dairy farm minus the water requirement in that case. Total wastewater collection in a typical dairy farm is 16 million gallons/yr. The water shortages in DLA, AD and ADMC are respectively 1,605, 1,498, and 1,154 million gallons/yr. The water balance of the three cases implies that dairy wastewater is not fully sufficient for any of the three cases. However, in terms of water inventory analysis, ADMC is the least water consumptive case. Water demand is higher in DLA and AD due to irrigation water requirement for the croplands. The anaerobic digestion of dairy manure in both AD and ADMC case requires 48 million gallons of water annually. AD demands additional water for crop irrigation (1,466 million gallons/yr in the typical dairy farm). Apart from water requirement for anaerobic digestion, ADMC also requires water for microalgae cultivation (1,122 million gallons/yr in the typical dairy farm). The water balance estimates imply that ADMC is the most sustainable case among all three cases of dairy manure management. Thus, given the arid and semi-arid attributes of New Mexico, the ADMC case can contribute to water conservation relative to both DLA and AD cases in addition to its contribution to renewable energy production. If ADMC is considered in isolation, it would require huge amounts of water to commercialize the microalgae based bio-energy. However, microalgae can be grown in wastewater from dairies as well as from other sectors, which can largely reduce the demand for fresh water in ADMC in New Mexico.

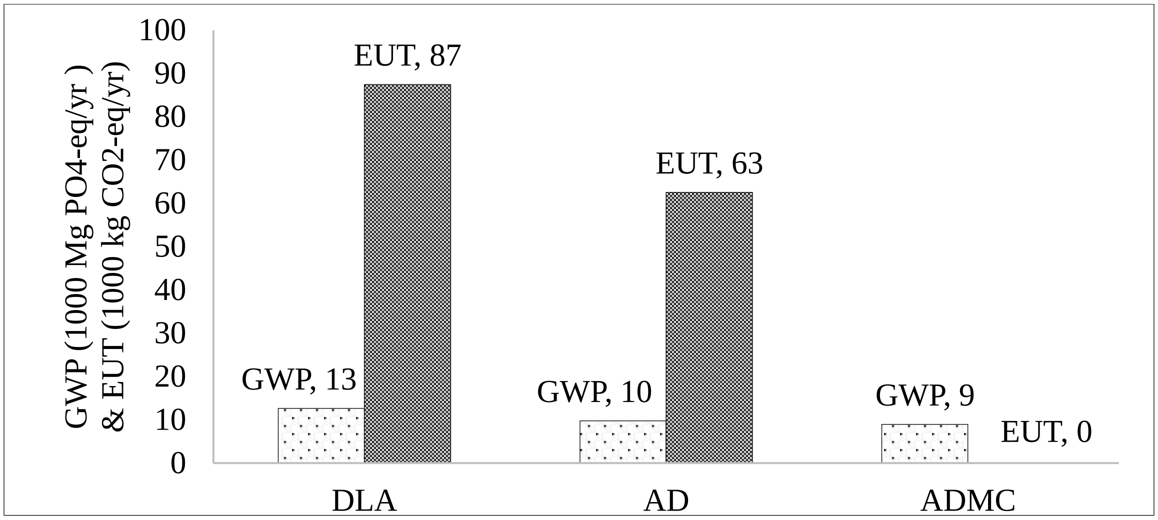
Figure 3.2: Water usage and water shortage in the DLA, AD, and ADMC cases



The DLA and AD cases are sensitive to eutrophication potential as manure is stored and applied to the cropland in both cases. For the ADMC case, as dairy manure is co-digested with microalgae throughout the year, there is no need to store dairy manure and thus, no nutrient emissions from such processes. There can be nutrients emissions through volatilization during microalgae production process, but studies have found that this type of emission is small (Cai et al., 2013; Smith et al., 2010). Following the literature (Cai et al., 2013; Smith et al., 2010), we conclude eutrophication potential is zero in the ADMC case. The eutrophication potential and global warming potential of all cases are presented in Figure 3.3. Eutrophication potential is 87,454 kg PO_4-eq/yr in the DLA case and 62,525 kg PO_4-eq/yr in the AD case for the typical large dairy farm. In terms of eutrophication potential, ADMC is the most sustainable followed by AD while DLA poses the highest risk of eutrophication. Global warming potential is highest in the

DLA case (13,000 Mg CO_2-eq/yr) and lowest in ADMC (9,000 Mg CO_2-eq/yr). Global warming potential in the AD case is 10,000 Mg CO_2-eq/yr, which is between DLA and ADMC. These results imply that ADMC is most sustainable in terms of global warming potential.

Figure 3.3: Global Warming Potential (in 1000 Mg CO2-equivalent per year) and Eutrophication Potential (kg PO4-eq/year) in the DLA, AD, and ADMC cases



3.3.2 CBA Results

3.3.2.1 Baseline Scenario

The net benefit estimates of DLA, AD, and ADMC under the baseline scenario are respectively -\$146.70 million, \$26.38 million and -\$5.12 million, as reported in the second row in Table 3.5. The net benefit is positive only in the AD case. The negative net benefits of the DLA and ADMC cases imply that these systems are not economically feasible under the baseline scenario. The net benefit is the lowest in the DLA case mainly due to the limitation of sufficient croplands on and surrounding the typical dairy farm such that the cost of off-site manure hauling is very high under the current nutrient management plans regulation. Higher costs and limited sources of income result in the negative net benefit in the ADMC case. The high cost of ADMC is associated with high energy input in the system and thereby reducing the energy surplus for sale.

Table 3.5: Present value of net benefits for the typical large dairy farm in New Mexico in DLA, AD, and ADMC under alternative scenarios (in million $)

Scenarios			DLA	AD	ADMC
Baseline			-146.70	26.38	-5.12
Policy	Current		-146.70	27.82	-3.68
	Prospective	Carbon credits	-146.70	27.04	-4.23
		Nutrient credits	-146.70	33.95	71.79
		Combined nutrient & carbon credits	-146.70	34.60	72.69

3.3.2.2 Policy Scenarios

The net benefits of all cases under the current policy scenario are reported in the third row in Table 3.5. The agricultural biomass income tax credit is not applicable to the DLA case and thus, net benefit of DLA remains the same as in the baseline scenario, which is about -$146.70 million. The tax credit under consideration is applicable to both AD and ADMC. Net benefit of AD is $27.82 million under the current green policy compared to $26.38 million in the baseline scenario. Similarly, net benefit of ADMC is -$3.68 million, compared to -$5.12 million in the baseline scenario. Under the tax credit scenario, net benefit of AD increases by more than $1 million from the baseline scenario.

Similarly, the tax credit also reduces the negative net benefit of ADMC from the baseline by about \$1.4 million, but it is still negative. The results imply that the current green policy in New Mexico can mitigate the cost burden of bioenergy projects, but the incentives may not be strong enough for the large dairy farms to switch from the status quo to alternative dairy manure management systems (e.g., AD and ADMC).

The results with nutrient credits and carbon credits are reported in the last three rows in Table 3.5. When only nutrient credits are applied, the net benefits of AD and ADMC are raised to \$33.95 million and \$71.79 million, respectively. In the baseline and current green policy scenario, the net benefit of the ADMC is negative; however, it increases drastically when nutrient credits are taken into account. The net benefit of the AD case has also increased from the baseline and current policy scenario by about \$6 million. However, the negative net benefit of ADMC in the earlier scenario is now highest by more than 50% relative to the net benefit of the AD. The net benefit of ADMC has increased drastically because it has no eutrophication potential under this scenario. Nutrient credits trading does not increase the net benefit of AD as it has a high eutrophication potential.

When only carbon credits are applied, the net benefits of AD and ADMC are \$27.04 million and -\$4.23 million, respectively. These numbers are almost the same as the baseline scenario and thus are smaller than the tax credit scenario. This is because global warming potential exists in all three cases despite being smallest in the ADMC case, and the credits are measured relative to the DLA case. Another reason for not having a significant impact of the carbon credits into the system is the minimal and fluctuating price of the credits (e.g., \$0.01/kg-CO_2). In the US, including New Mexico, regulations are strict in controlling nutrient loading into water bodies. The incentives have been adopted through various ways such as tax credits, grants, and R&D investments in green energy development, but the regulations are not strict in controlling GHG emissions. Thus, our results are consistent with these trends. In other words, strict regulatory policies increase the demand for the credits to maintain the regulatory compliance by emitters and this increases the market price of the credits.

When we allow the combined effects of nutrient and carbon credits, the net benefits of AD and ADMC are $34.60 million and $72.69 million, respectively. The CBA results under the prospective policy scenario imply that the economic competitiveness of anaerobic digestion coupled with microalgae production is obtained only when nutrients credits are accounted for in the analysis. The productivity of the anaerobic digestion increases when dairy manure is co-digested with microalgae. The ADMC is also relatively more environmentally friendly as it recycles the nutrients and emits the least global warming potential. However, microalgae bio-energy has not achieved commercial expansion due to high system costs. The costs can be reduced by innovation in the ADMC technologies and learning-by-doing (Haase et al., 2013). Given the current state of science and technology in the microalgae sector, public policies can play a vital role in providing incentives for technological innovations and reducing capital costs. When nutrient and carbon credits are combined together in all cases, the increments in the net benefit from the nutrients-only credits to the combined credits are a million dollars in each case. This implies that markets for nutrients and carbon credits help improve the economic benefits of the ADMC case substantially, making it the most profitable among all the cases.

3.3.3 Sensitivity Analysis

3.3.3.1 Cropland Availability for Dairy Manure Management

In New Mexico, about 20% of dairy farms own more than 800 ha of land (USDA, 2012). We simulate the possibility that the typical dairy farm owns sufficient land (800 ha) to manage the produced manure on-site. This means that there is no excess manure in this scenario and thus, there is no off-site hauling cost. Off-site hauling cost is only applicable in the DLA case under the baseline and policy scenarios, and thus, the O&M costs decrease in the DLA case in the absence of off-site hauling. The revenue also increases for the DLA in this scenario from the baseline and policy scenarios as the on-site cropland area has increased from 391 ha to 800 ha. Using the crop prices and yield rates of alfalfa, wheat and corn in New Mexico, the total revenue of the typical dairy farm from the sale of crops in the DLA case for 800 ha of land is $5,492,032/yr. The cost and revenue for AD and ADMC remain unchanged from the baseline scenario.

Under this scenario, the net benefits are $44.92 million, $26.38 million and -$5.12 million in DLA, AD and ADMC, respectively (see Table 3.6). The highest economic profits in the DLA case imply that if a dairy farm contains sufficient cropland suitable for receiving manure, the best and least costly manure management strategy is a direct land application. However, a dairy farm may not have sufficient land to use produced manure when following agronomic nitrogen application rate. In New Mexico, only 20% of dairy farmers own more than 800 ha of land and on average, the typical dairy farm in the state owns only about 391 ha of land. This validates the argument discussed in the earlier scenarios that the limitation of cropland is the major reason for the economic infeasibility of the DLA case. The implementation and enforcement of environmental regulations also influence dairy farmers' decision to make the alternative best use of the manure. For instance, any lack of enforcement of nutrient management plans in New Mexico may be one of the major reasons that (over-) application of dairy manure to croplands is very common in the state.

Table 3.6: Sensitivity analysis of present value of net benefits for the typical large dairy farm in New Mexico in DLA, AD, and ADMC under alternative scenarios (in million $)

		DLA	AD	ADMC
Cropland availability		44.92	26.38	-5.12
Rangeland availability		21.29	26.38	-5.12
Current policy	Tax credits (+25%)	-146.70	30.08	-3.32
	Tax credits (-25%)	-146.70	27.46	-4.26
Prospective policy	Carbon credits (+25%)	-146.70	27.20	-4.00
	Carbon credits (-25%)	-146.70	26.87	-4.45
	Nutrient credits (+25%)	-146.70	35.84	91.02
	Nutrient credits (-25%)	-146.70	32.06	52.57
	Combined nutrient & carbon credits (+25%)	-146.70	36.65	92.14
	Combined nutrient & carbon credits (-25%)	-146.70	32.54	53.23

3.3.3.2 Rangeland Availability for Dairy Manure Management

New Mexico's rangeland covers the 80% of the state's land, and the rangeland lacks necessary nutrients and organic matter (Cabrera et al., 2009). Despite having limited croplands to manage the produced manure from the dairy industry, excess manure could be applied to the nutrient deficient rangeland of the state. This could help meet the regulatory restrictions posed to the dairy producers and improve the quality of rangeland simultaneously. In this sensitivity analysis, we assume that the surrounding rangeland and croplands are both suitable for receiving the excess dairy manure. The land area that needed to be searched to manage excess manure ($\tilde{A}_r$) was calculated by using Equation (17), where σ_1^{crop} is the fraction of surrounding land that is suitable for receiving dairy manure for field crops farming, and $\sigma_1^{rangeland}$ is the fraction of surrounding land that is suitable for receiving dairy manure for ranging. Other procedures for calculating the hauling distance and hauling costs are the same as in the baseline scenario (see Appendix for Chapter 3, Table B.9 for parameter values).

$$\tilde{A}_r = \frac{TN_{offsite}^{DLA}}{\left(\sigma_1^{crop}\bar{N}_{crop} + \sigma_1^{rangeland}\bar{N}_{rangeland}\right)\sigma_2} \dots\dots\dots\dots(17)$$

We have $\sigma_1^{rangeland}$ =80% and from baseline scenario, σ_1^{crop}=1.4%. The agronomic N application rate for the maintenance of healthy rangeland ($\bar{N}_{rangeland}$) is 168 kgN/ha-yr (McFarland et al., 2007). Definitions and assumptions made for the other components of the hauling distance formula are the same as those in the baseline scenario. Using this information, the land to be searched off the farm is 416 ha/yr and the hauling distance in this case is 1 km. As a result, the hauling cost in the scenario is reduced to $46/km-ha, leading an annual hauling cost of a typical dairy farm to $19,136. Here, costs and revenue of the AD and ADMC remain unchanged while the costs of the DLA case are changed from the baseline scenario due to changes in the off-site average hauling distance and thus, the off-site hauling costs.

The net benefit of DLA in this scenario is $21.29 million while the corresponding values of AD and ADMC are the same as in the baseline case (see Table 3.6). When rangeland is included, the net benefit of DLA has not only become positive but has increased substantially from the baseline scenario. Results from this section augment the arguments made in the previous sensitivity analysis. That is, if a dairy farm owns sufficient land or has sufficient land in its vicinity, and if these lands are suitable and willing to accept manure, then this not only allows the dairy farmer to dispose the produced manure, but also to generate profits from it. However, this increased net benefit of DLA does not necessarily suggest that DLA is the economically most favorable case. When rangeland is included as off-site land, the net benefit of AD is more than that of DLA by over $5 million. The implication of the discussion is that looking for alternative best management strategies can benefit all parties in the system. The dairy farm reduces manure hauling costs along with maintaining the regulatory emission compliance while the nutrient deficient rangeland gets nutrients for free.

Rangeland plays a vital role in ecosystem health and the livestock industry (Havstad et al., 2007; Toombs et al., 2011). In the context of increasing regulatory compliance on nutrient emissions, nutrient-deficient rangeland can serve a vital role in the secure management of increasing manure volumes. The rangeland owners can also generate additional income through the reduction of nutrients loadings in the water sources and carbon sequestration potential under the environmental credit trading (George et al., 2011; Ritten et al., 2012; Torell et al., 2014). Currently, USDA and EPA are conducting studies and discussions to enhance public knowledge of environmental credit trading and may enact it as a possible policy instrument along with the existing cap-based environmental policies (Gross et al., 2008; US Environmental Protection Agency, 2013). Similar education programs are needed to increase the willingness of rangeland owners to accept manure as a nutrient supplement.

3.3.3.3 Policy Strength

We also perform a sensitivity analysis of New Mexico's current green policy strength by changing the agricultural biomass income tax credit for the dairy sector by ±25%. The changes affect the annual revenues of AD and ADMC but not DLA. The net benefit estimates for this scenario are reported in Table 3.6. With a 25% increase in the tax credit, the net benefits of AD and ADMC are about \$30.08 million and -\$3.32 million (a net increase of more than \$2 million in AD and less than half million dollars in ADMC). When the tax credit decreases by 25%, the net benefits of both AD and ADMC decrease by less than half million dollars from the status quo. Given that variation in the representative current policy incentives brings substantial changes in the economic benefits of the AD and ADMC cases, the results indicate that the current green policies in New Mexico can play significant role to motivate the large dairy farms to switch from the DLA to alternative dairy manure management systems (e.g., AD and ADMC).

In the sensitivity analysis of the prospective policy scenarios, the environmental credit prices are altered by ±25% to examine the economic strength of such policies in alternative cases. When the carbon credit price is changed by ±25%, the net benefit values of AD and ADMC change by about 1% in the same direction. Similarly, when the nutrient credit price is changed by ±25%, the net benefit values of AD and ADMC change by about 6% in the same direction. With a ±25% fluctuation in the prices of both carbon and nutrient credits, we find the same trend: a change in the credit prices causes a much smaller change in the net benefits of the AD and ADMC cases, and thus does not alter the economic desirability of DLA, AD, and ADMC under alternative policy scenarios. This sensitivity analysis demonstrates the robustness of our previous results.

[redacted] Conclusions

We assess environmental and economic impacts of three alternative dairy manure management cases in this study. A combination of life cycle assessment, cost-benefit analysis, and sensitivity analysis are used in the analysis. By modeling a typical large dairy farm in New Mexico, four environmental impacts and the present value of net benefits of each case are evaluated under a baseline scenario and different policy scenarios. In the LCA analysis, we find that the ADMC case is most favorable among all cases because of the lowest water balance, eutrophication potential, and global warming potential. From the energy balance perspective, AD is most attractive as its net energy surplus is about 50% more than that of the ADMC. The DLA case is the least favorable with regard to any of the environmental impacts. In the CBA analysis, we find that the AD is most profitable in the baseline, tax credit, and carbon credit scenarios. ADMC is most profitable in the presence of a market for nutrient credits. This is consistent with the results from the LCA analysis, because the low eutrophication potential of ADMC enables it to generate more nutrient credits.

When the typical dairy farm is assumed to have sufficient land to manage the produced manure, the net benefit of DLA increases significantly and becomes most profitable among all the cases. This partially explains why DLA is still the common approach of manure disposal in New Mexico despite it having the lowest profitability shown in the CBA analysis. The typical large dairy farm we model in this study contains 391 hectares of land. However, around 45% of the large dairy farms in New Mexico contain at least 405 ha of land and over 20% contain more than 800 ha of land (USDA, 2012). Given the current trend of expansion and consolidation, it is possible that a higher percentage of the large dairy farms in New Mexico will have sufficient on-site croplands for manure spreading.[20] This can be regarded as economies of scale and can be incentivized through public policy tools. On the other hand, more than four years of negotiation on amending the Dairy Rule might have led to some lack of enforcement of nutrient management plans and the Dairy Rule in New Mexico (see the Appendix for Chapter 3, Section B.1), which may be another reason that land application of dairy manure is still very common in the state, as the dairy farms without sufficient on-site cropland are not regulated to transport manure off-site. Historically, this is consistent with the defining characteristic of nonpoint source emissions in that they are prohibitively costly to monitor. In that case, the command-and-control type of policies like nutrient management plans and the Dairy Rule of New Mexico might not be effective. This is also the reason why this analysis has focused on incentive-based policies in the CBA scenarios.

In the sensitivity analysis of rangeland availability, the net benefit of DLA increases significantly by 81% of the net benefit of the most profitable AD compared to the baseline scenario. Thus, DLA case shows largest or substantially positive values for the net present value of benefits in the scenario that the dairy farms are assumed to own sufficient on-site croplands (i.e., zero hauling cost) or the assumption that the willingness to accept manure as a substitute for commercial fertilizer by off-site farmers is near to 100% (i.e., rangeland scenario where the hauling cost is only $19,136 per year). While, rangeland application scenarios is highly plausible options to manage the dairy manure, direct land application approach remains a costly option (since only 20% of large dairy

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[20] There is also the advantage of vertical integration, as those dairy farms with more on-site croplands are able to produce a higher percentage of their own feed as well.

farms contain more than 800 ha of land in New Mexico). Moreover, it should be noted that land application of the manure even by following agronomic nitrogen application rates does not entirely address the potential environmental burdens or unmonetized social costs (as illustrated by the highest EUT and GWP in the DLA case). Through application of dairy manure to rangelands, dairy farms can serve a dual purpose of dairy manure disposal and nutrient amendment to rangeland soil. In the sensitivity analysis of policy scenarios, we find that the current green policies in New Mexico can mitigate the cost burden of bioenergy projects like AD and ADMC, but the incentives are not strong enough for the large dairy farms to switch from the status quo (i.e., land application) to alternative dairy manure management systems. The sensitivity analyses of the prospective policy scenarios exemplify the potential high value co-products that can be generated through the best alternative uses of dairy manure and show the robustness of our results.

The results imply integration of dairy manure and bioenergy production processes is environmentally and economically sustainable. This integrated management approach also helps reduce the compliance costs. More importantly, in the context of growing concern over environmental pollution and security issues from the reliance on fossil fuels, our results shed light on the multi-fold benefits of alternative dairy manure management strategy coupled with renewable energy development. However, bioenergy produced through such systems may not sustain the competition in the current relatively low-cost fossil fuel market. Moreover, despite the economic favorability of AD and ADMC under different scenarios, dairy farmers or bioenergy producer face high upfront costs, which can hinder the adoption of such alternative options. This signifies the importance of financially motivating public policies as we discussed in the policy scenario simulation. Incentive-based policies including subsidies, tax credits, nutrient credits, and carbon credits are highly recommended for incentivizing alternative dairy manure management coupled with renewable energy production on large dairy farms in arid regions like New Mexico.[21] Specifically, policymakers can provide subsidies for bioenergy production from dairy manure (e.g., subsidies for installation of anaerobic digesters, microalgae cultivation for digestion feed, and algal biofuel production using dairy manure and wastewater), provide incentives for the consolidation of the dairy sector (e.g., tax credits and low interest loans), establish in-state markets for environmental credits (similar to Maryland's Nutrient Trading Program), and facilitate participation of in-state farms in out-of-state markets for environmental credits (e.g., California's carbon emissions trading system). Meanwhile, they can also develop education and outreach programs on alternative best manure management practices (e.g., technical assistance to dairy operators for anaerobic digestion systems and education of rangeland operator to increase their willingness to accept dairy manure).

Interpretation of the results should take into account the defined set of assumptions, units of analysis, and system boundary throughout the cases and scenarios. It is also advised to the readers to consider the source or methods of different parameter values, data sources and analytical approaches of data construction and justification, since this research has adapted various parameter values from different sources (past

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[21] Results from our analyses of a typical large dairy farm in New Mexico can be multiplied by the average number of such typical farms in New Mexico as a first step towards regional impacts assessment. For example, there were 109 large dairy farms in New Mexico in 2012 (USDA, 2012). At the regional level, the average net benefits from dairy manure management in the DLA, AD, and ADMC cases would then be, respectively, -\$17.1 billion, \$3.1 billion and -\$0.58 billion under the baseline scenario, and \$2.5 billion, \$3.1 billion and -\$0.58 billion with the possibility of applying excess dairy manure to rangelands of New Mexico.

studies conducted in other states and information available through policy briefs, technical reports or official websites of relevant state agency and academic institutions). Primarily, two caveats to consider when interpreting our results include the following. First is the assumption that the stylized, typical large dairy farm in New Mexico contains 2892 cows and 391 hectares of land. However, in practice, both the herd and land size can vary significantly. In future, it would be beneficial to evaluate our menu of policy alternatives for a range of sizes. Further, economies of scale in the larger industry appear likely to continue to be operative, pushing even larger dairy size and concentration. Thus, it would also be desirable to model the spatial distribution of large dairy farms across the state with full information on herd and land sizes, but we lack the information to do this here. We call for construction of a database of dairy CAFOs, especially for those leading dairy states. The public good aspect of reducing or mitigating the negative externalities of dairy manure pollution call for the collection of this information. Second, our results are based on deterministic crop yields and prices. However, climate change has been shown to affect crop yields, and crop prices have been volatile over the past decade. A future sensitivity analysis of crop yields and prices could provide an improved assessment.

Chapter 4: Temporal and Sectoral Analysis of Natural Gas Demand in the United States

[redacted] Introduction

Natural gas is an important fuel source from both economic and environmental perspectives. Since 2000, the natural gas boom, attributed to the advancement of drilling technology and existing completion technology, has resulted in an increased share in the national energy mix. The share of natural gas production among all fuel sources has been the largest since 2010, while the consumption represented the second most significant share, after petroleum products, in the US energy market since 2006 (EIA Energy Outlook, 2016).

The EIA Energy Outlook (2016) projections through 2040 suggest that the trend of a leading role of natural gas in the US energy mix will continue in the future. The relevance of natural gas also pertains to its environmental value in that it is a relatively clean energy source, since it emits fewer pollutants than other fossil fuels (Burnham et al., 2011; De Gouw et al., 2014; UCS, 2016). The existing natural gas infrastructures can also support the development of the renewable energy sector (e.g., contributing as a backup load to match the electricity demand with the intermittent renewable electricity supply and facilitating the utilization of gaseous renewable energy with existing natural gas infrastructures) (Mac Kinnon et al., 2017).

The objective of this research is to examine the sectoral natural gas demand function in the US. With the ongoing expansion of the natural gas industry, mainly, due to favorable policies in the exploration, production and distribution of natural gas, its downstream sector dynamics have a critical significance in sustainable energy planning in such areas as achieving market efficiency, energy security and environmental sustainability. Since natural gas is relatively less polluting, and because an abundance of natural gas reserves has been identified in the US, an empirical evaluation of the downstream segment of the natural gas market complements policy guidelines to achieve the optimal management of exhaustible natural gas resources. Energy planning based on well-informed consumption statistics (insights into the existing and expected future patterns) across the sectors over space and time, may integrate the goals of energy security, energy conservation, optimal energy resource re-allocation, environmental impact mitigation and sustainable development. These diversified objectives linked with the integrated energy planning concept, in part, require a superior understanding of consumer responses to the changes in the critical parameters of the natural gas market within and across the natural gas consuming sectors.

