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**ESSAYS ON THE COMPETITIVE EFFECTS OF DISASTER IN
ELECTRICAL POWER MARKETS**

A dissertation submitted in partial satisfaction
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

ECONOMICS

by

Cheyney Michael Thomas O'Fallon

June 2016

The Dissertation of
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Abstract

ESSAYS ON THE COMPETITIVE EFFECTS OF DISASTER IN ELECTRICAL POWER MARKETS

Cheyney Michael Thomas O'Fallon

Competition in the generation and marketing of electricity entails the use of a strategy space with many dimensions. Often requiring outlays in the hundreds of millions and occasionally billions of dollars to build, power plants are infrastructure investments with huge potential for economic impact. A variety of generating technologies currently compete to be the lowest cost provider and each of these options includes a set of externalities associated with producing power. Therefore, some competitive efforts, often manifested as lobbying, are directed towards preventing internalization of third party costs. Under standard operating conditions and mild deviations, electricity producers and marketers work hard to ensure a reliable and unremarkable (from the consumer perspective) supply of power. Natural disasters can offer windows into the strategic choices that define the structure of competition in electricity generation and subsequent market outcomes. The recent drought in the United States and the Tōhoku earthquake in Japan are the two disasters discussed in the pages that follow.

The development of hydroelectric facilities has cultivated a channel through which the state of water resources can affect the manner in which electricity is generated. In the first chapter, I evaluate the the short-term impacts of drought on the electrical power value chain for the contiguous United States. Using a novel data set constructed from six public sources, I show that drought reduces the energy content of inputs utilized for hydroelectric production and the output of these plants as well. Generation from natural gas plants substitutes for the lost hydropower. Precisely, a one standard deviation increase in drought severity decreases the share of hydroelectric generation by 8.9% and increases the share of natural gas generation by 5.0%. The pattern of substitution is most pronounced for the markets with the largest share of capacity coming from hydropower. The additional costs of production and environmental damages are estimated for each state. Between January of 2012, and September 2015 the California drought has induced additional electricity-related costs estimated at \$1.16 billion. For markets with little hydropower, mark-ups rise with drought. However, for markets with a large share of hydropower, mark-ups fall due to higher costs for an important input. Finally, drought is shown to reduce price volatility in wholesale markets where hydroelectric dams are most prevalent.

In the second chapter, I evaluate the U.S. lobbying response to the Nuclear Regulatory Commission's post Fukushima review of regulatory policy. I extract lobbying data from public disclosure filings and build a data set containing the lobbying expenditures, and records of lobbyists hired, issues lobbied,

and government agencies contacted for 15 quarters around the March 11, 2011 Tōhoku earthquake that lead to the Fukushima Daiichi nuclear disaster. With this information, it is possible to evaluate the change in lobbying strategies of clients within and outside of the energy sector. The nuclear industry responds to the disaster by increasing its expenditure levels by between 14.8 and 19.2 percent relative to the rest of the economy. Relative to the non-energy sectors the number of issues lobbied by the nuclear industry falls to around 73 percent the pre-disaster level. For non-nuclear firms in the electricity industry, proximity to nuclear competition is associated with a relatively larger reduction in lobbying after Fukushima. The nuclear meltdown has probably done more damage to the image of nuclear power than a counter-lobbying effort could alone.

Dedication

To my wife Lydia for a decade of friendship, education and adventure. Your love and support is a singular gift. May we write many chapters together. I also dedicate this dissertation to my father James and mother Ellen. Thank you for always cultivating a great place to study and the inquisitive nature to use it.