This research contributes to the literature on several fronts. It estimates short-run price elasticities of sectoral natural gas demand across states in the US. The natural gas consuming sectors, say the sectoral natural gas demand, in the US, are broadly categorized as residential, commercial, industrial and electric. Previous studies on natural gas demand are widely concentrated at the national level with the use of nationally aggregated data (e.g., Huntington, 2007; Maddala et al., 1997; Miljkovic et al., 2016). The studies are also exceptionally thin at the regional and state levels, and for the recent year data. The extant literature also lacks studies on the demand heterogeneity across and within the natural gas consumption sectors in the US. They focus mainly on the residential natural gas demand analysis (Dagher, 2012; Garcia-Cerrutti, 2000; Waheed and Martin, 2013; Yu, 1992).

For example, the most closely related study to the current investigation is by Bernstein and Griffin (2006), which addresses regional differences in the residential demand for natural gas in the US. In addition to the only focus of Bernstein and Griffin (2006) on the residential sector demand, their finding is based on the data from 1997 to 2003. Much has changed in the natural gas sector since 2003. Examples include the increasing production since 2005, declining price since 2008, and the US becoming the world's top natural gas producer since 2009 (US Energy Information Administration, 2018f, 2017a). This research aims to bridge these gaps in the literature by quantifying the changes in the sectoral natural gas quantity demanded caused by the changes in sectoral natural gas prices and the shift of demand due to regional weather attributes.

These changing circumstances, coupled with lack of studies covering sectoral natural gas demand analysis, particularly in the recent years highlights the unique contribution of this study in the literature. Apart from covering the recent dynamics of the natural gas demand sector, the findings of the research will allow to examine whether the natural gas demand elasticities of recent years are different from those of the past. The impacts driven by the weather attributes will help to understand why the demand changes in a particular season and what policies are needed with respect to this knowledge for the desired management of consumption (e.g., the best policy strategies to conserve energy consumption).

The sectoral demand analysis conducted at the state, regional and national levels facilitate comparison of the price elasticities and the weather impacts across spatial dimensions. The insightful information the decision makers and the industry learn from this is whether they require separate policies at the regional level or whether the national level estimates are adequate to guide their decision making process. With robust identification strategies, the empirical analysis uses disaggregated natural gas data from each natural gas consuming sector across the 50 states. The estimation controls for both spatial and temporal heterogeneity (state, and month-year fixed effects).

The results regarding price impacts indicate that sectoral natural gas consumers are not sensitive to respective sectoral natural gas price changes. While the impacts of sectoral natural gas prices on sectoral natural gas consumptions are statistically significant, the price impacts remain inelastic. This is illustrated by estimates that if natural gas prices in the residential, commercial, industrial and electric sectors increase by 10%, natural gas consumption will decline by 5.5%, 1.7%, 0.6% and 1.4%, respectively.

The findings suggest that natural gas pricing policies may result in mixed effects. The implication with respect to the price inelastic estimates is that public policies based on natural gas pricing may not support the objective of achieving energy efficiency through energy conservation. That is, policies aiming at adjusting natural gas prices through taxes (e.g., subsidies, taxes or tax credits as financial incentives) can be an expensive option to obtain the intended goal of energy conservation. However, the price inelastic demand responses of the natural gas sector can support the development of the renewable energy sector. For example, public policies aimed at deploying increased shares of relatively expensive renewable energy by providing subsidies or by taxing the fossil fuel sector (associated with high upfront costs) may increase the price of natural gas (e.g., Palmer and Burtraw (2005) find that renewable energy policies increase the natural gas prices), implying that price inelastic natural gas demand can remain resilient to such price increments in the sector. The broader policy relevance can also be connected to recent developments in climate change policies limiting greenhouse gases emissions (e.g., scaling up the energy efficiency standards or energy saving targets in the building codes, where it should be noted that reducing energy consumption is among the key tools to address myriad challenges across energy and environmental sectors).

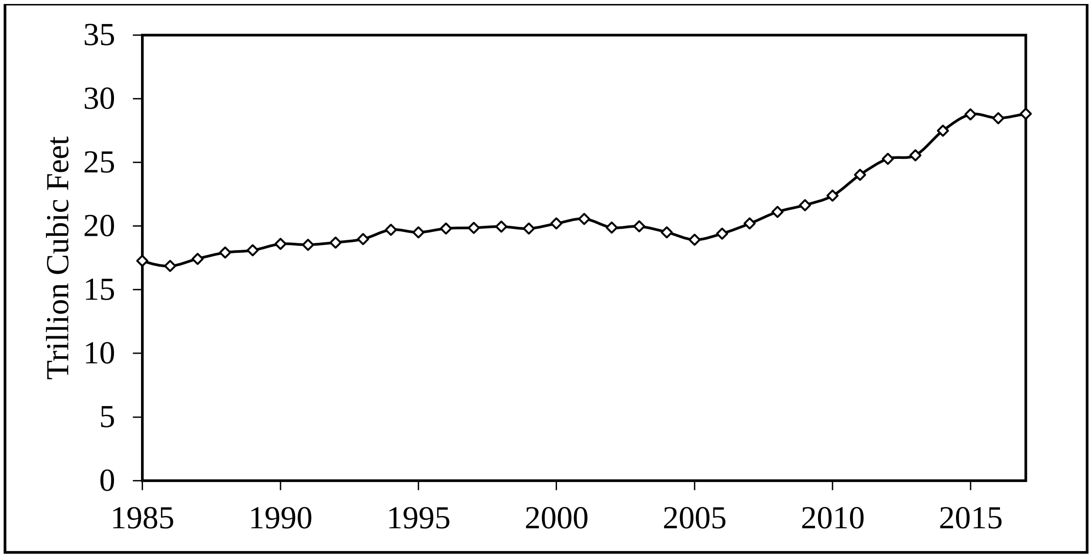
The results are also price inelastic in the context of intersectoral natural gas consumption, validating similar findings in the sectoral context (e.g., fixed appliance costs and time lags in responding to price changes). The intersectoral demand elasticity refers to the impact of other sectors' natural gas prices (e.g., industrial, commercial or electric) on one sector's consumption (e.g., the residential sector). The insensitive responses to price changes imply that sectoral prices may not be the key factors in reshuffling consumption patterns across and within sectors in the short-run.

The results show a noticeable difference in the impacts of heating and cooling degree days within the residential and electric sector: the impacts of heating degree days are relatively higher in the residential sector, while the impacts of cooling degree days impacts are relatively higher in the residential sector. Finally, results illustrate that state and regional differences in the impact of price and weather are substantial (while price impacts are still inelastic). This implies that policies based on national level price elasticity of quantity demanded for natural gas may not be suitable in addressing the desired energy management objectives of the states and regions. The price inelastic demand estimates of the current investigation are consistent with the closely related literature in the field (see literature review section), indicating that despite the changes in the natural gas sector dynamics in the US temporally and spatially, the trends of consumers' responses to the price changes remain almost identical with past patterns. However, it should be noted that magnitudes of responses with respect to the changes in sectoral natural gas prices and weather attributes vary significantly across spatial dimensions (across state and regional levels). Such spatial differences, that may be the result of varying degree of dependence on natural gas as a primary fuel source across states (e.g., availability of reliable substitutes to the natural gas), imply the varying degree of relevance or effectiveness relevant policies (e.g., policies aimed at promoting energy savings or transforming the energy sector with a greater reliance on renewable energy) across states and regions.

[redacted] Background

The US natural gas industry has experienced a massive structural change over the last few decades. The transformation with an increase in extraction (see Figure 4.1) has occurred as the result of advancements in natural gas extraction technologies (Insight, 2012; Krupnick et al., 2014). These technological advancements have led to the increased discovery of technically and economically extractable gas resources, such as the shale gas boom. As of 2016, such changes have led to an estimated 2,462 trillion cubic feet (tcf) of technically recoverable natural gas reserves in the US, which represents an increase of nearly 96% over the past decades. For example, it was 1,259 tcf in 1998 (Outlook, 2016) The stock is expected to last for 90 years at the current consumption rate of 27.2 tcf/year(US Energy Information Administration, 2018g).

Figure 4.1: The US marketed natural gas production, 1985-2017



Data Source: US Energy Information Administration-EIA, (2018)

The significance of the natural gas resources is also marked by its environmental benefits in comparison with other fossil fuels. Natural gas is relatively clean and more efficient than all the other fossil fuels. Natural gas combustion emits about 50% less CO_2 per unit of energy compared to coal and oil (De Gouw et al., 2014). While natural gas is expected to play a leading role in the energy mix in the foreseeable future, natural gas is an exhaustible resource and is not an entirely clean source of energy (UCS, 2016).

The natural gas is one of the primary energy sources that supplies about 27% of total energy consumption in the US (Outlook, 2016). Natural gas consumption in the US increased by about 23% from 2001 to 2016 (US Energy Information Administration, 2016). Residential, commercial, industrial and electric sectors are the primary natural gas consuming sectors excluding consumption in the natural gas production process - lease and plant fuel consumption and fuel use in the pipeline and distribution process. The transportation sector uses a negligible amount of natural gas in some states, and we have added such consumption to the commercial sector consumption. In 2016, the natural gas consumption share by the electric sector was the largest (39%), followed by 31% by the industrial sector, 17% by the residential sector and 13% by the commercial sector (US Energy Information Administration, 2018h).

The increased consumption of fossil fuel based energy also adds additional cost from negative externalities, such as air pollutions and greenhouse gasses (GHGs) emissions. Given the early phase of the clean energy development, the attributes of relatively less polluting natural gas and its abundant resource stock make it likely that natural gas will serve as a valuable transitional fuel (Economides and Wood, 2009; Outlook, 2016; Weber, 2012). Accordingly, understanding the natural gas market attributes, such as supply and demand structures, assist in devising an impactful energy planning system, in which natural gas can reserve its market space as a valuable transitional fuel. Demand analysis is an integral part of it (Brown et al., 2009; Knittel et al., 2016; Stern, 2008). Thus, the sustainable management considerations pertaining to reliable supply (i.e., energy security), energy efficiency, and the mitigated environmental footprints justify the scope and significance of the current investigation.

Understanding consumer responses observed through the partial multipliers of the demand function helps to make decisions about the optimal management of the limited natural gas commodities. The policymakers may recognize the need to reshuffle natural gas's market share (e.g., reducing consumption or increasing shares of renewable energy). If market restructuring is warranted for political, social, economic or environmental reasons, demand responsiveness of exogenous shocks guides in designing and quantifying the magnitude of such desired policies. The demand analysis also assists in developing policies that consider short-run and long-run energy management objectives, such as incentives or mandates for energy conservation and renewable energy development. For instance, with an annual expected increase in natural gas consumption by 0.9% into the future (US Energy Information Administration, 2016), decision-makers may consider policy adjustment to reallocate the natural gas in the context of energy security and resource sustainability.

[redacted] Previous Studies

Early empirical studies on energy demand elasticities date back to the 1950s (Denny et al., 1978; Fisher, 1962; Halvorsen, 1975; Houthakker, 1951; Pindyck, 1979a; Taylor, 1975, 1977). Energy demand literature is focused primarily on the empirical estimation of price and income elasticities with the widespread use of aggregated data of all sectors or an individual sector, such as residential, at the national level or in the cross-country context. The studies are also exceptionally thin at the regional and state levels (Adeyemi and Hunt, 2007; Dahl, 1993; Haas and Schipper, 1998; Lin et al., 1987; Liu, 1983, 2004; Maddala et al., 1997; Prosser, 1985).

With heterogeneity of empirical methods across the studies, such as time series or econometric panel methods, the empirical sophistication of those earlier studies was restricted by the unavailability of sufficient data (Bohi and Zimmerman, 1984). Following the oil price shock of the 1970s and the advancement of empirical econometric methods over the years, policy discussions targeted to the energy security and market stability led the rapid surge of studies in energy demand (Bohi, 1981; Bohi and Zimmerman, 1984; Engle and Granger, 1987; Granger, 1988; Madlener et al., 2011).

Despite the abundance of literature on the demand for energy, the number of natural gas demand studies are relatively fewer compared to other energy types, and they are even thinner at the local and state levels and based on recent data beyond 2000 (Dagher, 2012; Payne et al., 2011).

In an empirical analysis of natural gas demand, the fundamental structure of the covariates across the studies is similar despite the differences in data sources and types. However, their estimated price elasticities are heterogeneous. Using the state level data from 36 states in the US, Balestra and Nerlove (1966) estimate the natural gas demand in the residential and commercial sectors as a function of real revenue, population, and real natural gas price. The long-run price elasticity estimated by Balestra and Nerlove (1966) is - 0.63. With a specific focus on the impact of climate variability on natural gas demand, Berndt and Watkins (1977) follow the empirical specifications of Balestra and Nerlove (1966) (in the context of Ontario and British Colombia using the annual data from 1959 to 1974), and find that The natural gas consumption increases by 7.5% for 10% increase in average degree days elasticity (measured by mean degree days) of gas demand as found by Berndt and Watkins (1977) is 0.76.

Pindyck (1979) studies the residential and industrial demand for natural gas in the OECD countries and finds the price elasticities as ranging between -0.9 to -1.8 in the residential sector and -0.41 to –2.34 in the industrial sector. Using gas consumption data for winter months between 1971 and 1976 in New Jersey, Bloch (1980) formulates natural gas demand as a function of real gas price, number of heating days and a time trend and finds that the natural gas price elasticity is from -0.666 to -0.583. Following the discussion of potentially biased estimates of OLS and error component based energy demand studies (e.g. Balestra and Nerlove, 1966; Hock, 1978; Taylor, 1975)), Beierlein et al. (1981) use a seemingly unrelated error component regression model for each sector of natural gas demand in the 9 states of the northeastern census region of the US between 1967 and 1977. They find the variation in the price and income elasticities over different gas consuming sectors. Consistency in the nature of explanatory variables being used with different data types and sources and small variations in the elasticities of different sectors are explained by several natural gas demand studies of the 1980s (e.g., Barnes et al., 1982; Beierlein et al., 1981; Blattenberger et al., 1983; Lin et al., 1987; Taylor et al., 1984).

The price responsiveness to natural gas consumption can also vary across the states and sectors. Such variation in elasticities may be driven by differences in the social, economic and environmental attributes of the states and by variations in the data sources, sampled period, research objectives (e.g., short-run vs. long-run elasticities), and estimation methods (Al-Sahlawi, 1989; Dilaver et al., 2014). Yu, (1992) recognizes the policy relevance of spatial differences in price elasticities of residential natural gas demand across the US. Huntington (2007) finds that the short-run and long-run price elasticities of industrial natural gas in the US are -0.244 and -0.668, respectively.

Garcia-Cerrutti (2000) estimates residential natural gas demand in selected counties of California and finds insignificant results with negative signs for own-price elasticity and cooling degree days, while the results are positive and significant for heating degree days. For residential natural gas demand in Illinois, Payne et al. (2011) find the long-run and short-run price elasticities as -0.264 and -0.185, respectively. Dagher (2012) analyzes the residential sector natural gas demand dynamics at a utility in

Colorado for the period from 1994-2006 and finds illustrates smaller short-run price elasticity (-0.09) than the standard literature estimates because of the microdata application and Colorado's distinct economic attributes (low per capita energy expenditure and high per capita income). Waheed and Martin (2013) conduct a study on residential natural gas demand in Louisiana using a static log-linear model and find the long-run price and income elasticities to be -0.200 and -0.624, respectively. Table 4.1 summarizes major price elasticities estimates of natural gas from the most relevant studies to the current investigation.

Table 4.1: Literature survey of short-run price elasticities of natural gas

Study	Study Region	Period	Empirical Method	Short-Run Price Elasticity
Pindyck (1979a)	OECD	1959-1973	Cross-sectional model	Residential sector: -1.25 to -1.0 Industrial Sector: -1.17 to -0.22
Maddala et al. (1997)	US, 49 states	1970-1990	Panel model	-0.158
Li and Maddala (1999)	US	1970-1990	Time series model	-0.08 to - 0.48
Garcia-Cerrutti (2000)	California	1983-1997	Panel model	Insignificant
Olatubi and Zhang (2003)	US, 16 states	1977-1999	Panel model	-0.264
Bernstein and Griffin (2006)	US, 50 states	1977-2004	Panel model	Residential sector: −0.102
Payne et al. (2011)	Illinois	1970-2007	Time series model	Residential sector: -insignificant

[redacted] Estimation and Identification Strategies

Consistent with the underlying economic theory of consumer and producer behaviors, Equation (1) denotes the generic econometric specification for all sector.

$$N_{ijt} = \beta_{j0} + \beta_{i1}p_{ijt} + \beta_{i3}h_{ijt} + \beta_{i4}c_{ijt} + \mu_{it} + f_{ij} + \varepsilon_{ijt} \dots\dots\dots\dots (1)$$

In this model, t is index for years, i is the index representing the natural gas consumption sectors and j is the index denoting 50 states. N_{ijt} is the vector of sectoral natural gas consumptions, p_{ijt}, is the vector of sectoral natural gas prices, h_{ijt} denotes heating degree days (HDD), and c_{ijt} is the cooling degree days (CDD). The ε_{ijt} is the unobserved heterogeneity across time and space, μ_{it} is time dummies (month-year fixed effect) and f_{ij} is time invariant state fixed effect.

Following data attributes and research objectives, we discuss the identification issues, estimation techniques and econometric specification aspects. The first step in the identification process involves defining and justifying the scales of individual observations. Due to data limitations (lack of micro-data on natural gas consumption and prices in all sectors), the level of analysis for the study is the state level.

The Federal Regulatory Energy Commission (FERC) regulates the national and local natural gas markets in the US, mainly in the areas of granting permits for production, infrastructure development (e.g., storage, pipeline, and LNG plants) and the management of the abandoned sites. However, some sectors of the local natural gas market, such as retail distributors and local pipeline companies, who supply natural gas to the end-use consumers, do not fall under the jurisdiction of the FERC. Natural gas distribution pipelines are connected at the national and state levels, and the production in a state connects in an interstate natural gas pipeline system. Even though the national gas market is nationally interconnected, the sectoral price variations are observed across the states perhaps because of the varying policies, demand or both across the states. Thus, it is likely that the sectoral prices are endogenously determined. That is, the changes in the demand of one sector may influence the natural gas price in that sector. This illustrates the potential scenario of reverse causality in the empirical context.

To correct this potential endogeneity running as reverse causality, we select a within-sample instrument: lagged sectoral prices (Nair, 2007). In the context of cross-sectoral relationships between the prices and consumption, it is reasonable to assume that such cross-sectoral prices are exogenously determined. For instance, changes in the residential natural gas price may cause the variation in the natural gas consumption across the commercial, industrial and residential sectors, while the reverse causality is not expected to hold. The potential endogeneity also arises with respect to the covariates representing the heating and cooling degree days: natural gas consumption contributes to climate change through GHG emissions, whereas such climatic variables influence the consumption pattern of natural gas across the sectors. Again, we use the within-sample instruments as lagged heating and cooling degree days in this study.

To deal with endogeneity from potential omitted variables, we utilize a fixed effect model, where year, month and state are controlled to account for unobserved heterogeneity. A double log functional form is selected following the box-cox transformation methods (Box and Cox, 1964). The natural log transformation for the variables representing the heating and cooling is not performed, as they contain zero value observations.

The next final in the identification process involves the selection of appropriate empirical methods that fit the data structure. Following a series of graphical visualization and statistical tests, the data indicates heteroskedasticity across space and time and autocorrelation. The Pasaran cross-sectional dependence (contemporaneous correlation) test exhibits that the residuals are correlated across the entities. A modified Wald test for group-wise heteroskedasticity shows the presence of heteroskedasticity. The Lagrange-Multiplier test indicates the presence of autocorrelation in the panel data. Heteroscedasticity (Wald test) and autocorrelations (Wooldridge autocorrelation test) exist in the fixed effect panel regression model.

The use of OLS in such cases results in biased estimates due to the violation of the independently and identically distributed residuals. Thus, the Generalized Least Squares Method (GLS) with panel corrected standard errors (PCSE) in the presence of heteroscedasticity and autocorrelation produces efficient estimates. The PCSE is an OLS class estimator that eliminates the assumption of white noise residuals (Beck and Katz, 1995; Hoechle and others, 2007).

[redacted] Data Source

Data for natural gas consumption, city gate price, natural gas prices of each consumptive sectors, heating degree days and cooling days at the state level in the US are obtained from the US Energy Information Administration (US Energy Information Administration, 2018h). The Energy Information Administration (US Energy Information Administration, 2018h) defines the city gate price as, “A point or measuring station at which a distributing gas utility receives gas from a natural gas pipeline company or transmission system.” Monthly natural gas consumption data, which is the sum of all sectors, is available from 1989 to 2015, but most of the observations before 2001 (e.g., missing data in the electric power sector) are missing. Therefore, we use the monthly data from January 2001 to December 2015.

Since data on prices of electric sector natural gas consumption are missing, we use the city gate price data as a proxy for electric sector prices, across the states. Hartley et al. (2007)[22] also use the city gate price to measure the price elasticity in the natural gas sector in the US. Moreover, the few available electric sector data from across states were compared with the city gate price, where the observed minimum variance between these two series also validates the US of the city gate price as the proxy for electric sector price of natural gas.

These adjustments in data translate into a total of 9,000 observations in the sample across the 50 states in the residential, commercial and industrial sectors. Natural gas consumption data in the electric sector are missing for Wyoming for 2015. Thus, the sample for the electric sector consists of 49 states with 8,888 observations. The monthly data on HDD and CDD are collected from the US Energy Information Administration (US Energy Information Administration, 2017b). The HDD and CDD are the weather attributes, reflecting the amount of energy required to heat or cool the building depending on a comfortable need.

Figure 4.3 illustrates historical trends in natural gas prices across the sector. The natural gas prices in the industrial and electric sectors are moving in a similar direction, while the prices are highest in the residential sector. The seasonal breakdowns of the consumption of natural gas are shown in Figure 4.4. The consumption in the residential

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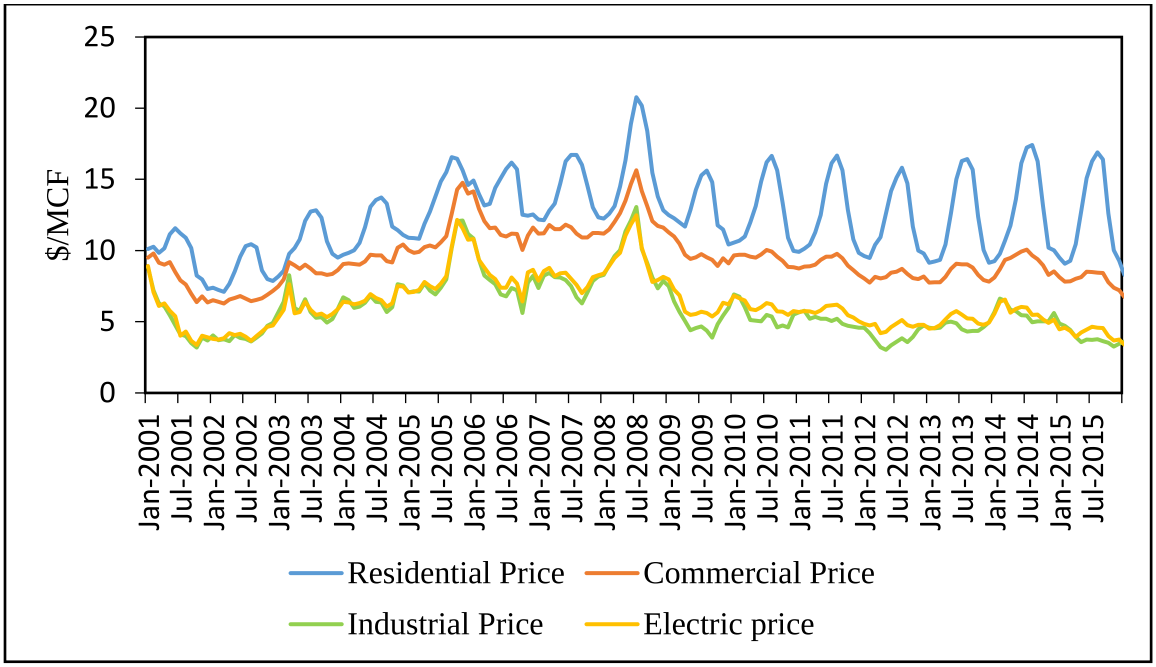
[22] Hartley et al. (2007) is a dissertation work.

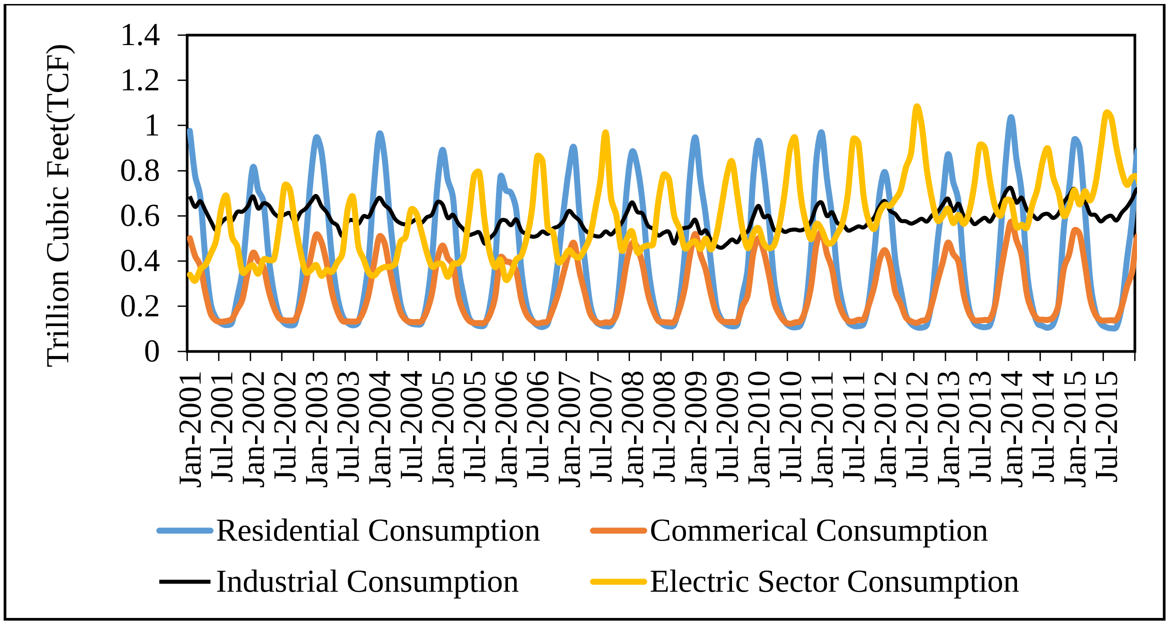
and commercial sectors follow similar seasonal consumption patterns (e.g., consumption increases during the winter months and decreases during the summer months), while the consumption in the electric sector exhibits the opposite seasonal patterns. Figure 4.4 also shows that natural gas consumption in the industrial sector does not follow any specific patterns based on the climatic seasons, and the trend looks almost constant over time.

Figure 4.2: Sectoral prices for natural gas



Data source: US Energy Information Administration (2018)

Figure 4.3: Sectoral Natural Gas Consumption in the United States



Data source: US Energy Information Administration (2018)

Table 4.2 provides descriptive statistics with definitions of the data used in the empirical analysis of this study. The monthly weighted average consumption of natural gas between January, 2001 and December, 2015 across the 50 states in the residential, commercial and industrial sectors are 7915.23 MMCF, 8180.94 MMCF, and 11,728 MMCF, respectively (where the standard deviations range between 6758 MMCF to 21631.53 MMCF). Such weighted average consumption in the electric sector across the 49 states (absent data for Wyoming in 2015) is 11805 MMCF with the standard deviation of 22326 MMCF. Likewise, the variation in prices across the sectors and weather attributes (heating and cooling degree days) across the regions are observed (see Table 4.2).

Table 4.2: Descriptive statistics

VARIABLES	DEFINITION	MEAN	SD	MIN VALUE	MAX VALUE
RESIDENTIAL	Residential natural gas consumption (MMCF)	7915.24	12901.82	18	101155
COMMERCIAL	Commercial natural gas consumption (MMCF)	5180.94	6757.79	65	52162
INDUSTRIAL	Industrial natural gas consumption (MMCF)	11727.87	21631.53	20	198261
ELECTRIC	Electric sector natural gas consumption (MMCF)	11805.22	22326.01	0	201213
RESPRICE	Residential natural gas price ($/MCF)	13.70	5.80	2.76	60.72
COMPRICE	Commercial natural gas price ($/MCF)	10.30	4.29	2.24	52.38
INDPRICE	Industrial natural gas price ($/MCF)	7.89	3.34	1.28	33.42
CGPRICE	City gate price ($/MCF)	6.75	3.142	0.58	38.56
HDD	Heating degree days (65-degree F as a reference temperature)	387.63	380.06	0	1518
CDD	Cooling degree days (65-degree F as a reference temperature)	109.31	141.23	0	719

Note: N=No. of Observations=9,000. All variables in this table are in levels, not in log transformation.

[redacted] Results and Discussion

The varying estimation approaches adopted in this research allow us to address the research objectives. Both the left and right-hand side variables in the empirical estimation are in natural logarithm except the HDD and CDD, since HDD and CDD also contain zero values. The results are presented in terms of the average change in covariates. In addition to the subtle identification strategies in the empirical estimations as discussed previously, the consistency of the estimates across the modeling scenario reflects the validation of the selected empirical models and the robustness of the estimations.

4.6.1 Sectoral Natural Gas Demand

Table 4.3 provides results for changes in sectoral natural gas consumption with respect to the changes in sectoral natural gas prices and climatic attributes (i.e., HDD and CDD) on average. The results indicate that own price elasticities of the sectoral natural gas demand are statistically significant at a 99% level of confidence. The interpretation of these estimated statistics is that, if the price of the natural gas in the residential sector increases by 10%, residential consumption for natural gas will decline by 5.5%. Similarly, for a 10% increase in the natural gas prices in the commercial, industrial and electric sectors, consumption will decline by 1.7%, 0.6% and 1.4%, respectively.

These results are consistent with the extant literature in the closely related topics in natural gas demand (e.g., Garcia-Cerrutti, 2000; Huntington, 2007; Payne et al., 2011). For instance, the short-run price elasticity in the residential sector in the current investigation (in the context of 50 states) is -0.5, while Dagher (2012) finds that Colorado’s residential sector price elasticity is -0.9 (see Table 4.1 for more details).

Table 4.3: Empirical results for individual sectors using the PCSE model

	(1)	(2)	(3)	(4)
VARIABLES	RESIDENTIAL	COMMERCIAL	INDUSTRIAL	ELECTRIC
RESPRICE	-0.547***			
	(0.0502)			
COMPRICE		-0.169***		
		(0.0294)		
INDPRICE			-0.062***	
			(0.0233)	
CGPRICE				-0.135***
				(0.0416)
HDD	0.000571***	0.000576***	0.000204***	1.69e-05
	(6.70e-05)	(5.22e-05)	(3.90e-05)	(7.99e-05)
CDD	-0.000405**	0.00102***	0.000425***	0.00226***
	(0.000174)	(0.000116)	(8.44e-05)	(0.000167)
CONSTANT	9.800***	8.181***	9.563***	8.702***
	(0.144)	(0.0809)	(0.0597)	(0.129)
YEAR-MONTH FE	YES	YES	YES	YES
STATE FE	YES	YES	YES	YES
OBSERVATIONS	9000	9000	9000	9000
R-SQUARED	0.966	0.946	0.887	0.656

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

There are many plausible explanations for these inelastic price responses. The small price elasticity estimates across natural gas consumption sectors in the short run reflect fixed cost effects; the fixed costs associated with built infrastructure and equipment (e.g., appliances) are relatively higher than the operating costs (i.e., variable costs) in the short-run (Berndt and Watkins, 1977). The built infrastructure in the context of natural gas consumption (e.g., installed natural gas pipelines and appliances in homes) contributes to the price inelastic responses to quantity demanded for natural gas. The time lag (i.e., the length of time between the onset of actual price changes and the onset of signs of adjustments to them in consumer behavior) is also an important indicator of consumer behavior across sectors. The theory of consumer inertia (Hortaçsu et al., 2017), the inertia of frictions/inattention and brand advantage, illustrates that consumers are often slow to switch from an incumbent fuel source to alternative fuels even when the alternative fuels are cheaper.

Although the price impacts are inelastic, the results illustrate that the responsiveness of consumption to price changes is relatively larger in the residential sector compared to other natural gas consuming sectors. The reasons could be that equipment stock effects and time-lag effects can be relatively higher for the commercial, industrial and electric sectors. The emergence of natural gas as a key feedstock in the industrial sector (e.g., chemicals and hydrogen) and electric sector (transition from peak load to base load provider) (MIT Energy Initiative, 2011) also justifies relatively smaller price impacts in these sectors (equivalent a necessity good concept).

Other factors that contribute to short-run price inelasticity in the electric and industrial sectors are the costs of natural gas feedstock in inter-fuel competition (e.g., natural gas competes with other fuels sources), built infrastructures, and reduced supply uncertainties as foreseen by favorable policies. For instance, regardless of the market conditions (e.g., the high price of natural gas), the electric sector may not have the economic incentives to respond quickly to price changes for several reasons (e.g., fixed costs and consumer trusts). Thus, the responsiveness of price changes in industrial and electric sectors is expected to be relatively small in the short-run. Whereas, residential consumers may have the relatively better flexibility to switch their consumption between natural gas and electricity depending on the respective costs; this is reflected in estimates of the relatively larger price impacts in the residential sector.

Table 4.4: Empirical results for within and across the sectors using the PCSE model

VARIABLES	(1) RESIDENTIAL	(2) COMMERCIAL	(3) INDUSTRIAL	(4) ELECTRIC
RESPRICE		-0.584***	-0.463***	0.326***
		(0.0276)	(0.0303)	(0.0793)
COMPRICE	-0.255***		-0.150***	-0.0808
	(0.0255)		(0.0230)	(0.0734)
INDPRICE	0.144***	0.105***		-0.147***
	(0.0205)	(0.0152)		(0.0441)
CGPRICE	-0.0419**	0.0287**	0.0597***	
	(0.0183)	(0.0132)	(0.0135)	
HDD	0.000704***	0.000484***	0.000520***	0.000511***
	(7.08e-05)	(4.53e-05)	(4.61e-05)	(0.000118)
CDD	-0.000999***	0.00152***	0.00147***	-0.000265
	(0.000186)	(0.000107)	(0.000109)	(0.000269)
CONSTANT	8.734***	9.062***	9.227***	7.688***
	(0.102)	(0.0873)	(0.0891)	(0.231)
YEAR-MONTH FE	YES	YES	YES	YES
STATE FE	YES	YES	YES	YES
OBSERVATIONS	8,999	8,999	8,999	8,617
R-SQUARED	0.968	0.946	0.948	0.652

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

The next relatively unique aspect of this research is understanding how consumption shifts across sectors when cross-sectoral prices change. These results, which are illustrated in Table 4.4, show that consumption movements across sectors with respect to cross-sectoral price changes exhibit similar patterns in residential and commercial sectors.

If residential price of natural gas increases by 10%, commercial sector consumption of natural gas declines by about 6%. Similarly, for 10% increase in commercial sector prices of natural gas, residential consumption declines by about 3%. This similarity in responses may be explained by the fact that the attributes that drive variations in natural gas consumption in both the sectors are often similar: (i) Most natural gas is consumed for heating purposes and (ii) historical price patterns are observed to move in a similar direction regardless of the relatively higher prices in the residential sector. The inelasticity of price responses in the cross-sectoral context validates the precision of the own price elasticities estimates; inelasticity of price responses to sectoral natural gas consumption due to the equipment stock effect and time-lag effect.

An important relationship is observed between residential price and natural gas demand in the electric sector. The coefficient is positive and statistically significant; this is because if natural gas becomes relatively expensive in the residential sector, then residential consumers may switch energy uses from natural gas to electricity. This causes increased consumption of electricity, which leads to increased consumption of natural gas in the electric sector to meet increased demand for electricity. For 10% increase in residential price, electric sector natural gas consumption increases by about 3% representing increment in consumption of about one-third of changes in residential sector natural gas prices. But, residential sector consumption of natural gas declines by only 0.4% for 10% increase in electric sector natural gas price. This indicates the shift of natural gas from being an end-use product from the residential sector to an input for the electric sector. This is consistent with the pattern of increasing share of natural gas in electricity generation in recent years.

In contrast, the impact of increases in commercial sector price on electric sector consumption is insignificant. This is consistent with the built infrastructure effect (fixed cost): The commercial sectors require heating infrastructures in a large capacity in terms of heat requirement, This indicates that there are fewer less economic incentives for commercial consumers to switch quickly between natural gas and electricity for the respective changes in their prices.

The negative impact of commercial price on industrial consumption may have many implications. For example, the commercial sector (e.g., large housing complexes, restaurants and shopping malls) demands final products from the industrial sector. Because, costs in general may increased because of increased fuel costs, the price of commercial sector products may also increase, this, in turn, reduces commercial sector sales (effects derived from increased price of commercial sector products). The less demand for industrial products by the commercial sector may reduce the consumption of natural gas in the industrial sector. A similar explanation may apply to a decline in industrial consumption by about 4% for a 10% increase in residential prices and 2% for a 10% increase in commercial prices.

The impacts of electric sector price on the sectoral consumption of natural gas are also mixed. The impacts are negatively significant for the residential sector, whereas they are positively significant for industrial and commercial sectors. Natural gas is popular mainly for its efficiency in heating and cooking purposes. The commercial sector, which demands energy for heating purposes in large amounts with accompanying built natural gas infrastructures (e.g., large heating boilers in academic institutions, restaurants and supermarkets), may also have an added infrastructure for the use of electricity (e.g., in the event of an accidental interruption of a natural gas-based energy supply for technical or operational reasons). In such various contexts (embedded built infrastructure), the demand for natural gas increases in the commercial and industrial sectors for an increase in the price of natural gas in the electric sector (which, in turn, makes the electricity generated from the natural gas expensive).

4.6.2 Consumption Variations by Weather

The elasticity interpretation does not apply to the impacts of heating and cooling degree days; the interpretation is applied in terms of the change in consumption for additional cooling degree days and heating degree days. Since the estimated model is log-linear for the cooling degree and heating degree days, the estimated coefficients are interpreted as: one additional degree day (cooling or heating) increases natural gas consumption by $100\left(e^{\beta_i}-1\right)$%. But, the estimated coefficients (absolute values) for the HDD and CDD are less 0.1, the estimated coefficients remain equivalent to their counterpart calculated by $\left(e^{\beta_i}-1\right)$.

The natural gas is mainly used either for heating (in residential, electric and commercial sectors) and cooling purposes or for generating electricity. The impacts of heating degree days and cooling degree days on consumption are mixed across sectors (see Table 4.3). In the residential sector, if heating degree days increase by one degree day, then the consumption of natural gas increases by 0.06%, while the natural gas consumption declines by 0.04% for a unit increment in the cooling degree days. Similarly, for an additional degree-day increase in heating degree days, the natural gas consumption in the commercial and industrial sectors increase by 0.06% and 0.02%, respectively. But the impact of heating degree days on electric sector natural gas consumption is not significant.

Noticeable findings with respect to heating and cooling degree days are that the impact of heating degree days on natural gas consumption is higher than the impact of cooling degree days within the residential, commercial and industrial sectors, but the impact of cooling degree days is higher in the electric sector. These relationships between the sectoral natural consumption, heating degree days and cooling degree days are consistent with the patterns that an increase in consumption of natural gas is observed during the winter months for heating purposes while demand for electricity is relatively higher during the warm months for cooling purposes, (which increases the uses of natural gas in the electric sector).

The key policy implications regarding the weather impacts are associated with reducing energy consumption by adopting energy efficiency measures across the sectors. As HDD and CDD are derived from the indoor and outdoor temperatures, they are also closely linked with climate change (i.e., temperature). Thus, HDD and CDD reflect important policy implication regarding the climate change impact mitigation. Energy conservation is known as an effective and feasible tool to mitigate the climate change impacts in the short- and medium-terms, as the alternative methods of addressing climate challenges (such as development of renewable energy so as to shift the energy use patterns to the clean source of energy, coupled with advancement of carbon-free technologies) are expected to take time to gain maturity. Climate resilient home design (energy efficient buildings) and use of energy efficient cooling and heating technologies can help to mitigate the HDD and CDD driven increase in energy consumption. Thus, the estimated weather driven changes in natural gas consumption, coupled with variation in consumption across the climate seasons can provide helpful guidance about to how to reshuffle energy consumption patterns or design policies to minimize the energy consumption. Currently, several financial incentives by private energy firms and government are provided to the consumers to reduce energy consumption during the peak hours or seasons. For example, electric utilities often offer credits to reduces electricity consumption during peak hours or summer months to address the challenges of maintaining grid load balance. The governments across states and federal level have also been implementing various energy conservation policies either by offering direct financial incentives to the consumers or by mandating the industry to do so (e.g., efficiency policies, such as the appliance standards, the building codes, the energy efficiency resource standards and so on).

4.6.3 Regional Perspective

This study also provides insights into the state and regional level comparisons of the price elasticities and weather impacts across the consumption sectors. Figures 4.5-4.8 illustrate the estimated average short-run price elasticities across sectors at regional level at 95% confidence interval. As shown in Table 4.5, the regional levels are defined by using the US Census' grouping of divisions within each region (Northeast, Midwest, South, West).

Table 4.5: regional grouping of states in the US

Northeast	**New England (NE)**	**Middle Atlantic (MA)**
	Connecticut Maine Massachusetts New Hampshire Rhode Island Vermont	New Jersey New York Pennsylvania
Midwest	**East North Central (ENC)**	**West North Central (WNC)**
	Illinois Indiana Michigan Ohio Wisconsin	Iowa Kansas Minnesota Missouri Nebraska North Dakota South Dakota
South	**South Atlantic (SA)**	**East South Central (ESC)**
	Delaware Florida Georgia Maryland North Carolina South Carolina Virginia West Virginia	Alabama Kentucky Mississippi Tennessee West South Central (WSC) Arkansas Louisiana Oklahoma Texas
West	**Mountain (MNT)**	**Pacific Coast (PC)**
	Arizona Colorado Idaho Montana Nevada New Mexico Utah Wyoming	Alaska California Hawaii Oregon Washington

Figures 4.5-4.8 show substantial heterogeneity in average price elasticity in each region for each sector. Such variations in price elasticities across regions suggest that policies developed from national level elasticity figures fail to accommodate such

regional nuances and needs in them (which are essential to improve policy effectiveness). While making the regional comparisons, it should be noted that demand responses to the price changes are still inelastic at the region level.

The price elasticities appear highest in the East South Central in the residential sector and the West South Central in the commercial sector, followed by the lowest in the Pacific Coast within residential and commercial sectors (See Figure 4.5 and 4.6). On the other hand, price elasticity appears highest in the Pacific Coast region in the industrial and electric sector. These patterns are consistent with the residential sector elasticity estimates by Bernstein and Griffin (2006), in terms of distribution of elasticity magnitudes across the regions. Nuances of the regional market attributes in terms of reliance on natural gas or accessibility to alternative fuels may be driving these differences. Regional variations in price elasticities of sectoral quantity demanded for natural gas (which may be because of varying income and substitution effects across regions resulting from changes in sectoral natural gas prices) imply the importance and efficacy of the regional energy policies in managing different energy sector challenges (e.g., energy security, energy efficiency and environmental externalities).

Figure 4.4: Estimated short-run residential-natural gas price elasticities by region

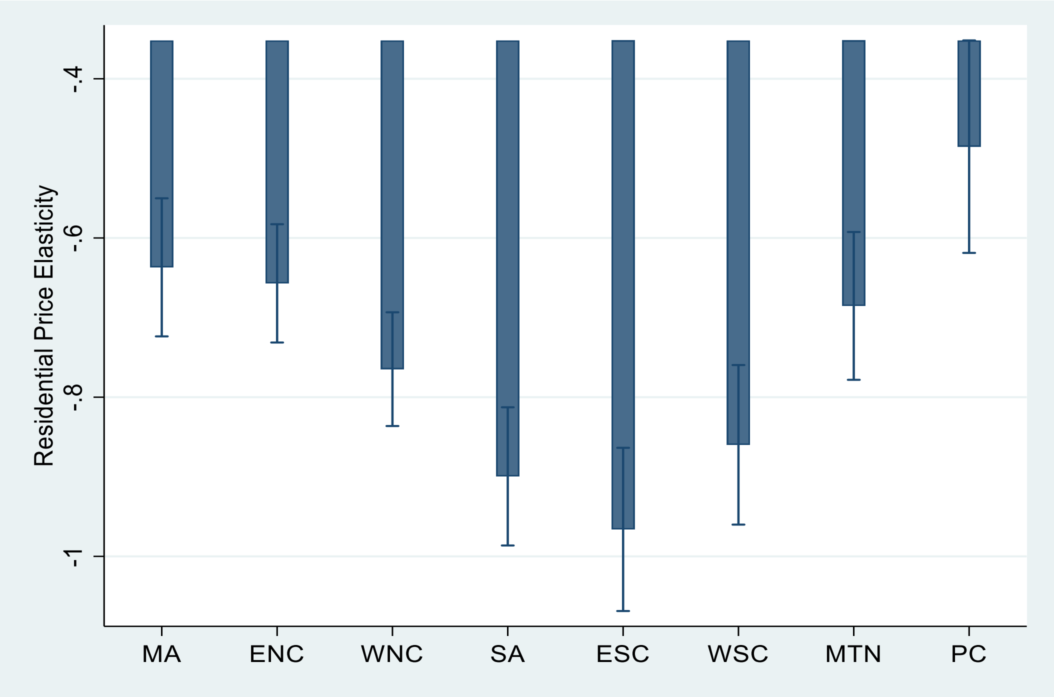


Figure 4.5: Estimated short-run commercial natural gas price elasticities by region

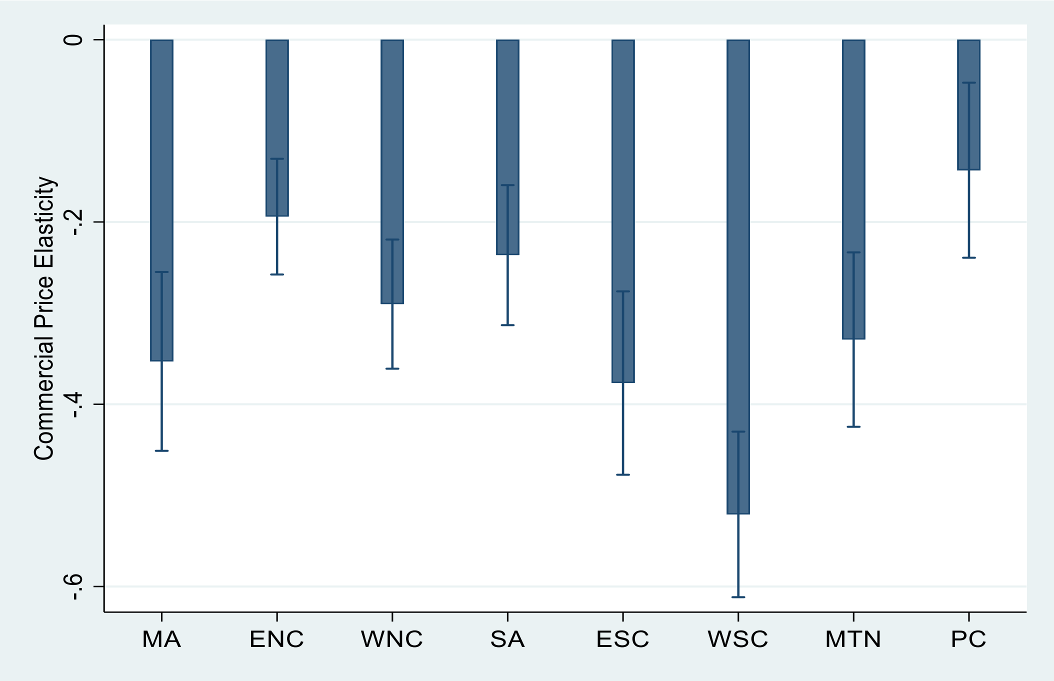


Figure 4.6: Estimated short-run industrial natural gas price elasticities by region

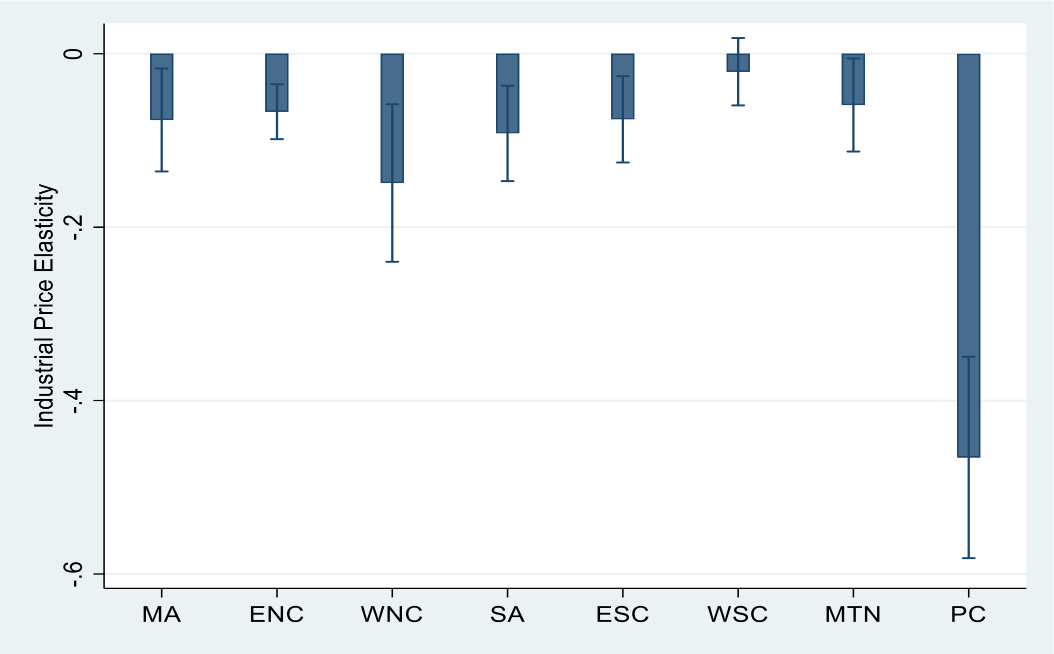
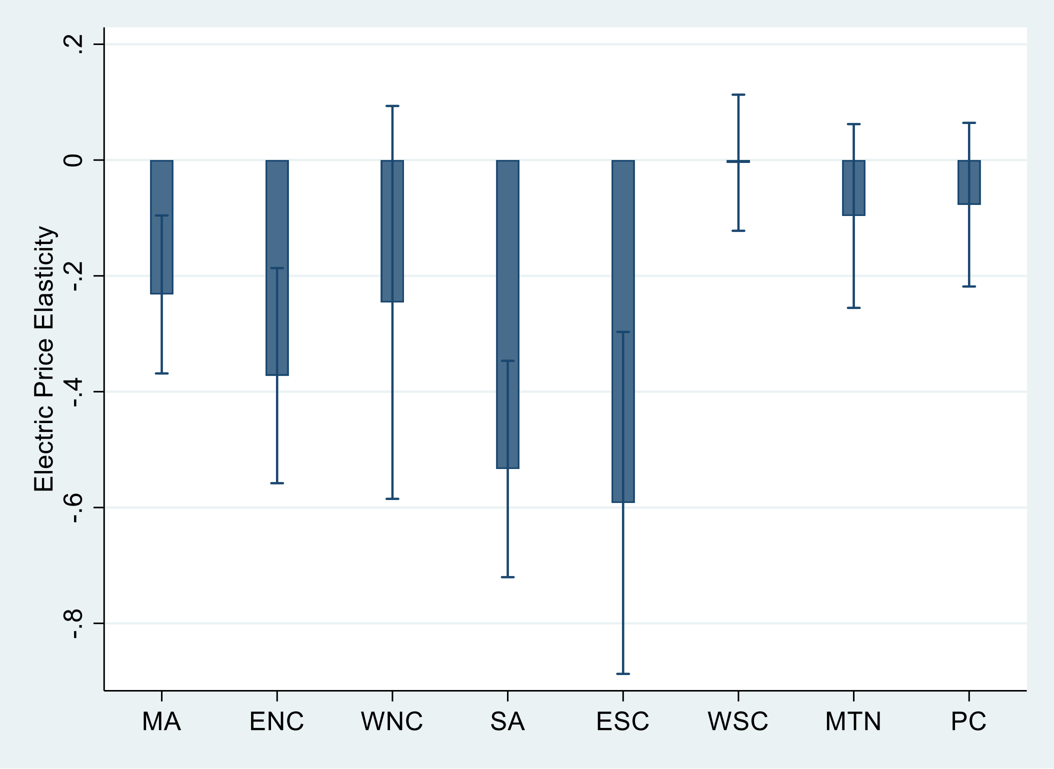


Figure 4.7: Estimated short-run electric sector natural gas price elasticities by region



The impacts of the heating and cooling degree days on the sectoral natural gas consumption across the regions are also heterogeneous, as Figures 4.9 and 4.10 show. The HDD impacts are positive in all regions for all sectors with the exception of electric sector in the MA region. Whereas, the HDD impacts are lowest in the industrial sector in the PC region. Interestingly, the CDD impacts are highest in the electric sector across the regions. This is consistent with findings in the national average scenario, where demand for natural gas becomes higher in the summer seasons for cooling purposes.