Acknowledgements

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Chapter 1

Shocked out of Water: The Effects of Drought on Wholesale Electricity Markets

1.1 Introduction

Extreme droughts cost the United States \$208 billion in damages and the lives of 2,993 people in the years since the National Climatic Data Center (NCDC) began estimating the human and monetary costs of billion-dollar weather and climate disasters in 1980. With the recent prevalence of drought in the Western and Southern portions of the country, increased media attention has focused on the impacts of drought on a growing subset of society.¹ Electricity markets

¹Krieger (2015) details the subsidence of cropland in California as the drought has led to increased groundwater extraction. Nagourney (2015) details the announcement of mandatory water restrictions in California.

are especially susceptible to extreme weather events and climatic hazards such as drought. This chapter analyses the effects of drought on wholesale power markets between 2001 and 2013; a period in which the NCDRC drought damage estimates sum to \$96 billion. Many of these damages accrue outside the electrical power sector, in agriculture, tourism and a variety of recreational and municipal settings. However, power generation and consumption are inextricably linked with water use and the two commodities are necessary inputs to production across all sectors of the economy.

The development of the American West relied on the water provided by large dams as well as the power generated by these facilities. These hydroelectric plants, in conjunction with their eastern counterparts, constitute the main mechanism through which shocks to the availability of water are transmitted to the electrical power industry and wholesale electricity markets. In some regions, the shocks could be quite profound given the scale of hydroelectric capacity and the number of consumers affected. In May of 2015, hydroelectric plants in California, Oregon and Washington produced 9,908 GWh, or enough electricity to meet the demands of 10.9 million residential customers in a region with a population of 49.8 million.² Also, hydropower is the most productive renewable generating technology by output in the United States, producing 258,748 GWh annually, or almost 50 percent more electricity than the next highest and fastest growing renewable technology: wind (181,791 GWh) in

²The population estimate for 2014 is from the U.S. Census Bureau. This is the most recent period for which state level generation data is presently available. In 2013, the EIA reported that the average U.S. residential customer consumed 909 kWh per month.

2014 (EIA). Therefore, shocks to hydroelectric production may entail large changes in the environmental cost of generating power.

This chapter contributes to the growing literature on the water-energy nexus by building a novel dataset from a unique group of sources on environmental conditions, generator level production, technological costs, and market level prices to systematically evaluate the empirical effect of drought on one of the nation's most strategically important sectors: electrical power. The extensive collection of data used in this chapter is sourced from the Energy Information Administration (EIA), The National Oceanic and Atmospheric Administration (NOAA), the Intercontinental Exchange (ICE), and several other agencies and energy data firms enumerated more fully in Section 1.2. Panels are constructed at the state and substate (climate division) level to evaluate the direct relation between hydrological drought and hydroelectric power. Furthermore, I construct a data set for ten wholesale markets around the country that links power plants by their physical location to environmental data on drought conditions and then to a set of nodes on the grid at which power is transacted. No other study, to my knowledge, combines geographical information with these market price series to generate a set of estimates of the effect of drought on key market variables for a representative sample of the United States.

This chapter offers answers to the following questions. How does drought impact the types and quantities of energy inputs used to generate electricity? To what extent does drought increase the production and environmental costs

of generating electricity as thermal technology is substituted for hydropower? Does the wholesale price of power change with drought? Finally, what do the effects of drought on mark-ups and price volatility imply about the nature of competition in wholesale power markets? A discussion of the technological substitution pattern exhibited in response to drought concludes the chapter with a focus on the implications for low-emission and renewable generation beyond hydroelectricity.

The analysis begins with a discussion of drought and the straightforward, but impactful mechanism through which this shock to hydroelectric generation propagates through wholesale power markets. I present empirical evidence that drought has a significant effect on costs, prices, mark-ups and price volatility in wholesale electricity markets. Before these more nuanced effects can be estimated, the analysis begins with the question of how drought impacts the amount of water resources employed in hydroelectric generation. If the resources employed to produce hydropower and thermal plant efficiency failed to change when drought became more severe, the effects of drought on power markets would be restricted to the demand side. My results reject this notion that the effects of drought are isolated to the demand side of electricity markets. I document this first result of drought using data on the energy content of resource inputs to electricity generation. A standard deviation increase in drought severity, or a standard drought shock, is associated with 746.2 billion fewer Btus of energy content in the water resources used to produce hydropower for the average state.