Figure 4.8: Impact of HDD on sectoral natural gas price elasticities by region

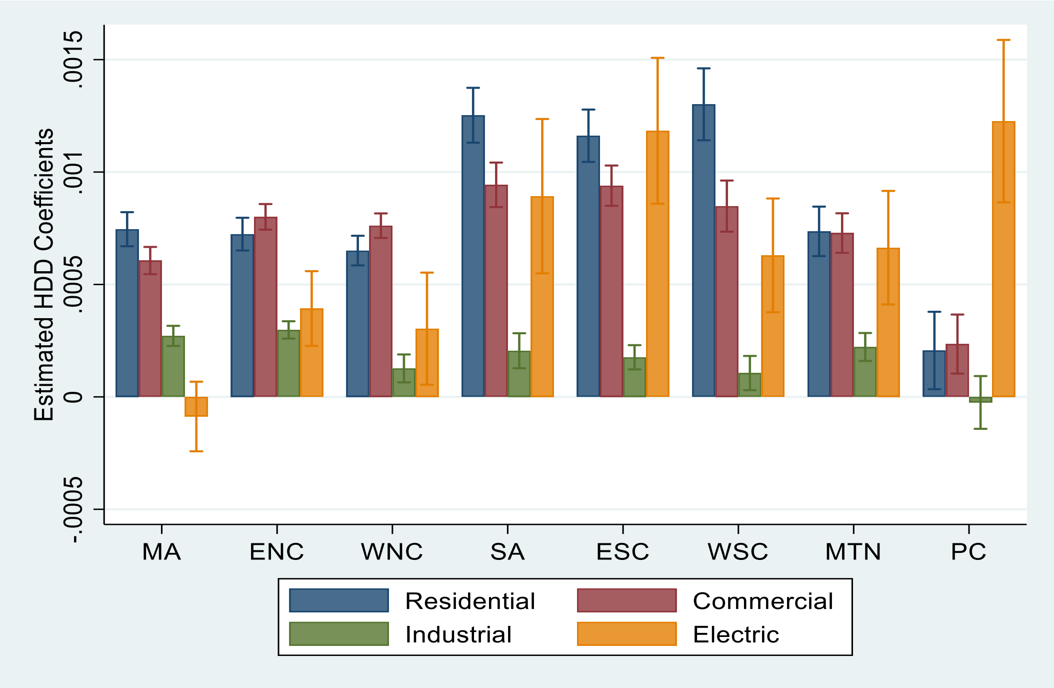


Figure 4.9: Impact of HDD on sectoral natural gas price elasticities by region

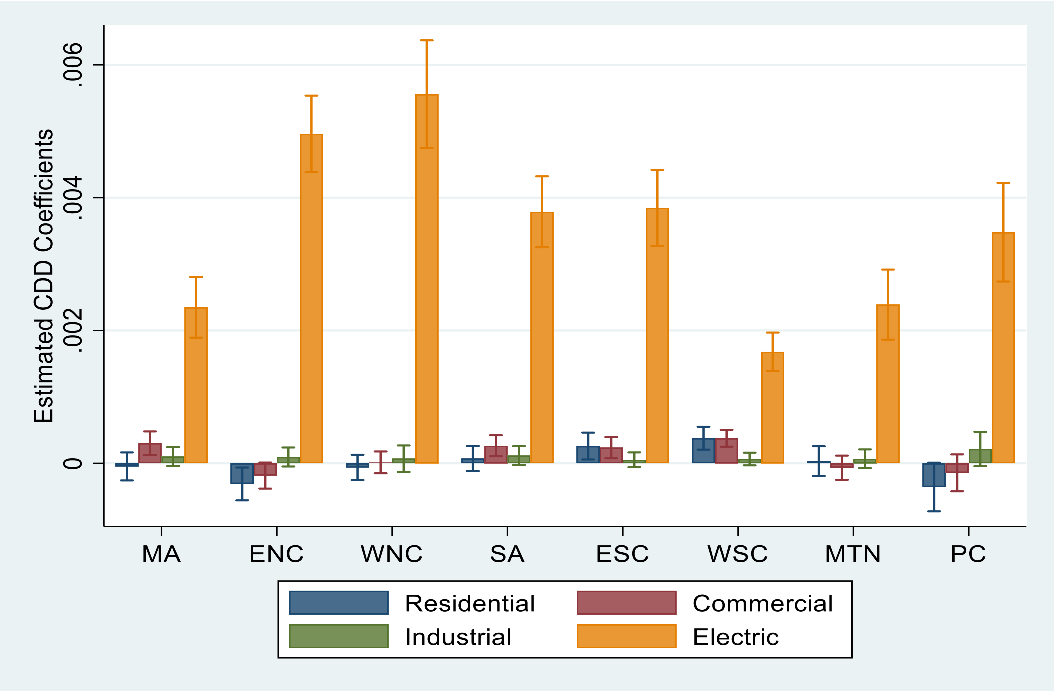


Figure 4.10: Estimated short-run residential natural gas price elasticities at the state level

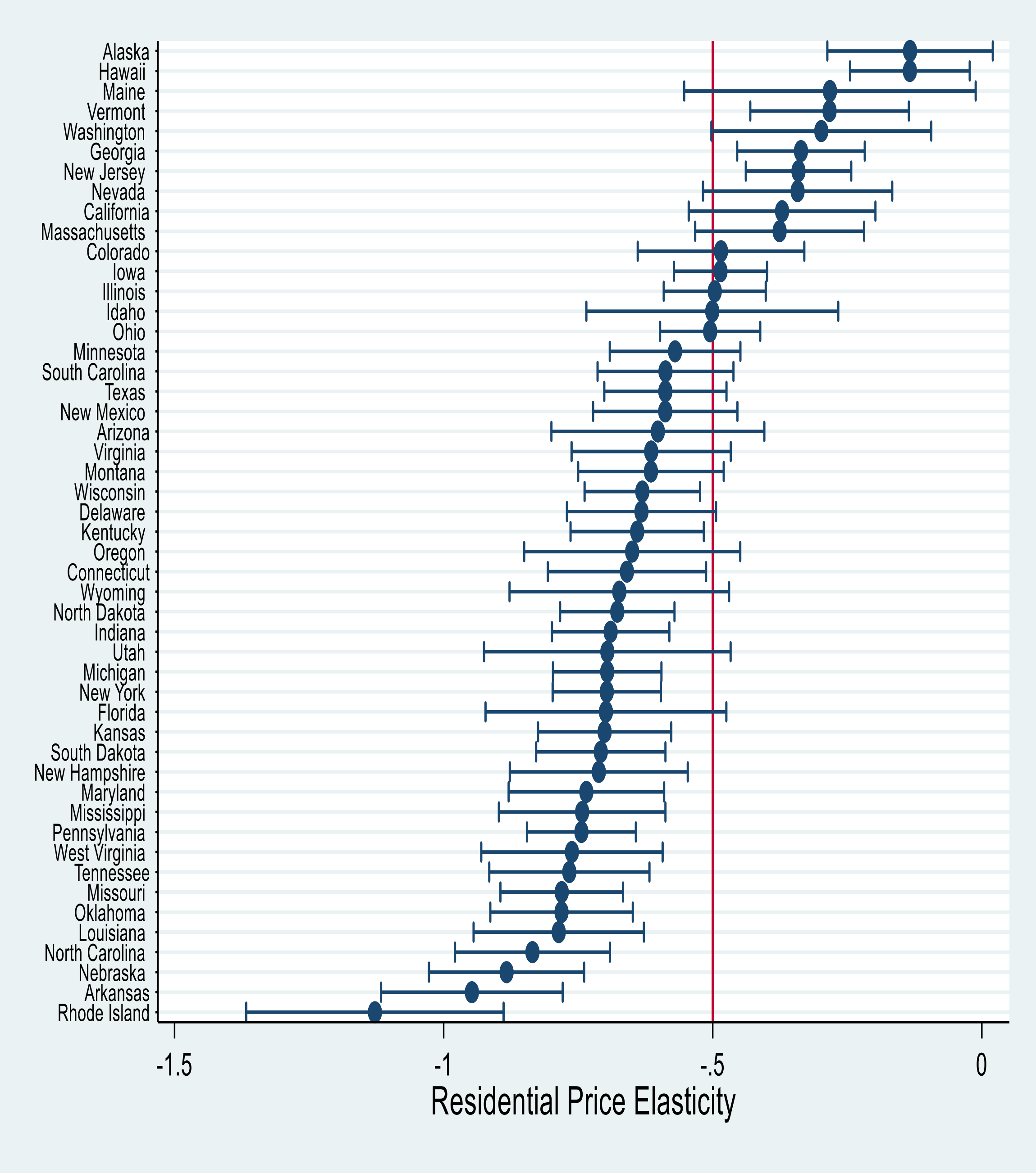


Figure 4.11: Estimated short-run commercial natural gas price elasticities at the state level

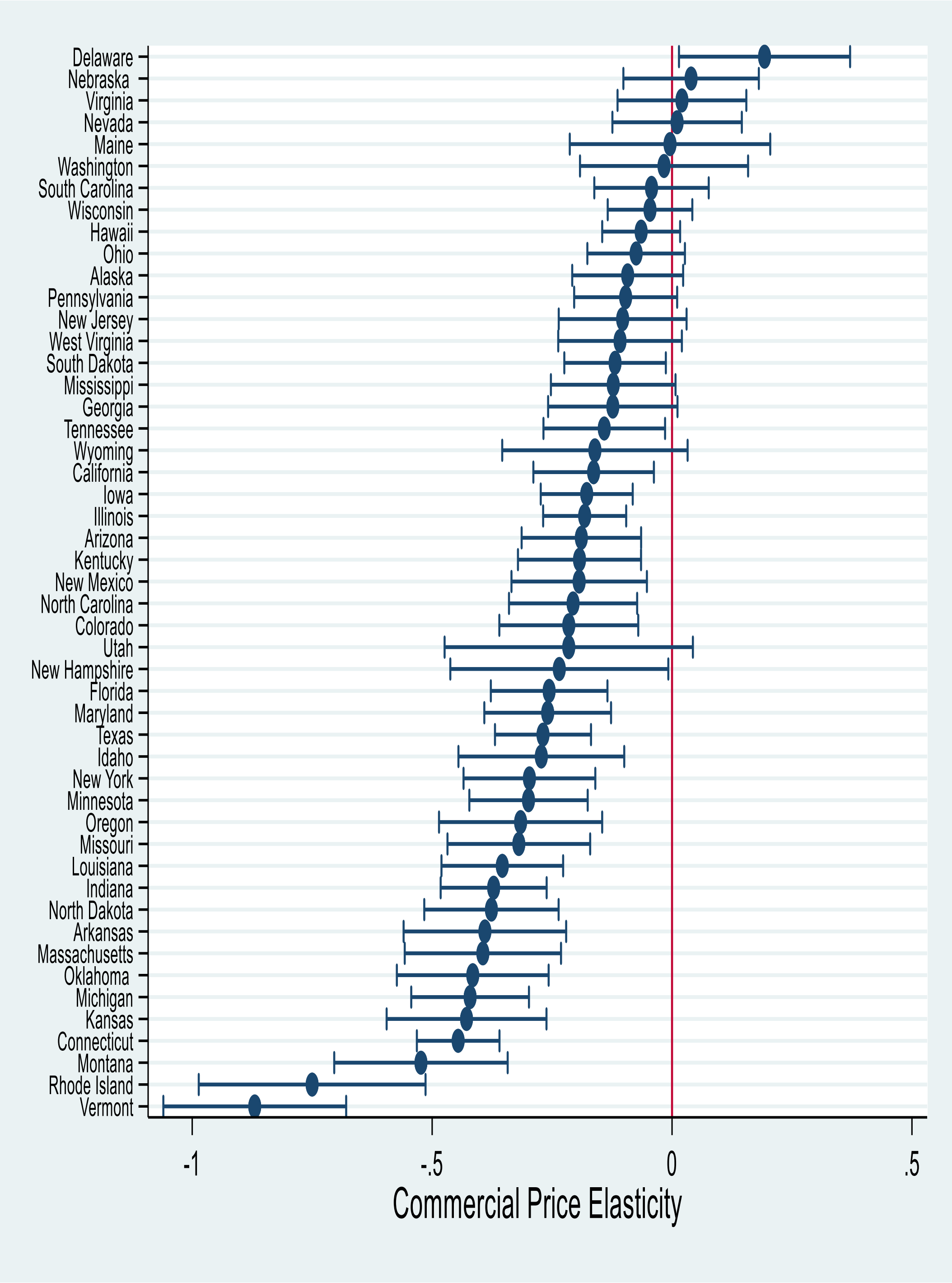


Figure 4.12: Estimated short-run industrial natural gas price elasticities at the state level

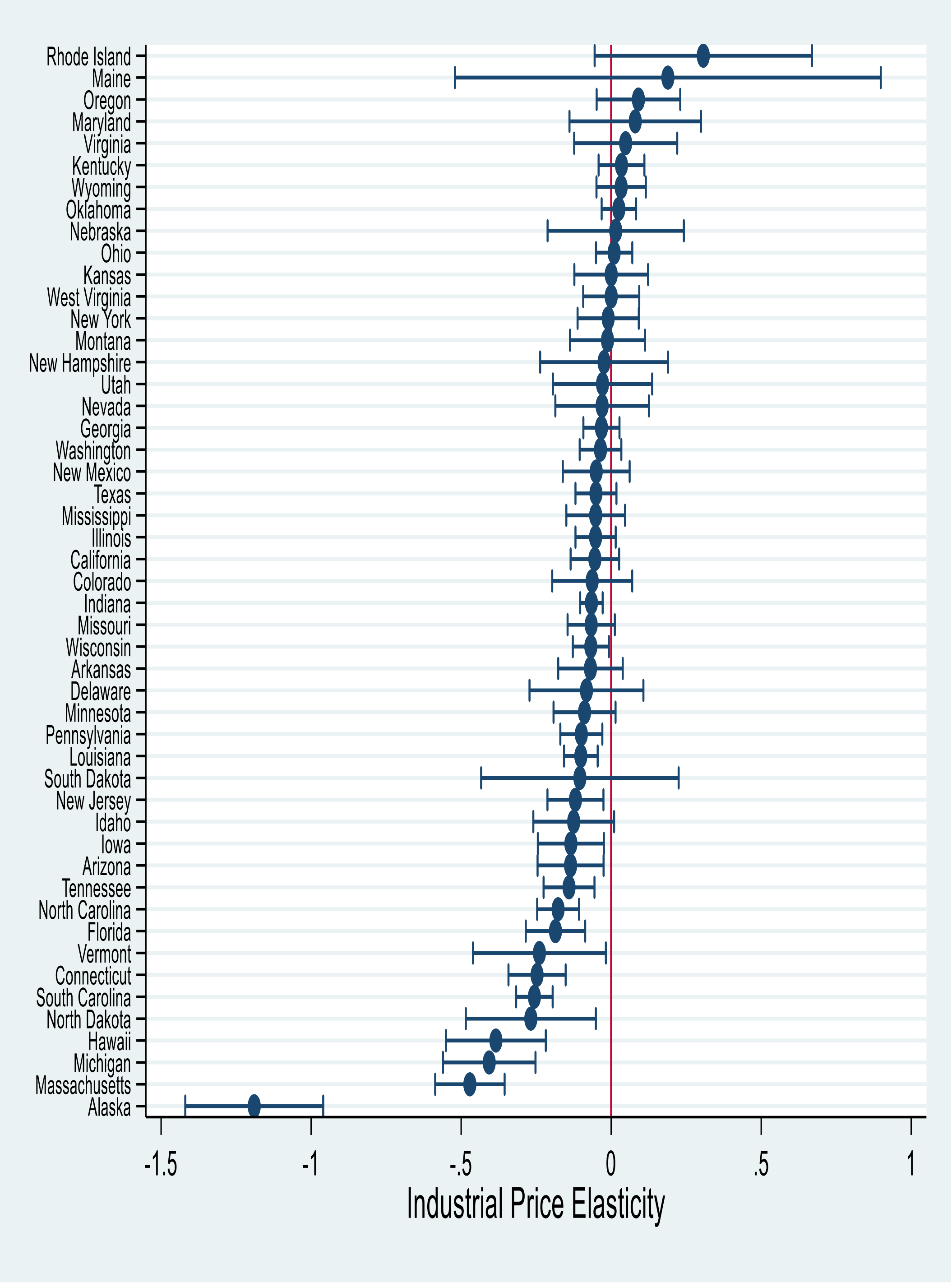
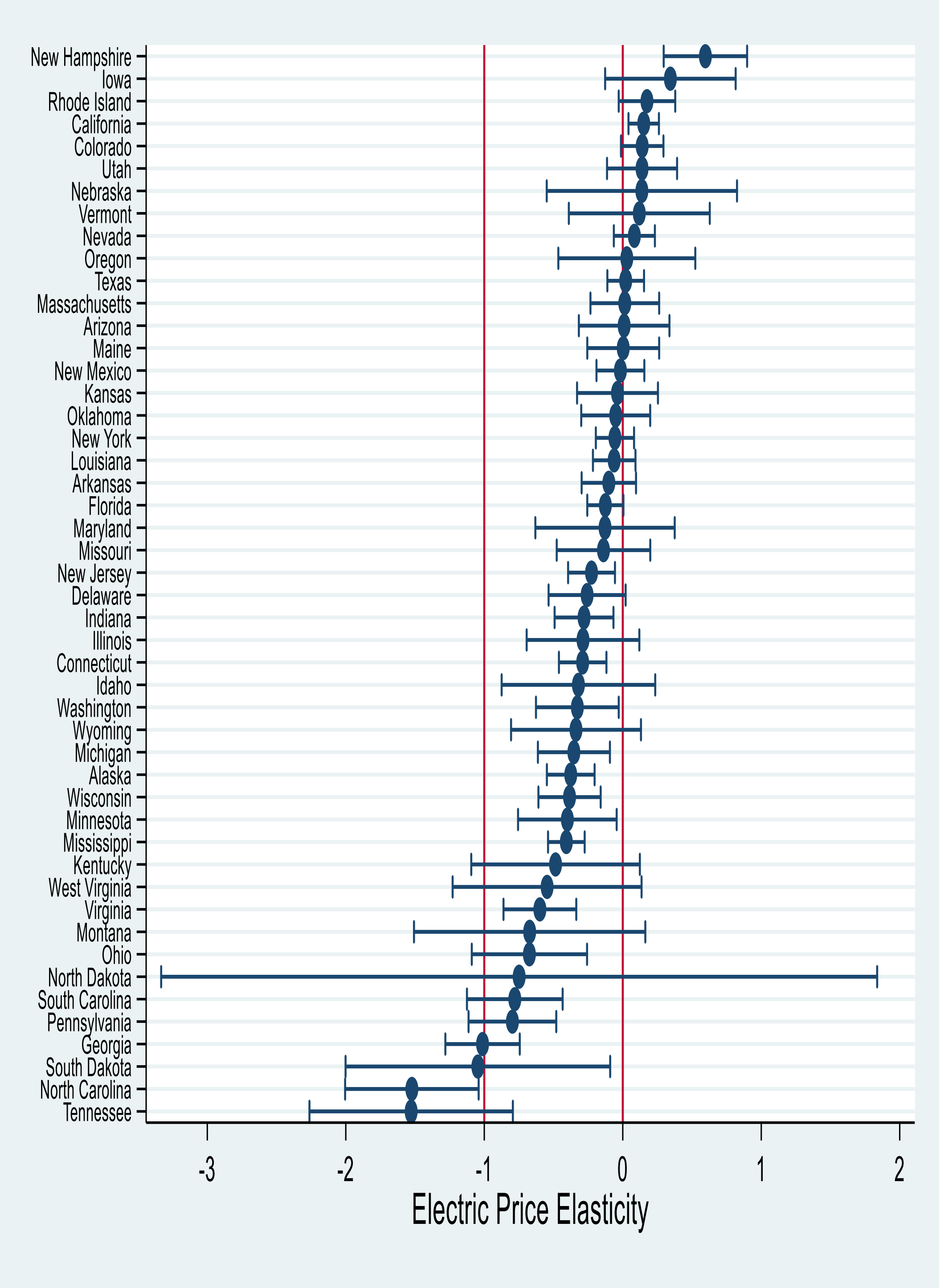


Figure 4.13: Estimated short-run electric natural gas price elasticities at the state level



The differences price elasticities become even more heterogeneous at the state level (see Tables C.1-C.4 in Appendix for Chapter 4 for details) as shown in Figure 4.11 – 4.14. With respect to policy relevance, reliable figures regarding the price and temperature elasticities provide important insights to both decision makers and industry (e.g., maximization of social welfare or private profits). The results indicate that the sectoral natural gas demand is price inelastic and weather impacts are mixed depending on the demand for natural gas for cooling and heating purposes across sectors. Moreover, the price elasticities in intersectoral context are also highly significant (implying consumption rearrangement possibilities across the sector if they are desirable).

The magnitudes of elasticities are consistent across the scenarios in a sense that changes in consumption are less than changes in prices, heating degree days and cooling degree days. As the estimates are narrowed to the regional and then to the state level, from the national level, the magnitude of variability in the estimates across the sectors become larger. The implication of such differences in price elasticity and weather impacts across the regions and states is that the policies based on national level elasticity estimate cannot accommodate the nuanced differences that are observed and can be typical at the local level.

The policies of interest in the natural gas sector, and more broadly in the fossil fuels sectors, including the policy responses to adapt with variation in the sectoral natural gas demand over the weather attributes, are about promoting energy efficiency (e.g., policies such energy efficiency standards or energy efficiency targets in building codes) to meet the intended environmental targets as well as to achieve energy security goals. The policy tools in such areas can be many, such as providing financial incentives to the consumers to adopt energy efficient appliance and build energy efficient homes. However, the low-price elasticity estimates across the sectors, regions and states, despite the differences in their magnitudes, indicate the policy driven changes in consumption may not be much effective tool to achieve such goals.

However, as the current focus across the local and national levels among the of governments, stakeholders and consumers are heading towards finding the cost-effective way of developing the renewable energy sector, relevant policies based on price inelastic natural gas demand can, in fact, be an effective instrument. This is particularly important because policies attempting to provide economic incentives to renewable energy sector (subsidizing renewable energy projects or mandating energy suppliers to accommodate relatively expensive fuel source in certain fraction) are likely to result in increased fossil fuel prices, including the natural prices at least in the short-run. The consumer resilience to the increased natural gas prices, as reflected in low price elasticity estimates of current investigation across sectors, regions and states indicate the flexibility of making intended changes in the natural gas market structure (e.g., policy driven changes in price of natural will have least impact on natural gas demand or natural gas market stability). However, it should also be noted that in some states (e.g., Rhode Island, Arkansas, Georgia, South Dakota, Tennessee), the price elasticity across sectors is elastic, signifying the importance of tailoring relevant energy sector policies at the state or regional level, rather than developing any such policies based on the national level average price elasticity estimates. Moreover, approximately consistent patterns on price inelasticity across regions and states (with few exceptions of price elastic responses in some states), future research should differentiate the impacts of energy efficiency policies (or any other relevant policies that are designed to reshuffle natural gas consumption structure) and compare impacts of such policies with price inelastic responses in natural gas consumption sector. The reason for this is that the inelastic price responses as found in this research might have been driven by declining natural gas prices and increasing importance of natural gas as a reliable fuel source (from both environmental and economic perspectives) in sectoral and regional energy mix.

[redacted] Conclusion

The objective of this research is to estimate the impact of natural gas prices on sectoral natural gas demand. Moreover, our study aims to provide significant literature in many aspects. First, none of the previous studies take into account the spatial and temporal attributes in sectoral natural gas demand estimation in the US. Second, the thinly available literature focuses only on a specific consumption sector (e.g., either residential sector or industrial sector), while current study aims to provide the comparative statistics across the sectors on the subject. Third, the study provides an important understanding in the field by using the monthly data during the recent years from across the 50 states, which is a completely new addition of information in the literature.

We use a panel fixed effect model with a robust examination of specification and identification issues. The data used in the study are taken from the US EIA, which are monthly from 2001-2015 at the state level in the US. We find that sectoral prices have a significant impact on the consumption behavior across the sectors (i.e., negative relationship between the price and consumption behavior), which is consistent with the standard economic theory of consumer behavior. We also find, as expected, the varied impacts of heating and cooling degree days across the sectors. The impacts of these climatic attributes are also consistent with the seasonal preferences for natural gas across the sectors. For example, residential consumers demand more natural gas during winter months for heating purposes, while they demand less during summer months when electricity (rather than natural gas) is used for cooling. Another finding of our research is that the substantial shifting of natural gas across the sectors is observed with respect to the sectoral prices.

In the context that discussions on transforming the energy market structure with transition to the renewable energy are gaining popularity on many fronts (economic costs, costs of public policies and environmental impacts of such desired shifts in energy sector), it is also widely recognized that the public policies targeted to promote the renewable sectors contribute to changing the existing market structure. For example, the Renewable Portfolio Standard adoption is found to increase the price of electricity and natural gas (Palmer and Burtraw, 2005). The finding of this research (price inelastic responses to the demand) signify the resilience of the natural gas market to such changing policy costs.

The significance of the study lies in the context of the increased popularity of natural gas as an important fuel source in the market due to both increased supply and associated environmental benefits. The estimated statistics sketch the dynamic visualization of the natural gas consumption structure with observed governing rules with respect to the changes in the covariate at both state and national levels. The major caveats are that, while we disaggregated our data at the sectoral levels in improving the precision of the estimates, our unit of measurement remained at the state level, because microdata at the household and firm levels were not available.

Chapter 5: Conclusion and Policy Implications

Energy is associated with just about every aspect of human well-being and is a critical determinant of sustainable economic development. Energy is also a market commodity that demonstrates demand and supply heterogeneity across spatial and temporal dimensions. Supply-side elements in identified sources of energy include extraction, harvesting and conversion technologies, and distribution infrastructure. Further, the demand heterogeneity is associated with the availability of the energy goods and services in many shapes and forms (liquid, solid, gas, and electricity) and with varying uses (e.g., production input or end-use consumer goods).

The importance of energy and its associated multilayered attributes of the entire energy system motivate the superior understanding of energy market attributes, associated technologies, and policies, so that the energy resources can be channeled into best uses in a sustainable way. The different stages of production and consumption activities of energy also generate an external cost to society and the economy. Energy market dynamics pertaining to the temporal and spatial heterogeneity in the supply and demand structures are significant elements in discussions on environmental damage mitigation and resource sustainability concerns.

Mitigating global climate change and local environmental damages (e.g., greenhouse gas emissions and air pollutions) and stabilizing energy resource sustainability (e.g., energy security) often appear as critical challenges in public policy discussions. Thus, the discussions in regard to the topics of applied energy economics go beyond the conventional market system of supply and demand dynamics.

A sustainable energy future can be ascertained by switching energy production and consumption from fossil fuels to renewable energy. However, the transition is expected to take considerable time, as several barriers are embedded in the renewable energy sector, such as lack of market competency to attract private investment, lack of flexibility (current renewable energy technologies are more focused on electricity generation, while some current energy consumption technologies only support other forms energy) and intermittent supply. Therefore, the role of public policies in developing different aspects of the renewable energy is crucial. Renewable portfolio standards (RPS) is one such policy. As RPS, a state-level policy, is designed to increase renewable electricity generation, it is important to understand the impact of the policy in achieving the intended outcomes. The RPS requires electricity suppliers to include a certain proportion (or quantity) of renewable electricity in their total electricity sales over a specified time period.

In the context of the significance of tailored energy policies, Chapter 2 of this dissertation empirically investigates the effectiveness of RPS across the US. This investigation uses annual data from 47 states, compiled from a variety of sources (e.g., Energy Information Administration, US Census, Department of Energy, and League of Conservative Voters) for the period of 1990 to 2014. The empirical analysis uses a panel fixed effect and spatial econometric methods.

The chapter incorporates the impacts of RPS heterogeneity across the states regarding policy design and stringency as well as such impacts for each different renewable technology. The primary conclusion of this chapter is that the RPS significantly contributes to the development of the renewable energy sector. The results illustrate that the RPS has driven a 194 MW increase in overall renewable capacity (representing more than one third of the average electricity capacity developed between 1990 and 2014 in 47 states). The results also suggest that the impacts of RPS, while exhibiting spatial dependencies, vary depending on the renewable energy source. RPS positively impacts renewable electricity capacity, the share of renewable electricity capacity in total electricity capacity, as well as the shares of solar and wind capacity in total electricity capacity (the impacts become 1.3 times larger for solar and about two thirds fold larger for wind with reference to their average counterparts). But, the impacts of RPS are not statistically significant for biomass or geothermal. These patterns suggest that RPS should consider stipulating the mandates for each technology separately to improve the aggregate RPS targets. The spatial dependencies are also incorporated into the analysis, and the results show that the RPS adoption translates into the increased policy strength when the coverage expands across the larger areas (i.e., additional states).

The policy implications are that expanding the coverage of the RPS across states and over time, as well as specifying RPS targets for different renewable energy sources can play effective roles in gaining economies of scales in the renewable energy sector (or such provisions and their interactions can serve as an effective carbon mitigating policy measure). More importantly, spatial dependencies of the RPS and renewable electricity as well as positively significant impacts of the REC imply the inter-state trading of the renewable electricity can create immediate economic incentives (as an indicator of additional avenue to generate revenue in the state). The regionalization of the renewable electricity market can create multiplier effects in the renewable sector. The intermittent nature of renewable electricity can also be an important factor in advancing its regional market structure, since efficiencies can be gained such trading system allows full utilizing the produced electricity. However, it should be noted that improvements of existing transmission and gridlines or development of new infrastructures may be needed to enhance regional trading potential of the renewable electricity.

The role of renewable energy in a sustainable energy system with different economic and technological barriers of the existing renewable energy industry illustrates the contextual significance of chapter 2. While highlighting the significance and policy implications, the caveats of the study should also be noted. The study uses the aggregated state level annual data in the empirical estimation, because of the lack of availability of full range of datasets covering covariates of the study at the micro-level.

However, the more precise impact of the RPS can be obtained by using microdata at utility or plant level. Moreover, the current study primarily focused on understanding the quantitative impacts of the RPS attributes on the renewable electricity capacity development by incorporating the existing RPS features. However, revisions on RPS targets and coverages continue across the states. Thus, future research should assess many aspects of the RPS impacts by incorporating revised RPS attributes, policy effect on prices of electricity and other fuels (e.g., economic cost or benefit of the policy), and the associated ripple effect of the policy. The impact of the policy on renewable electricity capacity from the distributed generations, where the current literature remains in interacting the electricity capacity built in the distributed generations sector with the RPS, should also be looked upon in the future research

As noted previously, the current state of renewable energy technologies has not achieved complete maturity to compete with the conventional fossil fuels. With recognized significance of the renewable energy in the modern economies, contributions in any amount from across the range of the sources that can produce renewable electricity should matter. Moreover, studies on sustainable energy should also incorporate the linkage of the energy sector with water and food sectors. These contexts are evaluated in chapter 3 of this dissertation. The case study is conducted by modeling a large dairy farm in New Mexico, which reflects the attributes of supply side and environmental policies of the energy system. The chapter evaluates both environmental and economic viability of for producing bio-energy by allowing the interactions among the energy, water and food aspects within the framework of identifying an alternative best dairy waste management method. The contextual relevance pertains to the fact that dairy waste management is a challenging issue, as improper management leads to environmental and public health impacts.

The methods used in the empirical analysis are the life cycle assessment (LCA) and cost-benefit analysis (CBA). By developing three cases, such as direct land application (DLA), anaerobic digestion (AD), and anaerobic digestion coupled with microalgae cultivation (ADMC), the investigation examines four environmental impacts (energy balance, water balance, eutrophication potential and global warming potential) and the present value of net benefits under the scenarios of baseline (excluding policy impacts), policy (incorporating existing and prospective environmental policies) and sensitivity analysis.

The LCA analysis shows that the ADMC case is most favorable among all cases because of the lowest water balance, eutrophication potential, and global warming potential. The AD case has highest energy balance (energy output minus energy input) as its net energy surplus is about 50% more than that of the ADMC (ADMC case has second higher energy balance, while the energy balance is negative in DLA case). The DLA case is also the least favorable with regard to any of the environmental impacts. Similarly, the CBA case illustrates that the AD is most profitable in the baseline, tax credit, and carbon credit scenarios among all cases. ADMC becomes most profitable of the scenario of a market for nutrient credits are incorporated in the analysis. These conclusions from both the LCA and CBA analyses are consistent across the cases.

The sensitivity analyses in chapter 3 consider (i) on-site management of manure by dairy farmers who own sufficient land (at least 800 ha), (ii) rangeland availability for off-site management of manure, and (iii) a 25% increase or decrease in system costs and benefits. The net benefits of DLA increase significantly and become most profitable in all scenarios when dairy farmers are assumed to own sufficient land. This suggests that when dairy farmers can manage manure by using agronomic nitrogen application rates (optimal manure application which avoids health and environmental impacts), farm profits also increase.

However, the typical dairy farm is much smaller than 800 ha (391 ha), which motivates exploration of alternative dairy waste management approaches (e.g., using manure for bioenergy production). When rangeland availability is considered in the modeling (i.e., applying excess manure to surrounding rangelands), the net benefits of DLA increase by 81% from the baseline scenario. The significance of utilizing rangelands to manage excess manure is that this can serve the dual goals of adequate dairy waste management (i.e., avoiding environmental and public health concerns) and nutrient fertilization of rangeland soils. Rangelands are an important ecosystem that supplies various environmental benefits (e.g., carbon sequestration and biodiversity), thus interventions, which enhance the functioning of these ecosystems should be encouraged and pursued.

The broader implication of chapter 3 is that the framework for integrating dairy manure and bioenergy production processes is environmentally and economically sustainable. This integrated management approach helps reduce dairy farmers´ compliance costs because of the reduced environmental impacts. In addition to health and environmental benefits, integrating dairy waste management and bioenergy production can also make a significant contribution to renewable energy production in the context of sustainable energy futures.

Notwithstanding the novel contributions of this chapter to the extant literature, two limitations need to be emphasized when using the findings of this research. First, this study is based on typical dairy farm that owns 2892 cows and 392 hectares of land. However, cattle stocks and farm sizes vary substantially between and within states and regions. Exploring how these heterogeneities affect the results reported herein would be an interesting avenue for future research. Second, deterministic crop yields and prices are assumed. However, in practice, neither of these metrics are temporally or spatially invariant. It could thus be fruitful for future research to relax these invariance assumptions to increase the empirical plausibility, and thus the practical utility, of the approach developed in this thesis.

Although natural gas is a fossil fuel, it has several economic and environmental advantages compared to other such fuels. Less carbon dioxide per thermal unit is emitted from burning natural gas, compared to other fossil fuels and increases in realizable natural gas reserves have been achieved in recent years with advances in drilling technology. Given that renewables have struggled to gain commercial viability, the potential role of natural gas in sustainable energy systems, should not be underestimated.

As the broader objective of this dissertation is to incorporate demand, supply, and policy considerations in an applied energy economics framework, chapter 4 reports a demand side assessment in the context of the US natural gas market. The objective is to understand the impact of natural gas prices and climatic variables on sectoral demand for natural gas. This investigation makes significant contributions to knowledge because there is a dearth of literature which controls for temporal and spatial dimensions in exploring US sectoral natural gas demand at the state and national levels. Furthermore, prior studies have tended to focus on specific consumption sectors (e.g., residential or industrial), while the work presented herein takes a multi-sector approach to understanding and explaining demand in this context.

The sectoral natural gas demand analysis applies a fixed-effects panel regression model using monthly data between 2001-2016 for different states. The results indicate that sectoral prices have a significantly negative, but inelastic impact on consumption across sectors, which is consistent with standard economic theory. The results also show how heating and cooling degree days have varying impacts across sectors but, with a few exceptions, consistent impacts across states. The nature of these impacts is consistent with seasonal preferences for natural gas across sectors. For example, residential consumers demand more natural gas during winter months for heating purposes, while they demand less during the summer when electricity (rather than natural gas) is used for cooling. Another salient finding is that the substantial shift of natural gas across sectors is less responsive to cross-sectoral price changes. Regardless of low price elasticities and weather impacts, substantial variations in consumption impacts are observed at the state and regional levels signifying that policies based on national level or sector specific considerations may not accommodate local subtleties (thereby, efficacy of policies focused in natural gas consumption sector also changes across spatial dimensions).

Inelastic prices imply that marked changes in natural gas supply can be the result of small changes in demand in response to the changes in natural gas prices. However, certain methodological limitations again need to be emphasized to understand if and how these results can be used for decision making purposes. While disaggregated data are utilized at the sectoral level to reap the benefits associated with greater degrees of freedom, the unit of analysis remained at the state level, because microdata at the household and firm levels were not available. Further, the role of sectoral natural consumption and price on renewable energy development is not explored

In sum, the objective of this dissertation has been to examine the role of energy policies in the renewable energy sector, as well as to understand the spatial and temporal variation of natural gas demand across the US. To this end, a multi-method approach is taken, harnessing econometric analysis, life cycle assessment, and cost-benefit analysis. Given the time-criticality of climate change mitigation and other pressing issues including energy security, the results and implications presented and discussed in this work could be highly relevant and important for various governmental and industrial stakeholders.

Appendix for Chapter 2

Following tables provide detailed estimates for the RPS impacts across different modeling scenarios (references regarding uses of these tables is provided in the result section of chapter 2).

Table A.1: Impact of RPS stringency on the share of solar capacity using the GLSPCSE

VARIABLE	(1)	(2)	(3)	(4)	(5)	(6)
RPS	0.00103*					
	(0.000622)					
ROBL		4.17e-10**				
		(2.07e-10)				
AGE			0.00131***			
			(0.000204)			
REC				0.00124*		
				(0.000706)		
REC_DEGREE					0.000186	
					(0.000327)	
EFF						0.00105
						(0.000822)
MGPO	0.000222	0.000469	-0.000172	0.000199	0.000420	0.000403
	(0.000462)	(0.000475)	(0.000382)	(0.000468)	(0.000480)	(0.000480)
NETMET	-0.000372	-0.000319	-0.000708	-0.000378	-0.000267	-0.000311
	(0.000725)	(0.000670)	(0.000512)	(0.000724)	(0.000729)	(0.000730)
INCOME	-3.75e-08	-3.15e-08	-2.36e-08	-3.90e-08	-3.71e-08	-3.57e-08
	(3.10e-08)	(3.02e-08)	(2.62e-08)	(3.15e-08)	(3.11e-08)	(3.07e-08)
HOUSE	-4.05e-06	-3.06e-06	-1.73e-06	-4.26e-06	-3.68e-06	-3.53e-06
	(6.69e-06)	(6.52e-06)	(5.09e-06)	(6.84e-06)	(6.73e-06)	(6.63e-06)
SENATE	-4.38e-06	-4.46e-06	-3.95e-06	-4.52e-06	-4.30e-06	-4.15e-06

	(3.38e-06)	(3.22e-06)	(2.44e-06)	(3.45e-06)	(3.40e-06)	(3.33e-06)
CONSUMER	3.87e-09**	2.65e-09	1.50e-09	3.87e-09**	4.10e-09**	4.03e-09**
	(1.94e-09)	(1.70e-09)	(1.74e-09)	(1.87e-09)	(2.04e-09)	(2.04e-09)
CONSTANT	-0.00695	-0.00446	-0.00225	-0.00688	-0.00748	-0.00738
	(0.00448)	(0.00402)	(0.00402)	(0.00435)	(0.00470)	(0.00471)
FE	YES	YES	YES	YES	YES	YES
R-squared	0.130	0.161	0.202	0.139	0.123	0.121
OBS	1,175	1,175	1,175	1,175	1,175	1,175

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

Table A.2: Impact of RPS stringency on the share of solar capacity using the SAR

VARIABLE	(1)	(2)	(3)	(4)	(5)	(6)
RPS	0.00239***					
	(0.000389)					
OBL		4.08e-10***				
		(0)				
AGE			0.000906***			
			(5.50e-05)			
REC				0.00256***		
				(0.000405)		
REC_DEGREE					-9.31e-06	
					(0.000671)	
EFF						0.00206***
						(0.000608)
MGPO	0.000519	0.00122*	0.000668	0.000369	0.000886	0.000957
	(0.000649)	(0.000632)	(0.000592)	(0.000651)	(0.000657)	(0.000654)
NETMET	-0.000430	0.000353	-0.000969***	-0.000370	0.000300	4.93e-05
	(0.000328)	(0.000299)	(0.000291)	(0.000323)	(0.000317)	(0.000318)
INCOME	-1.08e-07***	-9.81e-08***	-4.47e-08	-1.06e-07***	-1.29e-07***	-1.19e-07***
	(3.17e-08)	(3.09e-08)	(2.94e-08)	(3.17e-08)	(3.21e-08)	(3.20e-08)
HOUSE	-1.07e-05	-9.40e-06	-6.09e-06	-1.03e-05	-7.57e-06	-8.03e-06
	(8.27e-06)	(8.06e-06)	(7.57e-06)	(8.26e-06)	(8.38e-06)	(8.35e-06)
SENATE	-7.07e-06	-5.38e-06	-9.01e-06*	-6.32e-06	-1.34e-06	-1.98e-06
	(5.80e-06)	(5.60e-06)	(5.27e-06)	(5.77e-06)	(5.82e-06)	(5.79e-06)
CONSUMER	2.39e-09***	7.83e-10*	1.56e-09***	2.35e-09***	2.81e-09***	2.78e-09***
	(4.11e-10)	(4.44e-10)	(3.79e-10)	(4.11e-10)	(4.12e-10)	(4.10e-10)
FE	YES	YES	YES	YES	YES	YES
R-squared	0.067	0.145	0.161	0.069	0.054	0.057
OBS	1,175	1,175	1,175	1,175	1,175	1,175

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

Table A.3: Impact of RPS stringency on the share of wind capacity using the GLSPCSE

VARIABLE	(1)	(2)	(3)	(4)	(5)	(6)
RPS	0.00975***					
	(0.00202)					
OBL		1.17e-09***				
		(2.26e-10)				
AGE			0.00355***			
			(0.000429)			
REC				0.00853***		
				(0.00172)		
REC_DEGREE					0.00680**	
					(0.00316)	
EFF						0.00249
						(0.00166)
MGPO	0.0317***	0.0344***	0.0320***	0.0310***	0.0323***	0.0326***
	(0.00450)	(0.00490)	(0.00434)	(0.00449)	(0.00471)	(0.00481)
NETMET	0.00597*	0.00720**	0.00553**	0.00579*	0.00629*	0.00644*
	(0.00330)	(0.00340)	(0.00262)	(0.00330)	(0.00341)	(0.00346)
INCOME	1.09e-07	1.39e-07	1.38e-07	9.56e-08	8.19e-08	8.61e-08
	(1.65e-07)	(1.71e-07)	(1.52e-07)	(1.61e-07)	(1.63e-07)	(1.65e-07)
HOUSE	-7.38e-05	-7.02e-05	-6.50e-05	-7.07e-05	-6.82e-05	-6.63e-05
	(6.25e-05)	(6.48e-05)	(6.13e-05)	(6.13e-05)	(6.19e-05)	(6.18e-05)
SENATE	4.14e-06	4.99e-06	5.09e-06	3.28e-06	3.81e-06	4.76e-06
	(1.88e-05)	(1.98e-05)	(1.83e-05)	(1.85e-05)	(1.87e-05)	(1.90e-05)
CONSUMER	8.26e-09***	6.30e-09**	3.80e-09*	8.91e-09***	1.07e-08***	1.07e-08***
	(2.81e-09)	(2.70e-09)	(2.07e-09)	(2.92e-09)	(3.18e-09)	(3.15e-09)
CONSTANT	-0.0222**	-0.0192*	-0.0136	-0.0232**	-0.0266**	-0.0269**
	(0.0108)	(0.0108)	(0.00909)	(0.0108)	(0.0114)	(0.0114)
FE	YES	YES	YES	YES	YES	YES
R-SQUARED	0.224	0.227	0.244	0.209	0.196	0.197
OBS	1,175	1,175	1,175	1,175	1,175	1,175

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

Table A.4: Impact of RPS stringency on the share of wind capacity using the SAR

VARIABLE	(1)	(2)	(3)	(4)	(5)	(6)
RPS	0.00760***					
	(0.00289)					
OBL		1.17e-09***				
		(2.97e-10)				
AGE			0.000593			
			(0.000461)			
REC				0.00436		
				(0.00297)		
REC_DEGREE					0.00648	
					(0.00475)	
EFF						-0.0155***
				0.0490***	0.0499***	(0.00439)
MGPO	0.0487***	0.0508***	0.0497***	(0.00466)	(0.00461)	0.0494***
	(0.00464)	(0.00459)	(0.00462)	0.00946***	0.00992***	(0.00458)
NETMET	0.00855***	0.0107***	0.00987***	(0.00236)	(0.00230)	0.0117***
	(0.00237)	(0.00226)	(0.00231)	1.44e-06***	1.41e-06***	(0.00228)
INCOME	1.45e-06***	1.49e-06***	1.45e-06***	(2.28e-07)	(2.27e-07)	1.36e-06***
	(2.28e-07)	(2.27e-07)	(2.30e-07)	-0.000280***	-0.000276***	(2.26e-07)
HOUSE	-0.000286***	-0.000279***	-0.000274***	(5.88e-05)	(5.87e-05)	-0.000270***
	(5.88e-05)	(5.84e-05)	(5.87e-05)	8.02e-05*	8.57e-05**	(5.82e-05)
SENATE	7.08e-05*	7.69e-05*	8.38e-05**	(4.13e-05)	(4.09e-05)	9.24e-05**
	(4.14e-05)	(4.07e-05)	(4.11e-05)	-1.04e-08***	-9.65e-09***	(4.05e-05)
CONSUMER	-1.08e-08***	-1.55e-08***	-1.04e-08***	(2.97e-09)	(2.94e-09)	-1.01e-08***
	(2.96e-09)	(3.26e-09)	(2.97e-09)			(2.91e-09)
FE	YES	YES	YES	YES	YES	YES
R-SQUARED	0.095	0.077	0.092	0.091	0.092	0.083
OBS	1,175	1,175	1,175	1,175	1,175	1,175

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

Table A.5: Impact of RPS stringency on the share of geothermal capacity using the GLSPCSE

VARIABLE	(1)	(2)	(3)	(4)	(5)	(6)
RPS	-2.00e-05					
	(0.000212)					
OBL		-9.78e-11***				
		(0)				
AGE			0.000123*			
			(6.76e-05)			
REC				-0.000139		
				(0.000189)		
REC_DEGREE					9.44e-05	
					(6.31e-05)	
EFF						0.000376
						(0.000625)
MGPO	0.000216	0.000230	6.50e-05	0.000249	0.000205	0.000168
	(0.000194)	(0.000185)	(0.000210)	(0.000191)	(0.000193)	(0.000200)
NETMET	7.96e-07	2.66e-05	-8.60e-05	1.81e-05	-7.10e-06	-3.62e-05
	(0.000166)	(0.000171)	(0.000165)	(0.000168)	(0.000165)	(0.000164)
INCOME	-7.66e-09	-1.19e-08	-3.73e-09	-8.00e-09	-7.43e-09	-5.90e-09
	(1.09e-08)	(1.13e-08)	(1.03e-08)	(1.10e-08)	(1.09e-08)	(1.07e-08)
HOUSE	3.92e-06	3.69e-06	4.34e-06*	3.97e-06	3.90e-06	4.06e-06
	(2.77e-06)	(2.86e-06)	(2.57e-06)	(2.79e-06)	(2.75e-06)	(2.67e-06)
SENATE	5.58e-07	5.74e-07	7.26e-07	5.81e-07	5.55e-07	6.78e-07
	(9.63e-07)	(9.92e-07)	(8.94e-07)	(9.67e-07)	(9.53e-07)	(9.12e-07)
CONSUMER	-7.23e-10***	-3.53e-10*	-8.88e-10***	-6.99e-10***	-7.26e-10***	-7.15e-10***
	(2.01e-10)	(1.89e-10)	(2.36e-10)	(2.04e-10)	(2.09e-10)	(2.15e-10)
CONSTANT	0.00190***	0.00126*	0.00208***	0.00186***	0.00190***	0.00180***
	(0.000669)	(0.000645)	(0.000707)	(0.000674)	(0.000671)	(0.000672)
FE	YES	YES	YES	YES	YES	YES
R-SQUARED	0.895	0.914	0.819	0.897	0.892	0.868
OBS	1,175	1,175	1,175	1,175	1,175	1,175