With the first-stage supply shock established, I then examine production outcomes subsequent to the change in inputs. When a standard drought shock hits a state, the net generation of hydropower plants falls by 78.94 gigawatt-hours per month. What happens to production by plants employing alternate generating technologies is a question of substitution patterns. My results show that natural gas is the fuel most used to replace the hydroelectric generation lost to drought. In response to a standard drought shock, natural gas generation increases by 51.43 GWh for the average state. Natural gas is considerably cleaner than coal or petroleum as a fuel for electricity generation, but the combustion of any fossil fuel entails the emission of harmful pollutants and fuel expenditures. The drought-induced compositional shift to natural gas from hydroelectric power is not benign, but rather a step back in the recent push towards greater utilization of renewable and low emission generating technology. Indeed, for every GWh substituted toward natural gas, environmental damages exclusive of CO_2 emissions can reach \$8,500.³

This substitution also changes the cost structure of electricity supply, which consequently, affects the average cost of generation. In the short run, drought does not impact the fixed costs of generation at any plant.⁴ Instead drought leads to a 8.9 percent fall in the share of net generation produced with hydropower and a 5.0 percent increase in the share of natural gas plants. The marginal cost of generating electricity includes fuel costs and variable oper-

³This estimate is taken from Muller et al. (2011), which is discussed further in Section 1.4.2

⁴In the long run, fixed costs may change. As detailed in Wines (2014), extremely low reservoir levels can lead to the construction of new intake tunnels and other infrastructure that entails additional fixed costs for facility operators.

ating and maintenance (VOM) costs. Considerable heterogeneity exists in the cost-response of each state to drought. All told, the estimated additional cost of generation associated with a year-long standard drought shock ranges from nothing in hydroelectric-devoid Mississippi to \$398 million in Washington state. A standard drought shock raises the average variable generating costs in the Pacific Northwest's Mid Columbia market by 15.4 percent.

Precise estimates of CO_2 damages from fossil fuel generation depend on the social cost of carbon (SCC) and power plant efficiency (heat rate). When the social cost of carbon is included in the cost estimate at a value of \$40 per metric ton of CO_2 , the additional costs of using natural gas to replace lost hydropower climbs to \$246 million annually for the state of California. The current drought in California, which is now approximately two standard deviations more severe than my sample mean, has led to additional generating costs and environmental damages estimated at \$1.16 billion since January of 2012.

After evaluating the production response to drought, I turn to how this substitution changes competitive conduct in wholesale electricity markets. In a perfectly competitive market, cost shocks would be passed through entirely to the market rate as price equals marginal cost. Of course, wholesale electricity markets are not perfectly competitive, even after a long period of deregulation in power generation. The social costs of production are generally incompletely internalized by the industry as well, leading to further inefficiency.

The rich literature that exists on the nature of competition in deregulated

electricity markets is discussed in greater length at the end of this section. For now, two articles are sufficient to frame the setting. Market power is present in electricity markets and its exercise can have considerable effects on market prices. Borenstein et al. (2002) finds that 59 percent of the increase in electricity expenditures experienced in California between 1998 and 2000 is attributable to the exercise of market power. Rising production costs and competitive rents account for the rest of the rise in expenditures. The unique structure of the power sector means that temporary market exit of major generating facilities such as nuclear plants and large hydroelectric dams may impact the greater market for electricity. Davis and Hausman (2014) finds that the closure of the San Onofre Nuclear Generating Station led to congestion of transmission lines that raised the cost of generating and marketing electricity. Coupled with other physical constraints on the system, these conditions made the exercise of market power more profitable for some firms.

Further complicating the attempt to estimate the effect of drought on market outcomes is the potential for it to impact both the supply and demand for electricity, with the demand side effects being either positive or negative. The heat waves that often come with drought can increase demand for electricity used for air conditioning, but less water for irrigation can also mean less electricity used to pump water. Controlling for the temperature effects on demand through the use of cooling degree days is especially important for the market level analysis that follows.