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

Table A.6: Impact of RPS stringency on the share of geothermal capacity using the SAR

VARIABLE	(1)	(2)	(3)	(4)	(5)	(6)
RPS	2.52e-05					
	(0.000143)					
OBL		-1.66e-10***				
		(0)				
AGE			7.83e-05***			
			(2.18e-05)			
REC				-0.000176		
				(0.000149)		
REC_DEGREE					0.000238	
					(0.000244)	
EFF						0.000728***
						(0.000222)
MGPO	0.000516**	0.000385*	0.000500**	0.000555**	0.000521**	0.000545**
	(0.000240)	(0.000227)	(0.000238)	(0.000241)	(0.000239)	(0.000238)
NETMET	0.000211*	0.000209**	0.000101	0.000267**	0.000197*	0.000128
	(0.000121)	(0.000106)	(0.000116)	(0.000119)	(0.000114)	(0.000115)
INCOME	-3.41e-08***	-4.77e-08***	-2.65e-08**	-3.60e-08***	-3.39e-08***	-3.07e-08***
	(1.17e-08)	(1.11e-08)	(1.18e-08)	(1.17e-08)	(1.16e-08)	(1.16e-08)
HOUSE	8.77e-07	1.44e-06	1.17e-06	1.07e-06	8.71e-07	7.46e-07
	(3.05e-06)	(2.89e-06)	(3.03e-06)	(3.04e-06)	(3.04e-06)	(3.03e-06)
SENATE	-1.76e-06	-2.76e-08	-2.38e-06	-1.36e-06	-1.81e-06	-1.92e-06
	(2.14e-06)	(2.01e-06)	(2.11e-06)	(2.14e-06)	(2.12e-06)	(2.11e-06)
CONSUMER	-1.05e-09***	-2.06e-10	-1.16e-09***	-1.01e-09***	-1.04e-09***	-1.05e-09***
	(1.51e-10)	(1.60e-10)	(1.52e-10)	(1.52e-10)	(1.49e-10)	(1.49e-10)
FE	YES	YES	YES	YES	YES	YES
R-SQUARED	0.175	0.210	0.169	0.176	0.176	0.166
OBS	1,175	1,175	1,175	1,175	1,175	1,175

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

Table A.7: Impact of RPS stringency on the share of biomass capacity using the GLSPCSE

VARIABLE	(1)	(2)	(3)	(4)	(5)	(6)
RPS	-0.00229**					
	(0.000926)					
OBL		-1.70e-10**				
		(7.20e-11)				
AGE			0.000358***			
			(0.000125)			
REC				-0.00255***		
				(0.000966)		
REC_DEGREE					0.000185	
					(0.000823)	
EFF						-0.00968***
						(0.00282)
MGPO	-0.000841	-0.00134	-0.00155	-0.000734	-0.00134	-0.00144
	(0.00309)	(0.00309)	(0.00312)	(0.00310)	(0.00310)	(0.00285)
NETMET	-0.00166**	-0.00197***	-0.00220***	-0.00168**	-0.00200***	-0.00142**
	(0.000687)	(0.000707)	(0.000666)	(0.000689)	(0.000704)	(0.000678)
INCOME	6.42e-08	6.21e-08	7.09e-08	6.26e-08	6.60e-08	5.58e-08
	(5.86e-08)	(5.83e-08)	(5.77e-08)	(5.85e-08)	(5.82e-08)	(5.81e-08)
HOUSE	2.04e-05*	1.94e-05	1.99e-05*	2.09e-05*	1.94e-05*	1.75e-05
	(1.18e-05)	(1.18e-05)	(1.16e-05)	(1.18e-05)	(1.18e-05)	(1.18e-05)
SENATE	2.67e-06	2.26e-06	2.09e-06	2.72e-06	2.15e-06	1.78e-06
	(8.76e-06)	(8.74e-06)	(8.65e-06)	(8.73e-06)	(8.71e-06)	(8.65e-06)
CONSUMER	1.37e-09*	1.46e-09*	9.24e-11	1.39e-09*	7.88e-10	1.31e-09*
	(7.53e-10)	(8.21e-10)	(6.63e-10)	(7.57e-10)	(6.87e-10)	(7.49e-10)
CONSTANT	0.0153***	0.0152***	0.0179***	0.0153***	0.0165***	0.0159***
	(0.00393)	(0.00398)	(0.00372)	(0.00395)	(0.00382)	(0.00379)
FE	YES	YES	YES	YES	YES	YES
R-SQUARED	0.772	0.767	0.244	0.767	0.768	0.801
OBS	1,175	1,175	1,175	1,175	1,175	1,175

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

Table A.8: Impact of RPS stringency on the share of biomass capacity using the SAR

VARIABLE	(1)	(2)	(3)	(4)	(5)	(6)
RPS	-0.00122					
	(0.000752)					
OBL		-8.63e-11				
		(8.13e-11)				
AGE			0.000386***			
			(0.000115)			
REC				-0.00111		
				(0.000786)		
REC_DEGREE					0.000221	
					(0.00129)	
EFF						-0.00802***
						(0.00115)
MGPO	-0.00429***	-0.00455***	-0.00457***	-0.00425***	-0.00447***	-0.00472***
	(0.00126)	(0.00126)	(0.00126)	(0.00127)	(0.00126)	(0.00124)
NETMET	-0.00101	-0.00140**	-0.00198***	-0.00110*	-0.00142**	-0.000425
	(0.000640)	(0.000594)	(0.000617)	(0.000631)	(0.000606)	(0.000599)
INCOME	3.49e-08	3.98e-08	8.48e-08	3.60e-08	4.69e-08	4.19e-09
	(6.18e-08)	(6.17e-08)	(6.22e-08)	(6.18e-08)	(6.15e-08)	(6.05e-08)
HOUSE	-3.68e-05**	-3.79e-05**	-3.67e-05**	-3.72e-05**	-3.82e-05**	-3.69e-05**
	(1.60e-05)	(1.60e-05)	(1.59e-05)	(1.60e-05)	(1.60e-05)	(1.57e-05)
SENATE	4.15e-05***	3.94e-05***	3.52e-05***	4.07e-05***	3.84e-05***	4.11e-05***
	(1.13e-05)	(1.12e-05)	(1.11e-05)	(1.13e-05)	(1.12e-05)	(1.09e-05)
CONSUMER	4.17e-10	6.27e-10	-3.76e-10	3.99e-10	1.95e-10	3.14e-10
	(7.98e-10)	(8.87e-10)	(8.01e-10)	(8.00e-10)	(7.87e-10)	(7.71e-10)
FE	YES	YES	YES	YES	YES	YES
R-SQUARED	0.028	0.029	0.001	0.026	0.020	0.089
OBS	1,175	1,175	1,175	1,175	1,175	1,175

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

Appendix for Chapter 3

Supplementary Material for “Manure Management Coupled with Bioenergy Production: An Environmental and Economic Assessment of Large Dairies in New Mexico”, Chapter 3.

B.1 System Boundaries

System boundaries in the analysis of LCA and CBA are presented in Figure B.1, Figure B.2 and Figure B.3, respectively, for DLA, AD and ADMC cases. In each figure, the thick solid rectangular box is the system boundaries, the thin solid rectangular boxes indicate the unit processes, the dotted boxes are the material flows, and arrow lines indicate the direction of the respective material flows in the unit processor.

B.1.1 Environmental Regulation Regime

With the fast-growing dairy industry in New Mexico since the 1980s, the challenge of properly managing dairy manure to prevent nitrate pollution of scarce water resources has been emerging as a serious issue in the state (Wang and Joshi, 2015). Various environmental rules and policies regulate livestock manure management, especially for large dairy farms. In this section, we provide an overview of the existing federal and state regulations in the context of New Mexico’s dairy sector. Sections A.2.3 and A.2.4 provide a brief overview of relevant policies in the bioenergy sector.

B.1.2 Current Green Policies in New Mexico

Various incentive and mandatory policies concerning the renewable energy for both consumers and producers are available in New Mexico. New Mexico’s renewable portfolio standard (RPS) is a regulatory mandate to the investor-owned utility companies to maintain 20% share of renewable energy in the total power sales by 2020.[23] The RPS also mandates the rural electric cooperatives to supply 10% renewable power of the total power sales by 2020. In the 20% mandated share of renewable power, the investor-owned utility companies should supply no less than 30% of wind power, and no less than 20% of solar power, no less than 5% from other renewable sources (e.g., biomass, geothermal, and hydropower) and no less than 3% of distributed generation. Other regulatory policies are net metering, mandatory green power options, and interconnection standards. All of these regulations are intended to encourage small-scale power generation by the individual consumers as well as to educate consumers on energy conservation. Consumers are also given the incentives to conserve energy through energy efficiency programs.

The policy incentives vary by the types of renewable energy. The examples are solar market development tax credit, renewable energy production tax credit, sustainable building tax credit, geothermal heat pump tax credit, biodiesel facilities tax credit, agricultural biomass tax credit, alternative energy product manufacturers tax credit, biomass equipment and materials compensating tax deduction, and renewable electricity production tax credit [24]. The major green energy policies are described in Figure B.4. Some of these policies such as renewable energy production tax credit, agricultural biomass tax credit, and biomass equipment and materials compensating tax deduction also are also applicable to the green energy production from the anaerobic digestion of

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[23] New Mexico Public Regulation Commission: http://www.nmprc.state.nm.us/utilities/renewable-energy.html.

[24] Database of state incentives for renewable energy: http://programs.dsireusa.org/system/program?state=NM&.

dairy manure. However, the eligibility criteria for receiving these credits vary with the types of credits.

B.1.3 Environmental Credits

Environmental credits (ECs) such as carbon credit, nutrient credit, and water quality credit are designed to conserve the environmental and ecosystem services and to promote sustainable development. The ECs-trading creates incentives for the conservation of environmental amenities (e.g. clean air) by minimizing associated externalities. The ECs-trading also helps emitters meet regulatory emission requirement. The regulation restricts stakeholders to load or emit pollutions in specified amount (i.e. emission cap). The regulation also maintains flexible loading emission, which allows trade to occur between emitters. The least polluting agent can sell the conserved amount of pollution (i.e. difference between permitted emission and actual emission by emitters) to other agents who need to load more pollutants than the specified amount. The supply and demand mechanism determine the prices of such credits, normally, in the context of a competitive market.

Livestock sector practices such as poor animal feeding operations, overgrazing, improper manure handling and improper fertilizer applications are widely regarded among the major pollution emitters in the agricultural sector, particularly non-point source pollutions (EPA, 2005; Min and Jiao, 2002; Puckett, 1995; Ritter and Shirmohammadi, 2000). Given the incentives to reduce GHGs, water pollution, and other environmental externalities, ECs-trading is getting popular in the agricultural sector.

The dairy industry is one of the major contributors to nitrate pollution in the US (Almasri and Kaluarachchi, 2004). The overloadings of nutrients to surface water and groundwater has been a critical issue in the US (Chesapeake Bay Commission, 2012). For instance, the marine ecosystem of the Chesapeake Bay has long been deteriorating due to overloading of nutrients from various sources including the dairy sector (Kleinman et al., 2012). The US Environmental Protection Agency (EPA) has set "Total Maximum Daily Load (TMDL)" limits in the Chesapeake Bay to restore its ecosystem: 185.9 million pounds of nitrogen, 12.5 million pounds of phosphorus and 6.45 billion pounds of sediment per year (River, 2010). States in the Chesapeake Watershed have initiated the development of nutrient credit trading market as the cost-effective tool to meet such regulatory requirements.[25]

Despite the popularity of the nutrient credit trading concept, efforts to create a market for nutrient credits can be costly. One of the challenges of creating a market for nutrient credits is that it is a complicated task to measure the daily load of pollutants from different sources, such as residential, agricultural, industrial and other human activities. King and Kuch (2003) point out the popularity of nutrient credit trading and difficulties implementing it in the US. They find that the major obstacles of nutrient credit trading are the institutional barriers and market barriers. They find that market barriers such as the creation of supply and demand for the credits are a challenging task.

The market prices of nutrient credits are not well identified as its market only exist in limited areas of the US. The Coalition for an Affordable Bay Solution[26] (CABS)

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[25] Nutrient credit trading tool in the Chesapeake bay: http://www.chesbay.us/Publications/nutrient-trading-2012.pdf.

[26] The Coalition for an Affordable Bay Solution, http://affordablebaysolutions.org/

was formed to create a competitive bid for nitrogen credit in Pennsylvania. According to CABS, the transaction price of each nutrient credit range between $2.98 to $3.05 but manure generated nutrients credits will not be cost effective with prices below $8-$10 per credit (Kelli Barrett, 2013). The nitrogen price in the Pennsylvania nutrient credit market was $8/lbN in 2009 while the minimum price that sustains the farmers' willingness to enter into the credit market was $20/lbN (Jones et al., 2010). However, as pointed out by Jones et al. (2010), the credit prices are expected to increase with the expansion of the credit trading markets due to the growing concerns for emission control and increasing regulatory costs of pollution. Zhang et al. (2013) use the price of nutrient credit as $20/lbN, $10-$15/lbP and $0.005/kg-$CO_2$ in the environmental credit analysis.

Carbon credit market is relatively widespread at the global level, and carbon prices keep fluctuating with the surge in the supply and demand of carbon credits. Figure B.5 below illustrates the historical data on carbon prices in the US (California Carbon Dashboard, 2016; Chicago Climate Change Exchange, 2016). Carbon price used in the analysis is the average price of all years. We conducted a sensitivity analysis incorporating +/-25% change in the prices of N-, P- and CO2- credits to capture the economic impacts of fluctuating prices. Table B.8 Illustrates the N-, P- and CO2- credits earned in a typical dairy farm in New Mexico based on the nutrients and carbon prices discussed here.

B.2 Dairy Manure Characteristics

Excreted dairy manure consists of liquid and solid components containing various nutrients such as nitrogen, phosphorus, potassium, and other trace elements. The amounts of excretion, as well as the organic and inorganic compositions of dairy manure, vary depending on location, cow types, and diet. Nutrient contents also change with manure collection and storage methods (Florez-Margez et al., 2002). Cabrera et al. (2007) developed a stochastic dynamic model to predict seasonal excretion using herd characteristics of New Mexico and found that New Mexico's dairy manure characteristics were not substantially different from the estimates of ASAE (2005) and Van Horn et al. (2003, 1994). These estimates are also consistent with the findings of LPES (2013) and Van Horn et al. (1994). Given the consistency of the estimates from these previous studies, we used data from Van Horn et al. (1994) in this study and summarize the dairy manure characteristics in Table B.1. Table 2 displays the distribution of land in large dairy farms of New Mexico in 2012. Over 60% of the large dairy farms in the state contain at least 202 ha (500 acres) of land and around 45% contain at least 405 ha (1000 acres).

B.3 Major Field Crops and Land Distribution in New Mexico

Cropping patterns include crop rotations and crop arrangements within multiple crops (Pearson et al., 1995). The life cycle durations of major crops of New Mexico are reported in Table B.3 and the top five crops in New Mexico in 2012 in term of harvested acreage are reported in Table B.4. The top three field crops in New Mexico are alfalfa, wheat, and corn. Alfalfa is the leading field crop and number one cash crop in New Mexico, as it is one of the highest quality forages for milk cows. Corn and wheat are among the most flexible crops for marketing as they can be used either for grain or silage and thus help make a profitable choice depending on market prices (Marsalis, 2007). In the Southwestern US, summer corn for silage is usually followed by winter wheat for grain, so the harvest acreages of the two crops are very close; alfalfa is commonly rotated with the corn-wheat cropping system. According to Table B.4, the harvested acreage of alfalfa is four times that of corn-wheat. Therefore, we assume alfalfa is rotated every four years in New Mexico, which is consistent with the literature. As a result, the field crop composition is 80% alfalfa (all year with 3-5 cuttings per year) and 20% corn-wheat (summer corn and winter wheat) for an average year.

Another characteristic of the dairy sector in New Mexico is that most cows are concentrated in a small agricultural area. In 2012, five counties in southern and eastern New Mexico − Chaves, Curry, Roosevelt, Doña Ana and Lea − accommodate 90% of all the 318,878 milk cows in the state, as shown in Figure B.6 (USDA, 2012). The dairy sector has been an economic development driver in Southern New Mexico and has a significant economic impact on the region and the state. Cabrera et al. (2008) use an input-output model to estimate the economic impact of milk production in the state. Their results show that the New Mexico dairy industry accounted for 13.1% of the total agricultural outputs and 20.5% of the agricultural jobs, making it the top agricultural industry in the state. The increasing trends in sector consolidation and milk productivity indicate that the dairy industry will continue to play an important role in the agricultural economic development of New Mexico. As the large dairy farms in New Mexico are mainly concentrated in five counties (Curry, Roosevelt, Chaves, Doña Ana, and Lea), we calculate the fraction of surrounding land suitable for receiving dairy manure as the ratio of the total area of field crop lands in these five counties over the total area of the five counties for the off-site hauling cost considerations. Area of field crops and such five counties are presented in Table B.5.

Table B.1: Dairy manure characteristics in New Mexico

Dairy Manure Excretion and Nutrients	Unit	Value
Total Excretion wet	kg/cow-day	56.7
Total Dry Matter	kg/cow-day	6.9
Water Content	kg/cow-day	49.8
Volatile Solids	kg/cow-day	573
Total Nitrogen	kg/cow-day	0.296
Total Phosphorus	kg/cow-day	0.054

Source: Van Horn et al. (1994)

Table B.2: Land area in dairy farms with 500 or more milk cows in New Mexico

Land size category (acres)	Median value of land size (acres)	Number of farms	Percentage of farms
1 – 9	5.0	1	0.9%
10 - 49	29.5	1	0.9%
50 - 69	59.5	1	0.9%
70 - 99	84.5	7	6.4%
100 – 139	119.5	4	3.7%
140 – 179	159.5	6	5.5%
180 – 219	199.5	6	5.5%
220 – 259	239.5	6	5.5%
260 – 499	379.5	11	10.1%

500 – 999	749.5	18	16.5%
1,000 - 1,999	1499.5	26	23.9%
2,000 or more	2000.0	22	20.2%

Source: USDA (2012)

Table B.3: Planting and harvesting dates of New Mexico crops

Crop	Usual planting dates			Usual harvesting dates		
	Begin	Most active	End	Begin	Most active	End
Beans, dry edible	15-May	May 20 - Jun 1	15-Jun	15-Aug	Sep 1 - Sep 30	15-Oct
Corn for grain	15-Apr	Apr 20 - May 10	20-May	25-Sep	Oct 1 - Oct 30	20-Nov
Corn for silage	15-Apr	Apr 20 - May 10	20-May	1-Sep	Sep 10 - Oct 1	1-Nov
Cotton, all	10-Apr	Apr 20 - May 10	20-May	10-Oct	Oct 25 - Nov 30	20-Dec
Hay, alfalfa	(NA)	(NA)	(NA)	1-May	(NA)	20-Oct
Hay, other	(NA)	(NA)	(NA)	1-May	(NA)	20-Oct
Peanuts	10-May	May 15 - May 25	1-Jun	1-Oct	Oct 10 - Oct 30	10-Nov
Potatoes, fall	20-Apr	Apr 25 - May 5	10-May	1-Sep	Sep 25 - Oct 10	20-Oct
Sorghum for grain	15-May	May 20 - Jun 15	10-Jul	15-Oct	Oct 20 - Nov 15	15-Dec
Sorghum for silage	10-May	May 20 - Jun 10	20-Jun	5-Sep	Sep 15 - Oct 10	1-Nov
Wheat, winter	25-Aug	Sep 10 - Sep 24	15-Oct	15-Jun	Jun 20 - Jul 10	15-Jul

Source: USDA-NASS (2010)

Table B.4: Top five crops of New Mexico in term of harvested acreage

Crop	Acreage (acres)
Alfalfa[a]	343,032
Wheat for grain, all	87,504
Winter wheat for grain	86,434
Corn for silage	81,866
Pecans, all	41,331

[a] Forage-land used for all hay and haylage, grass silage, and greenchop. Source: USDA-NASS (2014)

Table B.5: Field crop land area in five southeastern counties of New Mexico (acres)

County	Corn	Wheat	Alfalfa	Total Area
Curry	15600	33,290	6,200	55,090
Roosevelt	9200	18,192	6,000	33,392
Chaves	13500	2169	20,000	35,669
Doña Ana	7300	953	17,500	25,753
Lea	6000	3,282	7,500	16,782
Total crop Land Area in 5 counties				166,686
Total area of 5 counties				11,594,240

Source: USDA (2012)

Figure B.1: LCA boundary of direct land application (DLA)

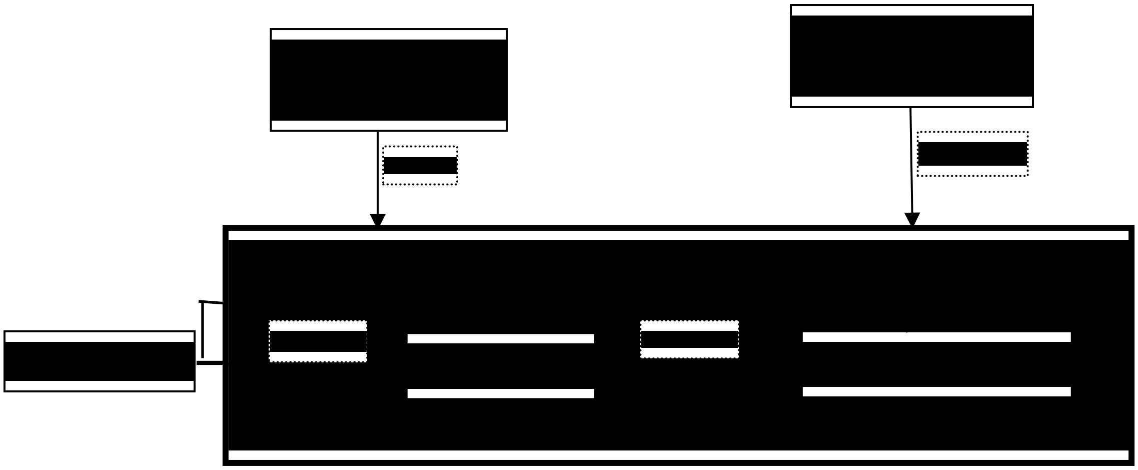


Figure B.2: LCA boundary of anaerobic digestion (AD)

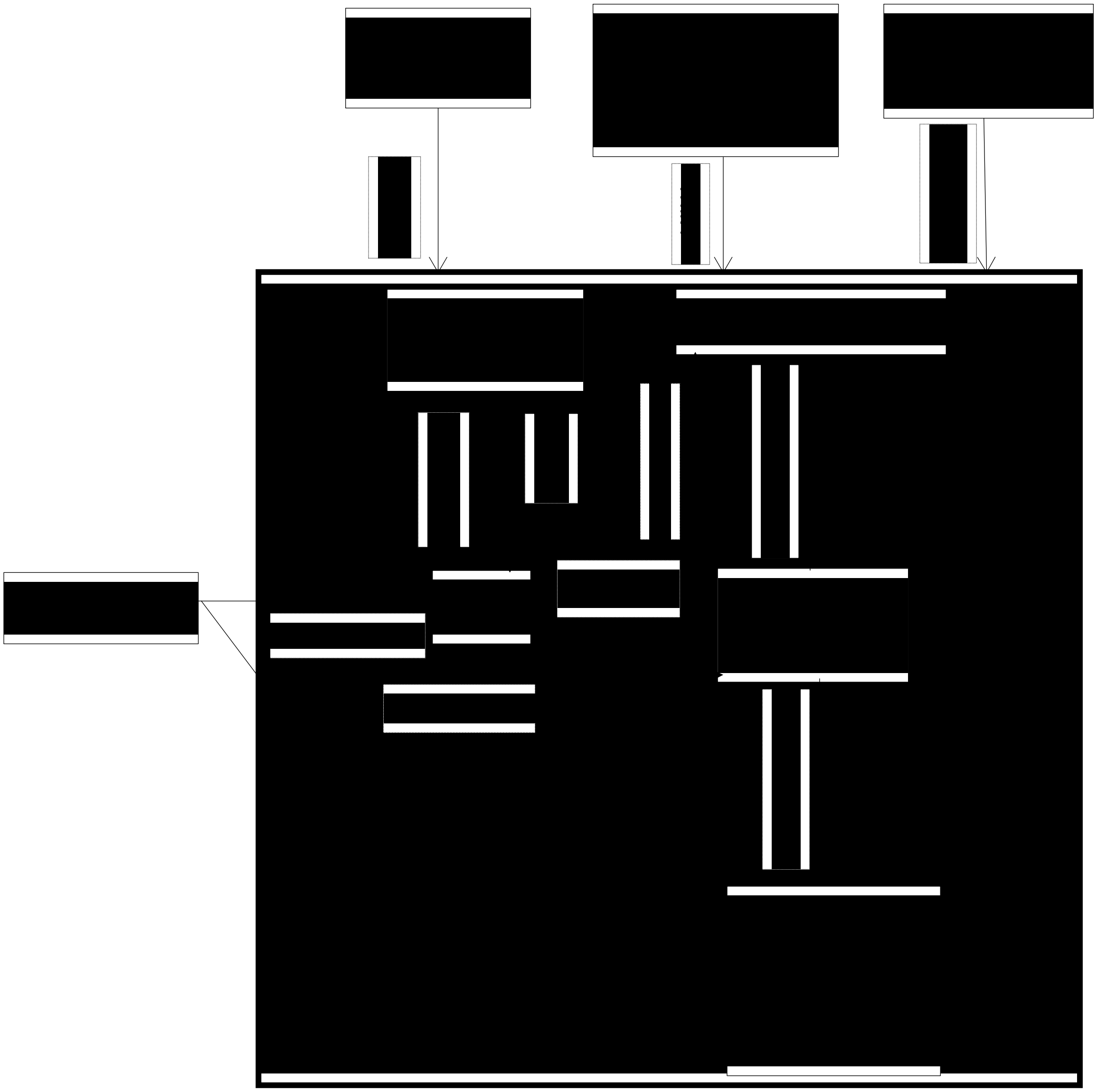


Figure B.3: LCA boundary of the anaerobic digestion of dairy manure coupled with microalgae cultivation (ADMC)

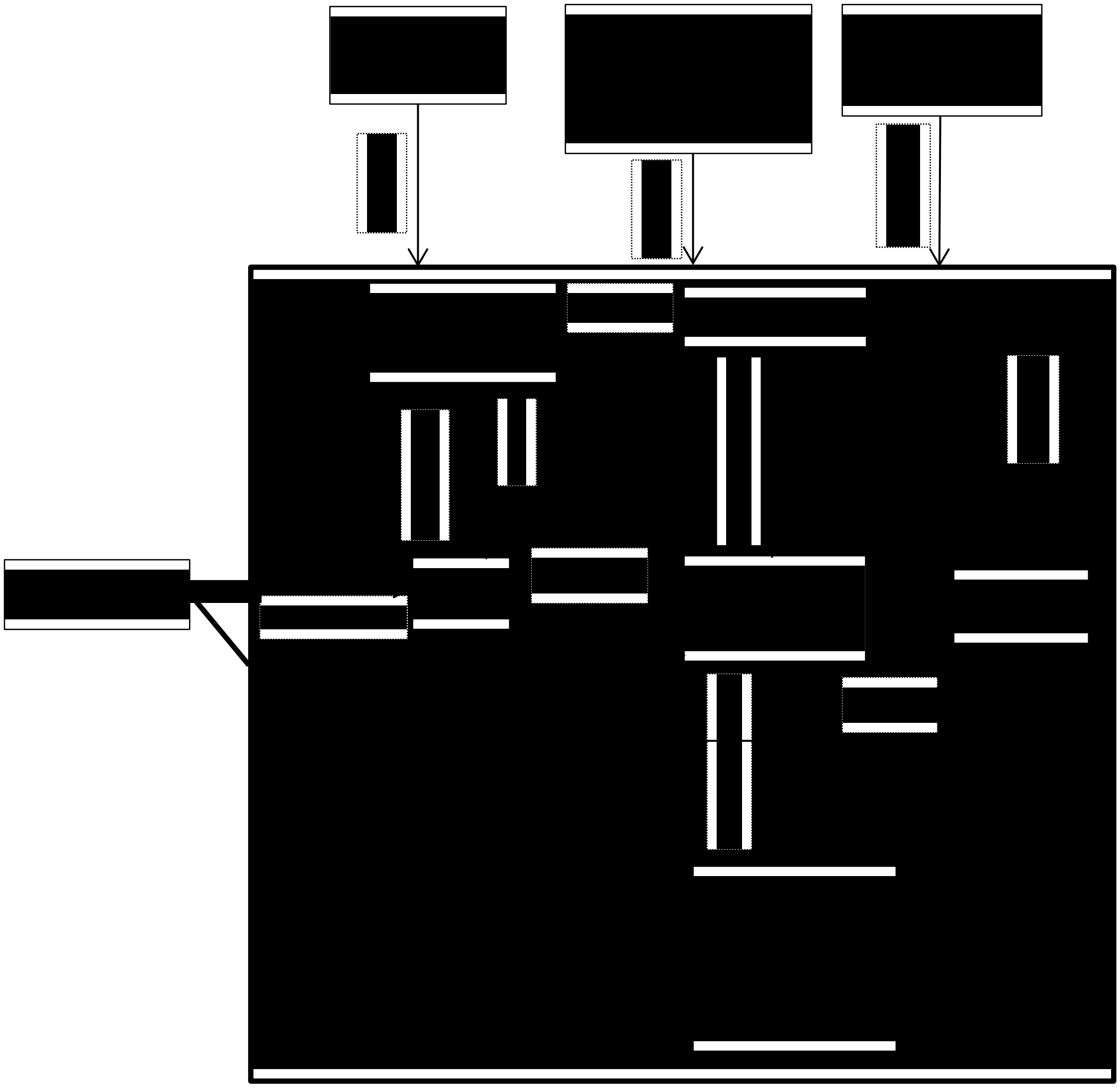


Figure B.4: Selected biofuel policies and regulations in the state of New Mexico

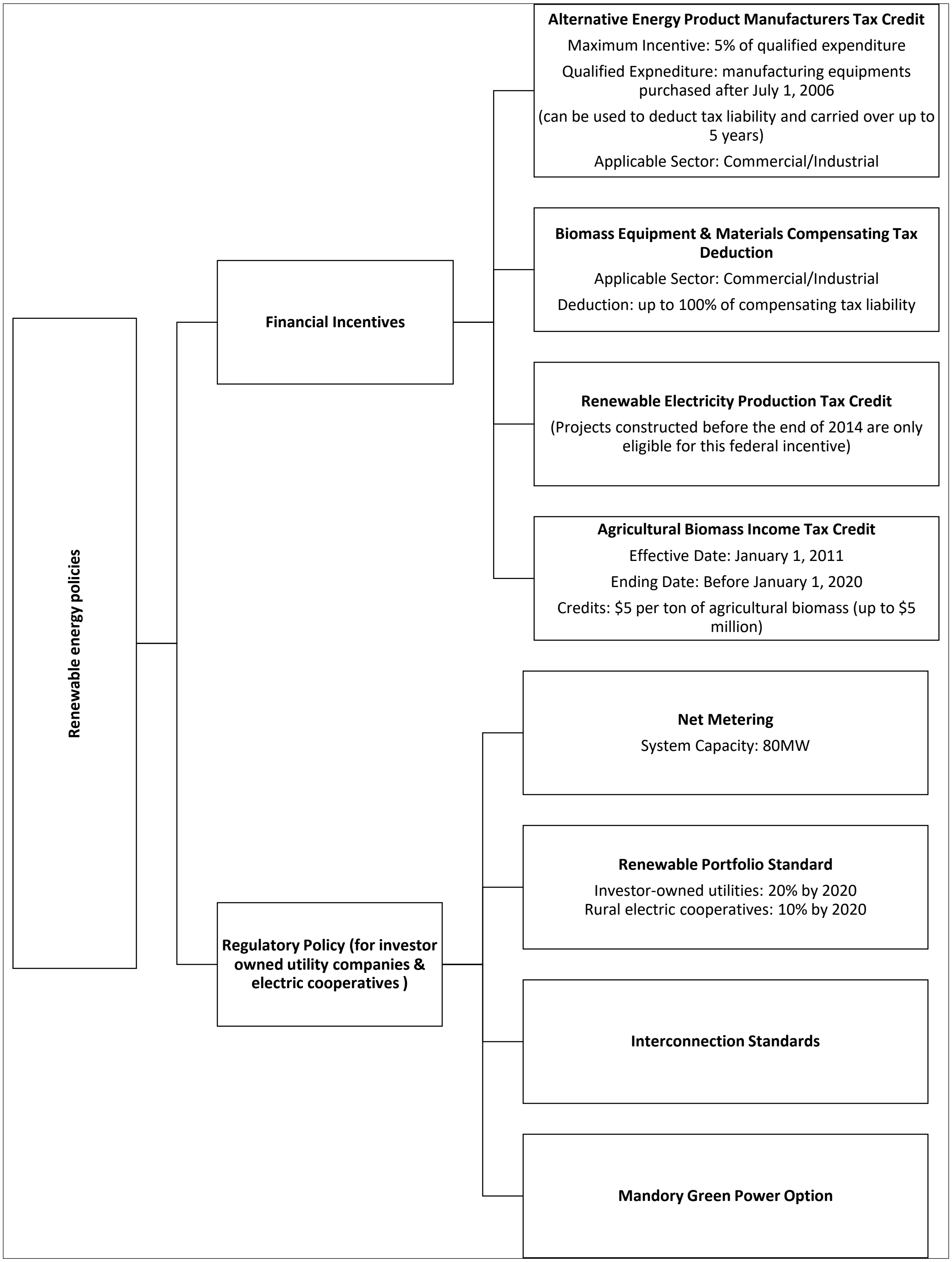


Figure B.5: Historical carbon credit prices of California carbon trading market

Data Source: California Carbon Dashboard (2016)

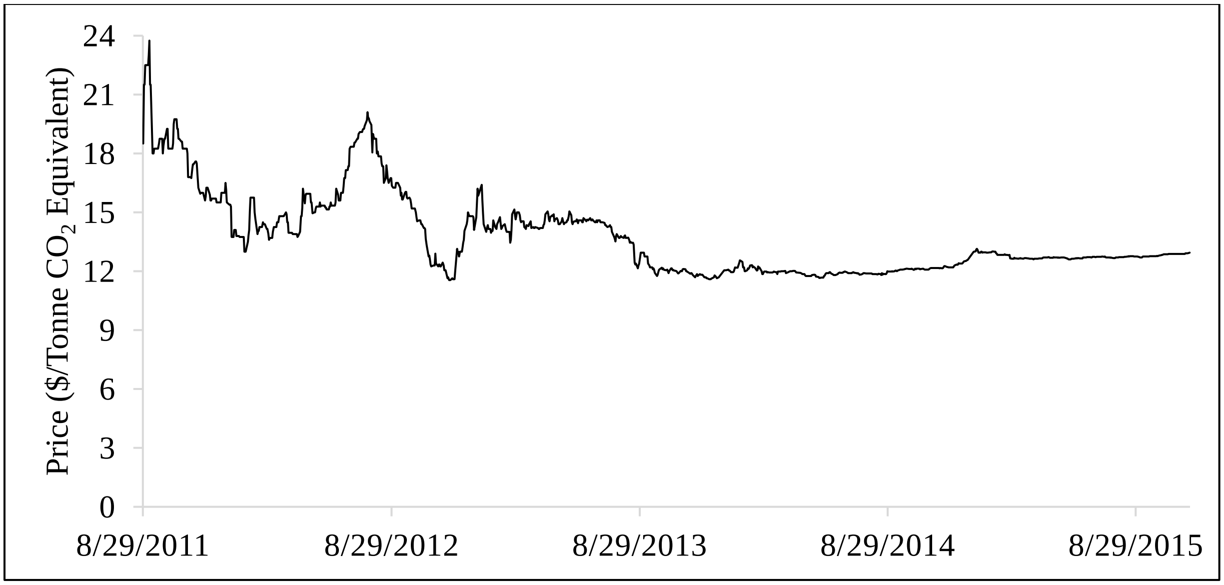
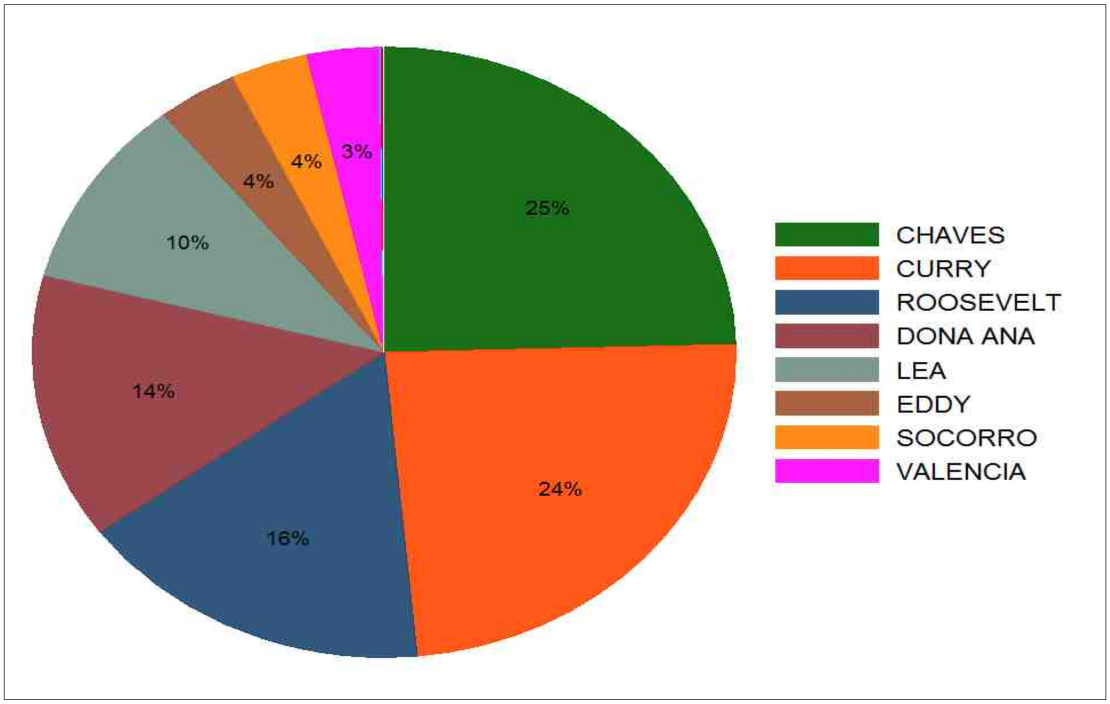


Figure B.6: Composition of milk cows in New Mexico in 2012 at the county level



Data Source: USDA (2012)

Table B.6: Energy use and fuel cost in manure hauling

Distance	Diesel use[a]	Fuel cost[b]
(km)	(gallon/km-ha)	($/ha)
1	12	46
2	14	54
3	15	58
4	17	65
5	20	77
6	22	85
7	25	96
8	28	108
9	32	123
10	36	139
11	41	156
12	46	176
13	52	199
14	59	225
15	66	255

[a] One gallon of diesel is equivalent to 0.15 GJ of energy.

[b] US energy information administration, 2014 annual average price for rocky mountain region of the United States, EPA: (http://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_r40_a.htm). Diesel price is $3.85 per gal.

Source: Sanford et al. (2009).

Table B.7: Yield rates and prices of major field crops in New Mexico

	Crop	Unit	Average values
Yield	corn	bushel/ha	432
	wheat	bushel/ha	59
	alfalfa	bushel/ha	420
Price	corn	\$/bushel[a]	7.42
	wheat	\$/bushel	7.73
	alfalfa	\$/bushel	7.00

[a] One bushel is equivalent to 27.2 kg.; Source: USDA (2012)

Table B.8: The annual N-, P- and CO2- credits earned in a typical dairy farm in New Mexico.

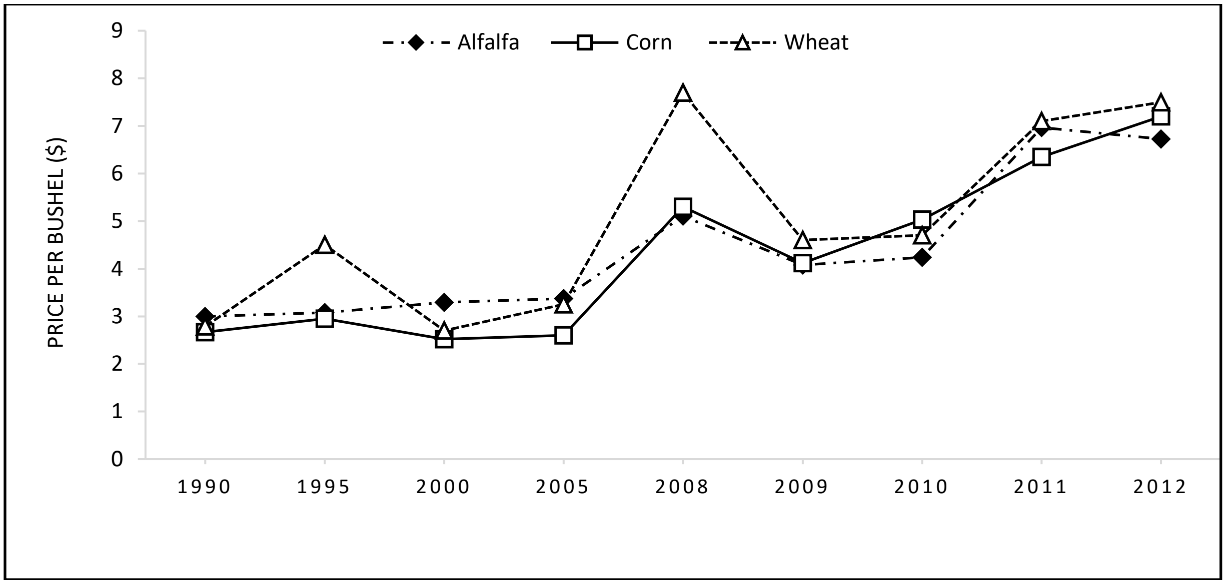
Credits	Unit	AD	ADMC
N Credit	Kg/year	84,995	866,282
P Credit	Kg/year	136	274
CO2 Credit	Kg/year	7,310,976	10,023,672

Source: Adapted from Zhang et al. (2013).

Table B.9: Parameters of sensitivity analysis

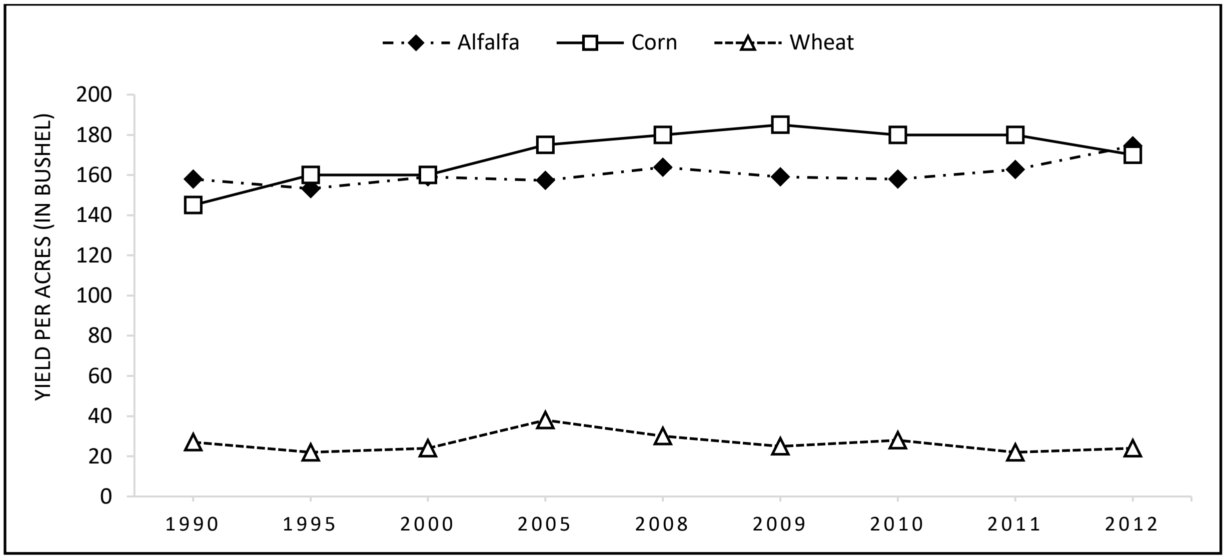
Variable	Definition	Unit	Value
Rangeland Availability			
$\tilde{A}_r$	The offsite land area to be searched to haul the excess manure	ha	416
ξ_1	The radius of the outer disk	km	1.6
ξ_2	The radius of the inner disk	km	1.2
$\hbar_d$	The average hauling distance of excess manure to off-site croplands	km	1

Figure B.7: Prices of alfalfa, wheat, and corn per bushel (in dollars)



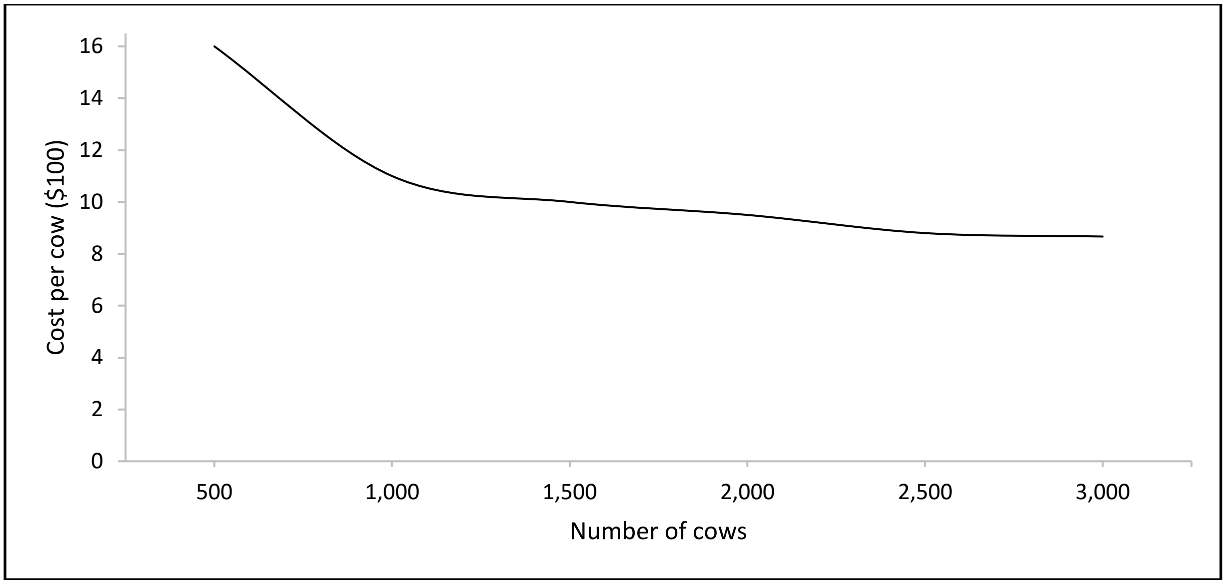
Data Source: USDA (2012)

Figure B.8: Alfalfa, wheat, and corn yield per acres (in bushels)



Data Source: USDA (2012)

Figure B.9: Initial outlay of anaerobic digestion per cow, based on farm size



Data Source: Lazarus (2014)

Figure B.10: Hauling cost with varying willingness to pay in the baseline scenario of DLA case.

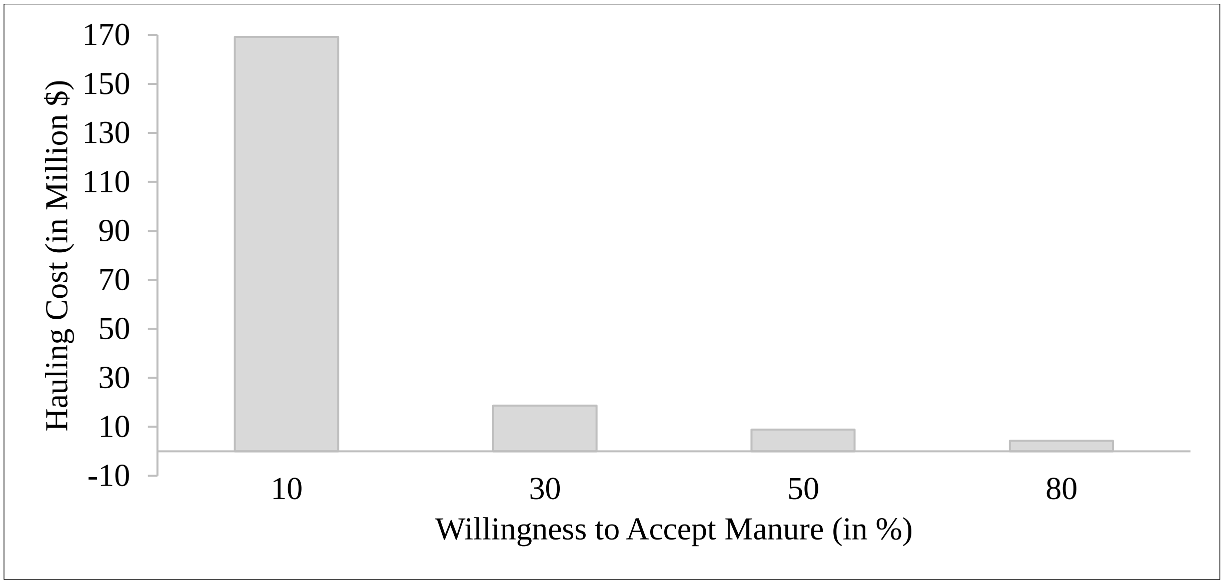
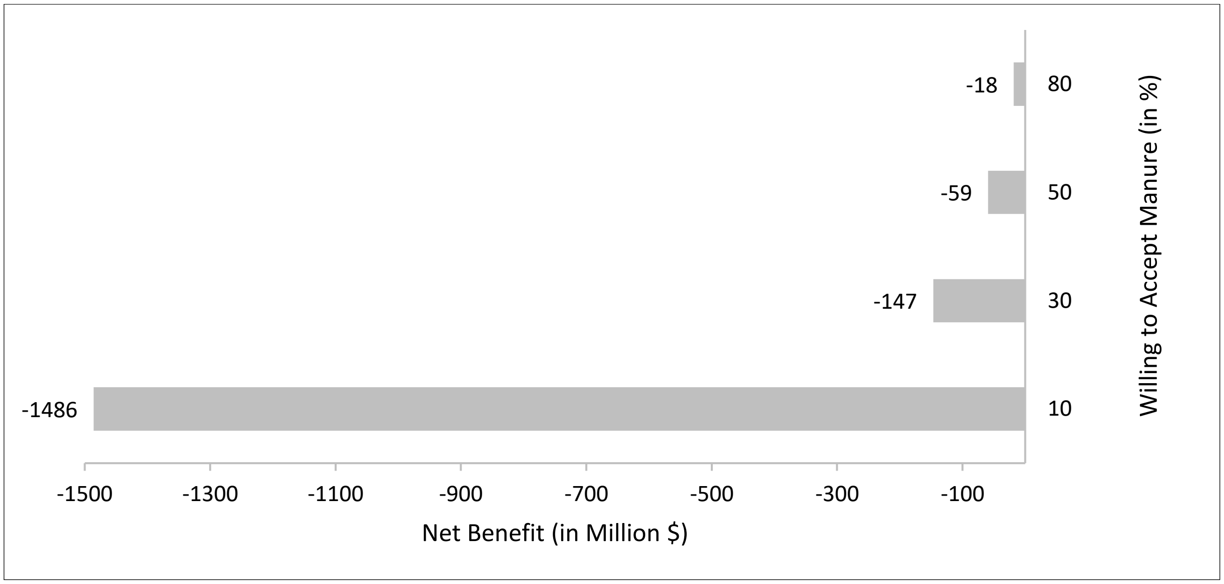


Figure B.11: Net present value with varying willingness to pay in the baseline scenario of DLA case.