What are the effects of drought on the nature of competition in wholesale

electricity markets? I use a difference-in-difference framework to interact the effect of drought with measures of the hydroelectric capacity share (effectively drought exposure) to estimate the impact of drought on costs, prices, mark-ups and volatility. For a market with the typical hydroelectric capacity share, a standard drought shock leads average variable costs to increase by 3.4 percent. A standard deviation increase in the measure of temperature implies a 4.4 percent increase in costs.

With price and cost estimates for each market, it is possible to estimate the mark-ups over production costs as a measure of competitive conduct in wholesale electricity markets. Markups, measured by the log price-cost ratio, rise with drought, but do so to a lesser extent when a region is heavily reliant on hydroelectric capacity for its generation. A market without any hydroelectric capacity would see markups rise 3.1 percent with a standard drought shock, but the effect falls to 1.8 percent for the market with the sample mean reliance on hydropower capacity. Mark-ups fall 2.9 percent with a standard drought shock for markets like the Mid-Columbia in the Pacific Northwest where hydroelectric power accounts for 60.4 percent of nameplate generating capacity. The threshold hydroelectric capacity share at which mark-ups fall is estimated at 31.4 percent. These results are consistent with drought being a demand shock for regions with little hydropower, and primarily a supply shock for regions with significant hydroelectric capacity.

The analysis concludes with an examination of price volatility in the ten wholesale electricity markets. The stability of commodity markets is important

to regular market participants, and in this, electricity is no different from other commodities. As drought can act as both a supply and demand shock, theory provides ambiguous conclusions with respect to the hazard's impact on price volatility. If drought acts as a pure supply shock, shifting the supply curve to the left, the market clearing point will shift left along the demand curve. The price elasticity of demand rises with such a drought shock under reasonable assumptions, and as such the price of electricity should respond in a less volatile manner to natural, environmentally driven, fluctuations in demand. Of course, demand for electricity may also shift outwards or inwards with the arrival of drought. As drought contracts economic activity among agricultural firms, demand for electricity should fall for that sector. On the other hand, less available water and higher temperatures may lead to greater electricity consumption as market participants work to mitigate the ill-effects of drought.⁵ The sign of drought's impact on demand determines whether the effects of the supply shock are amplified or attenuated in a given region.

For the average market, a standard drought shock leads the price volatility to fall by four percentage points. The extent of this fall is amplified by the share of nameplate capacity that is hydroelectric. In the Pacific Northwest's Mid Columbia market, a standard drought shock decreases volatility by 19.0

⁵Some water-stressed cities like San Diego, California have opted to employ desalination technology to counter the water deficiency. Despite significant decreases in unit costs reported by Zhou and Tol (2005), desalination technology still uses large quantities of electricity. Elimelech and Phillip (2011) reviews the energy requirements and environmental implications of current and potential desalination technology. The most energy-efficient means of desalinating seawater that was discussed in the review used $1.8 \text{ kWh} / \text{m}^3$ for the desalination step. MacHarg et al. (2008) reports achieving what the authors regard as a world record energy efficiency ratio of $1.58 \text{ kWh} / \text{m}^3$ for desalinated seawater under certain conditions.

percent. The exhibited fall in volatility is consistent with higher price elasticities of demand and thus less movement in prices due to typical fluctuations in demand.

1.1.1 Related Literature

I contribute to the literature on the economic costs of drought by documenting its impacts on the electrical power sector and related wholesale markets. Prior research has evaluated the impact of drought on other sectors and subsets of society. Carroll et al. (2009) finds a severe negative effect of spring drought on life satisfaction in rural areas. In the Ethiopian highlands, Holden and Shiferaw (2004) finds that drought affects family welfare more through market prices than through changes to productivity.

I document the substitution of natural gas generation for lost hydropower, contributing to the literature on market responses to plant outages. Large hydroelectric plants may not experience complete outages due to drought, but their reduced production can have the same types of effects on wholesale markets as outages at other low marginal cost generators. Davis and Hausman (2014) documents the dispatch of relatively inefficient plants after the unforeseen closure of San Onofre Nuclear Generating Station occurred. My research further documents the linkage between hydroelectric facilities and thermal generation examined by Bushnell (2003). The findings contained within this article document wholesale electricity markets with imperfect competition that is not dissimilar to the Cournot framework modeled in Puller (2007).