Appendix for Chapter 4

Tables C.1-C.4 are the state level estimates for the impacts of sectoral prices, HDD, and CDD on sectoral natural gas consumption (the uses of these tables are indexed in the result section of chapter 4).

Table C.1: Residential natural gas consumption- state level impacts

VARIABLES	RESPRICE	HDD	CDD
ALABAMA	-1.246***	0.00101***	0.000473***
	(0.0898)	(7.65e-05)	(0.000128)
ALASKA	-0.133*	5.90e-05	-0.00153***
	(0.0784)	(0.000152)	(0.000356)
ARIZONA	-0.602***	0.000893***	0.00113***
	(0.101)	(9.87e-05)	(0.000191)
ARKANSAS	-0.948***	0.00133***	-9.51e-06
	(0.0861)	(0.000107)	(0.000115)
CALIFORNIA	-0.371***	0.000616***	0.00125***
	(0.0885)	(0.000114)	(0.000252)
COLORADO	-0.485***	0.000767***	-0.000423**
	(0.0790)	(8.09e-05)	(0.000180)
CONNECTICUT	-0.659***	0.000625***	5.34e-05
	(0.0750)	(4.74e-05)	(0.000173)
DELAWARE	-0.632***	0.00129***	-0.000530***
	(0.0707)	(0.000100)	(0.000148)
FLORIDA	-0.698***	0.000387***	0.00100***
	(0.114)	(0.000100)	(0.000147)
GEORGIA	-0.336***	0.00169***	0.000809***
	(0.0605)	(8.68e-05)	(0.000135)
HAWAII	-0.134**	-0.00131***	0.000792***
	(0.0567)	(0.000111)	(0.000249)
IDAHO	-0.501***	0.000794***	-0.000876***
	(0.119)	(8.50e-05)	(0.000187)
ILLINOIS	-0.496***	0.000715***	-0.000215
	(0.0484)	(4.07e-05)	(0.000145)
INDIANA	-0.690***	0.000804***	-7.65e-05
	(0.0556)	(4.43e-05)	(0.000157)
IOWA	-0.486***	0.000750***	-0.000236**
	(0.0442)	(3.82e-05)	(0.000116)
KANSAS	-0.701***	0.000741***	0.000405***
	(0.0632)	(4.72e-05)	(0.000135)
KENTUCKY	-0.640***	0.00132***	-0.000174
	(0.0632)	(6.89e-05)	(0.000124)
LOUISIANA	-0.786***	0.00137***	0.000692***
	(0.0807)	(0.000103)	(0.000107)
MAINE	-0.282**	0.000750***	-0.000382
	(0.138)	(6.54e-05)	(0.000300)
MARYLAND	-0.735***	0.00135***	-0.000123
	(0.0737)	(8.49e-05)	(0.000137)
MASSACHUSETTS	-0.376***	0.000667***	-0.000242

	(0.0801)	(4.64e-05)	(0.000190)
MICHIGAN	-0.696***	0.000602***	-0.000669***
	(0.0514)	(3.99e-05)	(0.000144)
MINNESOTA	-0.570***	0.000767***	-0.000329**
	(0.0619)	(4.10e-05)	(0.000140)
MISSISSIPPI	-0.743***	0.00122***	0.000524***
	(0.0789)	(8.15e-05)	(0.000144)
MISSOURI	-0.781***	0.000657***	0.000325**
	(0.0581)	(4.70e-05)	(0.000134)
MONTANA	-0.615***	0.000471***	-0.00103***
	(0.0690)	(7.48e-05)	(0.000164)
NEBRASKA	-0.883***	0.000601***	0.000367**
	(0.0736)	(4.93e-05)	(0.000155)
NEVADA	-0.342***	0.000951***	0.000986***
	(0.0897)	(8.36e-05)	(0.000164)
NEW HAMPSHIRE	-0.712***	0.000666***	-0.000103
	(0.0844)	(4.74e-05)	(0.000195)
NEW JERSEY	-0.341***	0.000916***	0.000175
	(0.0499)	(4.28e-05)	(0.000137)
NEW MEXICO	-0.588***	0.000948***	0.000763***
	(0.0684)	(7.82e-05)	(0.000161)
NEW YORK	-0.697***	0.000541***	-0.000163
	(0.0513)	(4.03e-05)	(0.000116)
NORTH CAROLINA	-0.835***	0.00173***	-3.83e-05
	(0.0734)	(9.43e-05)	(0.000149)
NORTH DAKOTA	-0.677***	0.000571***	-0.000670***
	(0.0543)	(4.35e-05)	(0.000152)
OHIO	-0.505***	0.000765***	-0.000334**
	(0.0475)	(4.57e-05)	(0.000163)
OKLAHOMA	-0.781***	0.00122***	0.000129
	(0.0676)	(0.000116)	(0.000119)
OREGON	-0.650***	0.000955***	-0.000872***
	(0.102)	(0.000111)	(0.000248)
PENNSYLVANIA	-0.744***	0.000768***	-0.000149
	(0.0516)	(4.16e-05)	(0.000117)
RHODE ISLAND	-1.128***	0.000433***	1.66e-05
	(0.122)	(5.98e-05)	(0.000229)
SOUTH CAROLINA	-0.588***	0.00192***	4.53e-05
	(0.0644)	(0.000102)	(0.000152)
SOUTH DAKOTA	-0.708***	0.000603***	-0.000689***
	(0.0613)	(3.99e-05)	(0.000134)
TENNESSEE	-0.766***	0.00137***	-6.58e-05
	(0.0759)	(7.72e-05)	(0.000132)
TEXAS	-0.588***	0.00162***	0.000617***
	(0.0579)	(9.30e-05)	(9.68e-05)
UTAH	-0.696***	0.000997***	0.000354*
	(0.117)	(8.97e-05)	(0.000200)
VERMONT	-0.283***	0.000622***	-0.000554***
	(0.0752)	(5.20e-05)	(0.000208)
VIRGINIA	-0.614***	0.00160***	-0.000168
	(0.0755)	(8.80e-05)	(0.000142)
WASHINGTON	-0.298***	0.000774***	-0.00143***
	(0.104)	(0.000118)	(0.000266)
WEST VIRGINIA	-0.762***	0.00105***	-0.00157***
	(0.0860)	(0.000110)	(0.000185)
WISCONSIN	-0.631***	0.000794***	-0.000509***

	(0.0547)	(4.00e-05)	(0.000154)
WYOMING	-0.674***	0.000398***	-0.000763***
	(0.104)	(0.000101)	(0.000237)
OBS		8,999	
R-SQUARED		0.985	

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

Table C.2: Commercial natural gas consumption- state level impacts

VARIABLES	COMPRICE	HDD	CDD
ALABAMA	-0.377***	0.000796***	0.000382***
	(0.0909)	(5.75e-05)	(0.000104)
ALASKA	-0.0925	0.000458***	-0.000963***
	(0.0590)	(0.000121)	(0.000277)
ARIZONA	-0.189***	0.000324***	0.000680***
	(0.0635)	(5.02e-05)	(0.000107)
ARKANSAS	-0.390***	0.000832***	0.000262***
	(0.0864)	(7.97e-05)	(8.52e-05)
CALIFORNIA	-0.163**	-4.27e-05	0.000775***
	(0.0641)	(8.85e-05)	(0.000196)
COLORADO	-0.215***	0.00100***	-0.000406***
	(0.0739)	(6.75e-05)	(0.000147)
CONNECTICUT	-0.446***	0.000537***	0.000649***
	(0.0439)	(3.48e-05)	(0.000132)
DELAWARE	0.193**	0.00127***	-0.000112
	(0.0910)	(9.19e-05)	(0.000136)
FLORIDA	-0.256***	-8.17e-05	0.000732***
	(0.0620)	(5.69e-05)	(9.23e-05)
GEORGIA	-0.123*	0.00146***	0.000544***
	(0.0688)	(8.15e-05)	(0.000126)
HAWAII	-0.0644	-0.000889***	0.000555***
	(0.0414)	(8.07e-05)	(0.000179)
IDAHO	-0.272***	0.000901***	-0.000161
	(0.0882)	(6.29e-05)	(0.000136)
ILLINOIS	-0.182***	0.000687***	5.29e-05
	(0.0441)	(3.19e-05)	(0.000115)
INDIANA	-0.372***	0.000855***	-0.000119
	(0.0564)	(3.68e-05)	(0.000141)
IOWA	-0.178***	0.000722***	-0.000230**
	(0.0489)	(3.31e-05)	(0.000111)
KANSAS	-0.428***	0.000822***	0.000888***
	(0.0850)	(4.70e-05)	(0.000146)
KENTUCKY	-0.193***	0.00130***	-0.000127
	(0.0654)	(5.53e-05)	(9.84e-05)
LOUISIANA	-0.354***	0.000688***	0.000467***
	(0.0647)	(7.27e-05)	(7.97e-05)
MAINE	-0.00427	0.000619***	8.30e-05
	(0.107)	(5.93e-05)	(0.000259)
MARYLAND	-0.259***	0.000925***	-5.85e-05

	(0.0674)	(7.22e-05)	(0.000111)
MASSACHUSETTS	-0.394***	0.000673***	-0.000198
	(0.0831)	(4.90e-05)	(0.000207)
MICHIGAN	-0.421***	0.000718***	-0.000194
	(0.0626)	(3.47e-05)	(0.000128)
MINNESOTA	-0.299***	0.000839***	-0.000145
	(0.0629)	(4.06e-05)	(0.000139)
MISSISSIPPI	-0.123*	0.000778***	0.000480***
	(0.0662)	(6.08e-05)	(0.000112)
MISSOURI	-0.319***	0.000740***	0.000192*
	(0.0759)	(3.46e-05)	(0.000109)
MONTANA	-0.523***	0.000768***	-0.000414**
	(0.0922)	(8.29e-05)	(0.000183)
NEBRASKA	0.0397	0.000648***	0.000278**
	(0.0720)	(4.02e-05)	(0.000136)
NEVADA	0.0105	0.000352***	0.000579***
	(0.0688)	(5.79e-05)	(0.000125)
NEW HAMPSHIRE	-0.235**	0.000782***	-0.000102
	(0.116)	(5.31e-05)	(0.000234)
NEW JERSEY	-0.103	0.000503***	0.000347**
	(0.0680)	(4.60e-05)	(0.000158)
NEW MEXICO	-0.194***	0.000840***	0.000320*
	(0.0720)	(7.77e-05)	(0.000169)
NEW YORK	-0.297***	0.000441***	0.000666***
	(0.0701)	(4.27e-05)	(0.000146)
NORTH CAROLINA	-0.206***	0.00121***	0.000290**
	(0.0681)	(7.44e-05)	(0.000116)
NORTH DAKOTA	-0.376***	0.000845***	-0.000532***
	(0.0714)	(4.49e-05)	(0.000159)
OHIO	-0.0748	0.000912***	-0.000283**
	(0.0519)	(3.63e-05)	(0.000138)
OKLAHOMA	-0.415***	0.00115***	6.14e-05
	(0.0807)	(0.000113)	(0.000112)
OREGON	-0.316***	0.00103***	-0.000378*
	(0.0868)	(8.78e-05)	(0.000194)
PENNSYLVANIA	-0.0967*	0.000893***	-0.000138
	(0.0548)	(3.34e-05)	(0.000104)
RHODE ISLAND	-0.750***	0.000777***	-0.000141
	(0.121)	(5.95e-05)	(0.000250)
SOUTH CAROLINA	-0.0428	0.000889***	0.000592***
	(0.0608)	(6.92e-05)	(0.000109)
SOUTH DAKOTA	-0.119**	0.000771***	-0.000512***
	(0.0540)	(3.46e-05)	(0.000116)
TENNESSEE	-0.141**	0.00101***	0.000198**
	(0.0647)	(5.46e-05)	(9.77e-05)
TEXAS	-0.269***	0.000854***	0.000631***
	(0.0511)	(6.84e-05)	(7.44e-05)
UTAH	-0.215	0.00111***	-3.74e-05
	(0.132)	(8.97e-05)	(0.000198)
VERMONT	-0.870***	0.000674***	-0.000291
	(0.0972)	(5.44e-05)	(0.000236)
VIRGINIA	0.0206	0.00118***	9.79e-05
	(0.0685)	(6.98e-05)	(0.000109)
WASHINGTON	-0.0167	0.000745***	-0.000487**
	(0.0894)	(8.88e-05)	(0.000197)
WEST VIRGINIA	-0.108*	0.000886***	-5.63e-05

	(0.0657)	(9.11e-05)	(0.000140)
WISCONSIN	-0.0459	0.000846***	-0.000315**
	(0.0450)	(3.40e-05)	(0.000130)
WYOMING	-0.161	0.000717***	-0.000953***
	(0.0986)	(8.90e-05)	(0.000194)
OBS		8,999	
R-SQUARED		0.974	

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

Table C.3: Industrial natural gas consumption- state level impacts

VARIABLES	INDPRICE	HDD	CDD
ALABAMA	-0.142***	0.000141***	7.92e-05
	(0.0282)	(2.99e-05)	(6.14e-05)
ALASKA	-1.190***	-0.000385*	0.000504
	(0.117)	(0.000212)	(0.000473)
ARIZONA	-0.135**	0.000343***	0.000140
	(0.0561)	(4.37e-05)	(9.53e-05)
ARKANSAS	-0.0689	0.000183***	-0.000139**
	(0.0549)	(4.81e-05)	(5.88e-05)
CALIFORNIA	-0.0543	-4.85e-05	0.000356***
	(0.0412)	(5.44e-05)	(0.000115)
COLORADO	-0.0633	0.000625***	0.000598***
	(0.0680)	(7.56e-05)	(0.000167)
CONNECTICUT	-0.247***	0.000321***	0.000269**
	(0.0486)	(3.32e-05)	(0.000121)
DELAWARE	-0.0823	0.000226*	-0.000248
	(0.0968)	(0.000117)	(0.000183)
FLORIDA	-0.186***	7.75e-05	1.53e-05
	(0.0504)	(5.51e-05)	(9.10e-05)
GEORGIA	-0.0325	0.000111**	0.000106
	(0.0307)	(4.37e-05)	(7.75e-05)
HAWAII	-0.384***	-5.19e-05	0.000441**
	(0.0849)	(9.78e-05)	(0.000216)
IDAHO	-0.125*	7.25e-05	-0.000336***
	(0.0687)	(4.83e-05)	(0.000107)
ILLINOIS	-0.0519	0.000277***	8.44e-05
	(0.0342)	(2.30e-05)	(8.51e-05)
INDIANA	-0.0659***	0.000220***	0.000237***
	(0.0192)	(2.48e-05)	(9.20e-05)
IOWA	-0.134**	0.000143***	-0.000106
	(0.0562)	(3.56e-05)	(0.000115)
KANSAS	0.000111	0.000124***	0.000701***
	(0.0627)	(3.85e-05)	(0.000117)
KENTUCKY	0.0344	0.000238***	-3.09e-05
	(0.0389)	(3.66e-05)	(7.26e-05)
LOUISIANA	-0.101***	8.34e-05*	0.000106*

	(0.0286)	(4.67e-05)	(5.61e-05)
MAINE	0.189	0.000166	-0.000249
	(0.362)	(0.000247)	(0.000936)
MARYLAND	0.0802	0.000388***	0.000265
	(0.112)	(0.000107)	(0.000171)
MASSACHUSETTS	-0.471***	0.000627***	-0.000258
	(0.0591)	(6.01e-05)	(0.000237)
MICHIGAN	-0.406***	0.000316***	8.88e-05
	(0.0787)	(3.10e-05)	(0.000119)
MINNESOTA	-0.0888*	0.000200***	2.71e-05
	(0.0527)	(3.69e-05)	(0.000119)
MISSISSIPPI	-0.0517	8.51e-05*	0.000109
	(0.0499)	(4.45e-05)	(8.29e-05)
MISSOURI	-0.0666*	0.000306***	0.000169**
	(0.0402)	(2.36e-05)	(7.87e-05)
MONTANA	-0.0122	0.000299***	-0.000208
	(0.0638)	(6.79e-05)	(0.000150)
NEBRASKA	0.0152	6.53e-05	0.000844***
	(0.116)	(6.11e-05)	(0.000202)
NEVADA	-0.0301	0.000117**	-1.89e-05
	(0.0796)	(5.12e-05)	(0.000112)
NEW HAMPSHIRE	-0.0237	0.000362***	2.27e-05
	(0.109)	(6.68e-05)	(0.000261)
NEW JERSEY	-0.119**	0.000243***	0.000138
	(0.0476)	(3.29e-05)	(0.000110)
NEW MEXICO	-0.0499	0.000107*	0.000230
	(0.0569)	(6.47e-05)	(0.000142)
NEW YORK	-0.00995	0.000362***	0.000105
	(0.0520)	(3.00e-05)	(9.95e-05)
NORTH CAROLINA	-0.177***	0.000226***	-2.71e-05
	(0.0356)	(4.38e-05)	(7.40e-05)
NORTH DAKOTA	-0.268**	-0.000129	-0.00132***
	(0.111)	(8.30e-05)	(0.000272)
OHIO	0.00990	0.000268***	7.80e-05
	(0.0309)	(2.26e-05)	(8.38e-05)
OKLAHOMA	0.0256	5.37e-05	-3.62e-06
	(0.0293)	(6.91e-05)	(7.61e-05)
OREGON	0.0908	0.000134**	-8.74e-05
	(0.0711)	(5.79e-05)	(0.000128)
PENNSYLVANIA	-0.0995***	0.000216***	2.27e-05
	(0.0357)	(2.44e-05)	(7.47e-05)
RHODE ISLAND	0.307*	4.42e-05	-0.000124
	(0.185)	(8.12e-05)	(0.000324)
SOUTH CAROLINA	-0.256***	8.81e-05**	7.88e-05
	(0.0311)	(4.35e-05)	(7.68e-05)
SOUTH DAKOTA	-0.104	0.000133*	3.98e-05
	(0.168)	(7.58e-05)	(0.000249)
TENNESSEE	-0.140***	0.000219***	-2.00e-05
	(0.0433)	(3.56e-05)	(6.89e-05)
TEXAS	-0.0508	9.54e-05*	0.000231***
	(0.0348)	(5.37e-05)	(6.42e-05)
UTAH	-0.0288	7.70e-05	-1.91e-05
	(0.0844)	(5.86e-05)	(0.000122)
VERMONT	-0.239**	0.000282***	-0.000144
	(0.113)	(5.47e-05)	(0.000214)
VIRGINIA	0.0483	0.000201*	0.000513***

	(0.0876)	(0.000108)	(0.000169)
WASHINGTON	-0.0356	0.000124**	-0.000284**
	(0.0354)	(5.12e-05)	(0.000110)
WEST VIRGINIA	8.75e-05	0.000288***	3.98e-05
	(0.0476)	(6.86e-05)	(0.000114)
WISCONSIN	-0.0678**	0.000402***	-8.47e-05
	(0.0307)	(2.40e-05)	(9.06e-05)
WYOMING	0.0332	0.000100**	-2.47e-05
	(0.0420)	(4.32e-05)	(9.47e-05)
OBS		8,999	
R-SQUARED		0.905	

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

Table C.4: Electric sector natural gas consumption- state level impacts

VARIABLES	CGPRICE	HDD	CDD
ALABAMA	-0.592***	0.000679***	0.00235***
	(0.106)	(0.000118)	(0.000206)
ALASKA	-0.376***	0.000580***	0.000559
	(0.0879)	(0.000186)	(0.000393)
ARIZONA	0.0101	0.000170	0.00253***
	(0.167)	(0.000191)	(0.000394)
ARKANSAS	-0.101	0.000713***	0.00226***
	(0.100)	(0.000217)	(0.000238)
CALIFORNIA	0.151***	0.000552***	0.00268***
	(0.0561)	(0.000161)	(0.000329)
COLORADO	0.140*	0.000692***	0.00209***
	(0.0782)	(0.000139)	(0.000291)
CONNECTICUT	-0.289***	-9.38e-05	0.00138***
	(0.0875)	(8.54e-05)	(0.000302)
DELAWARE	-0.257*	0.000291	0.00314***
	(0.142)	(0.000262)	(0.000405)
FLORIDA	-0.126*	-9.30e-05	0.000813***
	(0.0665)	(0.000125)	(0.000201)
GEORGIA	-1.012***	0.000711***	0.00360***
	(0.137)	(0.000212)	(0.000329)
IDAHO	-0.320	0.00160***	0.00402***
	(0.283)	(0.000316)	(0.000680)
ILLINOIS	-0.287	0.000327**	0.00659***
	(0.208)	(0.000151)	(0.000568)
INDIANA	-0.280***	0.000489***	0.00451***
	(0.108)	(9.66e-05)	(0.000353)
IOWA	0.344	0.000575***	0.00488***
	(0.240)	(0.000158)	(0.000526)
KANSAS	-0.0378	2.98e-05	0.00453***
	(0.149)	(0.000109)	(0.000346)
KENTUCKY	-0.485	0.00164***	0.00471***
	(0.311)	(0.000322)	(0.000576)

LOUISIANA	-0.0618	0.000425***	0.00131***
	(0.0783)	(0.000136)	(0.000154)
MAINE	0.00335	0.000143	0.00180***
	(0.132)	(0.000151)	(0.000629)
MARYLAND	-0.128	0.000413	0.00412***
	(0.257)	(0.000344)	(0.000537)
MASSACHUSETTS	0.0148	-0.000214**	0.00154***
	(0.127)	(0.000109)	(0.000413)
MICHIGAN	-0.353***	0.000459***	0.00372***
	(0.133)	(8.71e-05)	(0.000291)
MINNESOTA	-0.400**	0.000571***	0.00442***
	(0.182)	(0.000129)	(0.000424)
MISSISSIPPI	-0.407***	0.000491***	0.00210***
	(0.0675)	(0.000102)	(0.000183)
MISSOURI	-0.139	0.000429***	0.00522***
	(0.172)	(0.000111)	(0.000345)
MONTANA	-0.672	0.000731	0.00337***
	(0.426)	(0.000477)	(0.00104)
NEBRASKA	0.138	7.25e-05	0.00628***
	(0.350)	(0.000209)	(0.000694)
NEVADA	0.0838	0.000483***	0.00194***
	(0.0756)	(0.000122)	(0.000242)
NEW HAMPSHIRE	0.597***	-6.95e-05	0.000575
	(0.154)	(0.000202)	(0.000789)
NEW JERSEY	-0.226***	-6.77e-05	0.00213***
	(0.0863)	(7.85e-05)	(0.000239)
NEW MEXICO	-0.0170	0.000378***	0.00194***
	(0.0882)	(0.000130)	(0.000270)
NEW YORK	-0.0563	-5.71e-05	0.00204***
	(0.0704)	(8.10e-05)	(0.000253)
NORTH CAROLINA	-1.523***	0.00180***	0.00590***
	(0.246)	(0.000339)	(0.000518)
NORTH DAKOTA	-0.748	-0.000118	0.00708*
	(1.319)	(0.000763)	(0.00362)
OHIO	-0.674***	0.000170	0.00545***
	(0.212)	(0.000183)	(0.000704)
OKLAHOMA	-0.0508	0.000843***	0.00187***
	(0.127)	(0.000162)	(0.000177)
OREGON	0.0293	0.00194***	0.00463***
	(0.252)	(0.000288)	(0.000620)
PENNSYLVANIA	-0.797***	-0.000232**	0.00283***
	(0.162)	(0.000113)	(0.000344)
RHODE ISLAND	0.175*	-0.000105	0.00115***
	(0.104)	(0.000111)	(0.000415)
SOUTH CAROLINA	-0.779***	0.00131***	0.00419***
	(0.176)	(0.000270)	(0.000398)
SOUTH DAKOTA	-1.046**	0.000259	0.00806***
	(0.487)	(0.000323)	(0.00110)
TENNESSEE	-1.528***	0.00191***	0.00627***
	(0.375)	(0.000304)	(0.000538)
TEXAS	0.0213	0.000509***	0.00134***
	(0.0675)	(0.000124)	(0.000143)
UTAH	0.139	0.000513***	0.00209***
	(0.129)	(0.000156)	(0.000340)
VERMONT	0.120	3.57e-06	-0.000510
	(0.260)	(0.000152)	(0.000604)

VIRGINIA	-0.598***	0.00131***	0.00450***
	(0.134)	(0.000190)	(0.000311)
WASHINGTON	-0.328**	0.00189***	0.00616***
	(0.152)	(0.000242)	(0.000530)
WEST VIRGINIA	-0.546	0.00122**	0.00417***
	(0.348)	(0.000502)	(0.000788)
WISCONSIN	-0.384***	0.000499***	0.00446***
	(0.115)	(9.26e-05)	(0.000334)
OBS		8,617	
R-SQUARED		0.905	

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

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