I also add to the literature by developing a method for estimating the additional generating costs and environmental damages associated with a standard drought shock. This approach uses estimates of the gross external damages associated with electrical generation from Muller et al. (2011). Estimates of the social cost of carbon emissions are obtained from the environmental protection agency (EPA). Consumers are generally unaware of the precise distribution of demand shocks, which makes it difficult to respond to the true marginal price of electricity in the block rate structures that often define electricity prices. Borenstein (2009) presents evidence that consumers do not respond to the actual marginal price of electricity; instead relying on expectations or more inferior criteria. Ito (2012) examines evidence from non-linear pricing schemes and finds that consumers tend to respond to the average rather than the marginal cost of electricity. This means that electricity consumers are unlikely to exhibit an efficient behavioral response to drought.

Ultimately, wholesale power markets have the unenviable task of linking a geographically dispersed set of technologically differentiated producers to the utilities, power marketers and other parties responsible for serving the inelastic demand of somewhat informed final consumers. Borenstein and Holland (2003) argues that market efficiency improves as the share of customers that can be charged real time prices increases. Borenstein (2005) finds that the efficiency gains from real-time pricing are of considerable size in the long-run. Holland and Mansur (2008) shows that the environmental benefit from achieving reduced consumption through real-time pricing depends integrally on the

technology employed by the marginal curtailed producer.

I contribute to a sizable literature on competition in electricity markets by constructing a panel of wholesale electricity markets and evaluating the state of competition through observing the response of key market indicators to drought. Borenstein and Bushnell (1999) finds that the potential for market power in the California electricity market is most prominent in the high-demand hours during periods of low hydroelectric output. My findings corroborate this earlier research for regions without hydropower, but suggest that market power falls with drought for hydroelectric-rich regions. Joskow and Kahn (2002) found withholdings of supply contributed to the 500 percent increase in prices over the previous year for Californians in the summer of 2000. Drought may entail a series of involuntary withholdings for dams with low reservoirs. Wolfram (1999) analyzes duopoly power in the British electricity market, finding prices above marginal cost, but below oligopoly prices due to the threat of entry, regulatory constraints or the existence of contracts. Effective hydroelectric generating capacity exits the market temporarily with drought, reducing the remaining threat of competition.

In the deregulated electricity markets imperfect competition is common and rooted in a number of physical and institutional constraints.⁶ The inadequacy of concentration measures in the evaluation of market power in electricity markets is studied in Borenstein et al. (1999). Borenstein et al. (2000) finds that in a deregulated power market the degree of competition between geographi-

⁶A thoughtful discussion of market restructuring can be found in Wilson (2002). Borenstein (2002) offers another comprehensive review of the challenging restructuring process.

cally distributed power plants is determined by transmission capacity. Cardell et al. (1997) examines the nontraditional exercise of market power embodied in a producer's choice to increase production in order to benefit from the induced transmission congestion. Joskow and Tirole (2000) evaluates the role of transmission rights allocation in influencing producer behavior. Bushnell et al. (2008) finds that a lack of vertical integration can lead prices to be higher. Large integrated producers that also must buy power for their own customers have a reduced incentive to encourage high prices.

An improved understanding of how wholesale electricity markets and their participants respond to drought is valuable for the present and the foreseeable future. Efforts to develop variable renewable generation technologies have generally relied on hydropower to ensure reliability. If, as some climate models project,⁷ drought proves to be a consistent scourge in the future, the rapid development and implementation of alternative technological guarantors of reliability will be imperative to the continued construction and operation of variable-output, renewable generating facilities. At present, the *de facto* choice in the absence of hydropower is to burn more fossil fuels in the form of natural gas.

While Williams et al. (2015) found that climate change did not cause the current drought in California, the drought was made considerably more severe

⁷Barnett et al. (2005) and Seager and Vecchi (2010) finds that global warming is expected to reduce the share of precipitation that falls as snow in winter months these regions. Consequently, peak runoff and streamflow occurs earlier in the spring, at a time when demand for electricity is at relatively low levels. Such seasonal changes may increase the effective scarcity of water. These effects are relatively pronounced for the snowmelt-fed water basins like those found in the Southwest United States and the Rocky Mountain region.

by climate change. How current infrastructure of all varieties will cope with climate change is a major question for industry, government and private citizens alike. Several studies in the climate literature indicate that drought frequency and severity may increase in the future with climate change.⁸ Historical evaluations of drought have found evidence of extreme variability in past water availability.⁹ Taken together, this trend towards dry times in a region with a historical record of extreme droughts and deluges indicates that the relative absence or abundance of hydropower will continue to impact wholesale electricity markets for years to come.

The rest of the chapter is organized as follows. Section 1.2 describes the various sources of data employed in the state level analysis of drought. Section 1.3 presents empirical evidence at the state and climate division levels. Section 1.4 evaluates the environmental and production costs of substituting natural gas generation for lost hydropower. Market level analysis is conducted in Section 1.5. Section 1.6 contains a discussion of how the findings of this chapter fit into broader energy policy and the future of the electrical sector. Section 1.7 concludes and offers discussion of the main findings.

⁸Sheffield and Wood (2008) examines the future frequency of drought using scenarios from the IPCC AR4; finding significant increases in several varieties of drought for large portions of the globe. Strzepek et al. (2010) projects that hydrological drought will be a more frequent hazard for most of the country.

⁹Cook et al. (2004) finds that recent droughts are considerably less severe and persistent than those observed for some regions during the MCA. Nelson et al. (2011) examines a 6,000 year climate record to find that multi-decadal events are common in the history of the Pacific Northwest. Steinman et al. (2012) establishes a 1,500 year record of winter precipitation for the same region and finds that the MCA entailed exceptionally wet conditions in winter.

1.2 Drought and Power Plant Data

A vast amount of high quality data exists on power markets and environmental conditions; both in the public domain and behind paywalls at major syndicated data firms. This chapter ventures to leverage the wealth of public data presently available to offer a novel, timely and comprehensive evaluation of drought's impacts on wholesale power markets in the United States. The baseline analysis presented in this chapter requires data on wholesale electricity price levels and movements, the location of each market hub, the location, technology and electrical output of U.S. power plants, as well as drought data at the climate division level. The following sections discuss each type of data, its source, and how the data is merged.

1.2.1 Drought Data and Climate Divisions

Drought entails shocks to many sectors of the economy. Wilhite et al. (2007) finds that no other climatic hazard affects as many people. However, these effects are often unobvious outside of the agricultural sector. Withering crops are salient to most observers, but shocks to tourism, industrial production and municipal uses also exist.¹⁰ A sound definition of drought is necessary to proceed.¹¹ Palmer (1965) presents the theoretical definition used in this chapter:

“A drought period may now be defined as an interval of time, generally of the

¹⁰Interest in skiing and other winter sports diminish when a lack of precipitation reduces the number resorts that can afford to operate. In a travel cost analysis conducted for a subset of California reservoirs, Ward et al. (1996), finds recreational values per acre-foot between \$6 and \$600. As drought decreases the water level, the value of recreational services provided by a reservoir can fall considerably.

¹¹Appendix A offers a brief primer on drought.

order of months or years in duration, during which the actual moisture supply at a given place rather consistently falls short of the climatically expected or climatically appropriate moisture supply. Further, the severity of drought may be considered as being a function of both the duration and magnitude of the moisture deficiency.”

The National Climatic Data Center (NCDC), under the organization of NOAA, maintains data on the long-term and short-term severity of droughts in the form of the Palmer Indices developed in the paper just mentioned. These Palmer Indices are available for 344 climate divisions, with each region wholly contained within a state. Observations are recorded as far back as 1895. The longevity, and spatial comparability of the Palmer Indices commend them to a study of drought shocks across the country. Any plant in the contiguous United States can be assigned to a climate division and thus matched with data on water availability.

Most relevant for this project is the Palmer Hydrological Drought Index (PHDI), a long-term oriented measure that focuses on the effects of drought on groundwater, streamflows and reservoir levels, from Palmer (1965).¹² The PHDI measure is useful as the energy content of water resources available as inputs to hydroelectric production is a function of streamflows and reservoir levels.¹³ Hydrological drought is the supply shock impacting hydroelectric

¹²A review of the various drought metrics, including the Palmer Indices and Surface Water Supply Index (SWSI) can be found in Heim (2002). While the SWSI is known to perform better in the alpine climates that are home to much of the country’s hydropower, the SWSI is only available for a subset of states: Colorado, Idaho, Montana, New Mexico, Oregon, Utah and Wyoming.

¹³Appendix B discusses the simple mechanism through which drought impacts hydropower and the markets reliant on its production.

production through reduced streamflows and reservoir levels. PHDI is my measure of choice, but as Kallis (2008) discusses how difficult it is to measure the true effects of drought with a single indicator, two other alternatives are evaluated for robustness.

The shorter-term measures of meteorological drought and standardized precipitation may be more pertinent to the demand response to drought. The Modified Palmer Drought Severity Index (PMDI) is the operational version of the Palmer Drought Severity Index (PDSI) that selects between one of three intermediate indices.¹⁴ The third main index of drought severity employed in this chapter is the Palmer Z Index (ZNDX). The Palmer Z Index, computed monthly, is a standardized measure of the climate's departure from typically prevalent moisture conditions.¹⁵ The temporal gradient between PHDI, PMDI and the ZNDX will produce results indicative of which types of water scarcity entail more impactful effects than others. For the most part, dips in the ZNDX are not nearly as pertinent to hydroelectric production as comparable falls in the PHDI.

Let $\mathbf{D}_{i,t}$, defined in Equation (1.1), denote one of the three drought measures. Unless otherwise stated, t indicates the month of an observation. The unit of analysis, indexed by i , can indicate a climate division (c), a state (s)

¹⁴The modified version accounts for the fact that any observed climate pattern may be part of a longer term, countervailing, climate pattern. For example, when an extremely wet month is observed after a long series of very dry months, the researcher must determine whether the long-term drought has come to a conclusion or if the recent moisture is simply fleeting. There is some probability that the drought is truly over. One of the three intermediate indices is used when the probability of drought being over is at 100 percent. Another intermediate index is used if the probability of a wet spell being over is at 100 percent. The third index is employed when there is some positive probability of the long term trend ending or continuing.

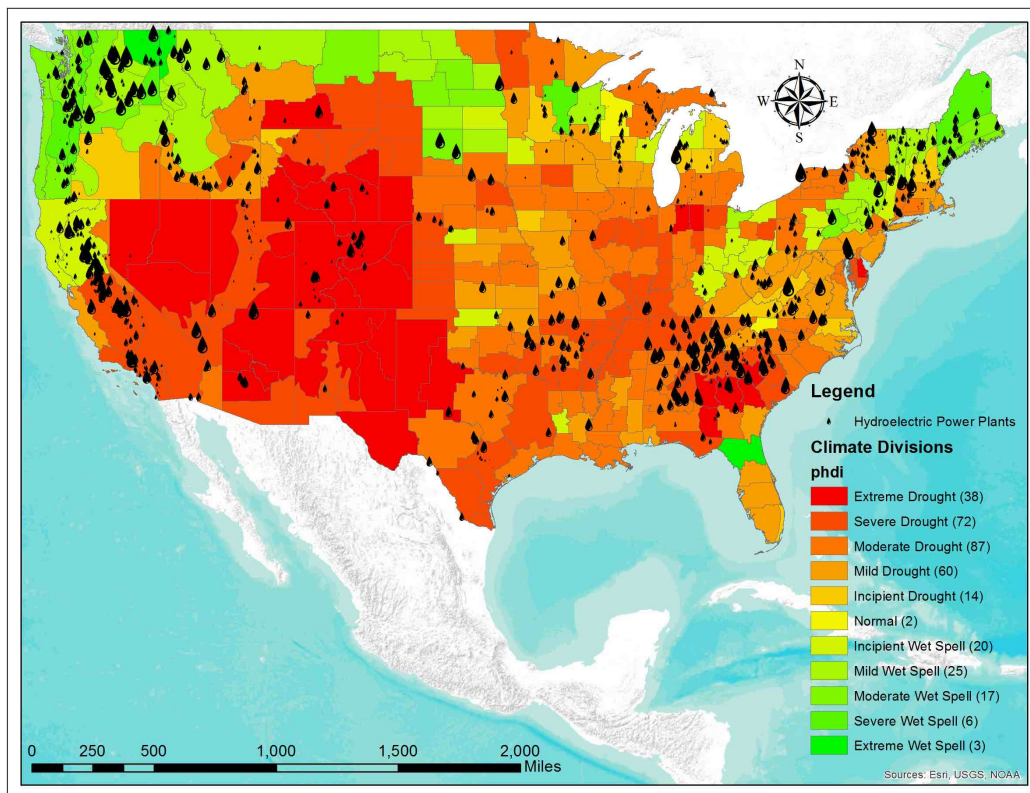
¹⁵In this case, the values are calibrated using data from 1931-1990.

or a wholesale market (m). For notational simplicity, regression specifications may use $\mathbf{D}_{i,t}$ instead of the individual names of each measure.

$$\text{For } i \in \{c, s, m\}, \mathbf{D}_{i,t} = \begin{cases} PHDI_{i,t} & \text{Palmer Hydrological Drought Index} \\ PMDI_{i,t} & \text{Modified Palmer Drought Severity Index} \\ ZNDX_{i,t} & \text{Palmer Z Index} \end{cases} \quad (1.1)$$

Figure 1.1 presents the June 2012 PHDI values for all climate divisions in the contiguous United States. The data on hydroelectric power plant locations is also depicted in Figure 1.1. This power plant data is discussed in the following section.

Figure 1.1: Hydroelectric Facilities and Drought in June 2012



Along with the Palmer Indices, records of the heating and cooling degree days for each climate division are obtained from the NCDC. A degree day is an indicator of the departure of the average daily temperature from the comfort benchmark set at 65 degrees Fahrenheit. When the average daily temperature is 76, the day registers as 11 cooling degree days (CDDs). If the average temperature is 51, the day counts as 14 heating degree days. The first example day records zero heating degree days and the second day records zero cooling degree days. Neither metric can take on negative values. The measure of cooling degree days used in the monthly panel analyses is the average number of CDDs per day for a given month. Electricity is used to both heat and cool customers in the United States. However, as electricity is a much more common fuel for air conditioners than it is for space heating for reasons of efficiency, the inclusion of cooling degree days in regression analysis will allow us to decompose the effects of drought into two main parts: the heat component, which mainly impacts demand for electricity; and the water availability component, which determines the supply of inputs for hydroelectric production.

The Palmer Indices facilitate the measurement and observation of drought, but in order to estimate the impact of the environmental disaster on power markets, drought data must be linked to data on inputs to production at hydroelectric plants. This requires identifying and locating power plants using the next source of data.

1.2.2 Power Plant Data

The Energy Information Administration (EIA) is the primary source for data on the operations and output of the U.S. electrical power sector. The EIA 860 Form records information on generator-level technology for all grid-connected electricity generating plants of at least 1 MW of nameplate capacity.¹⁶ Data collected by the EIA includes detailed information on the location and technology employed to generate electricity at the generator (sub-plant) and plant level. The street address of each of these plants is included in the original data. Google’s geocoding service was used to extract latitude and longitude coordinates from each address. Accurate locational data for the generation infrastructure is essential to the matching of power plant and location-specific drought data.

Nameplate capacity as well as both summer and winter capacity is recorded by the survey. Capacity information is a first order descriptor of plant size. When coupled with an estimate of a plant’s capacity factor, the nameplate capacity is informative with respect to the upper bound on total output of a given plant over a known time period.¹⁷

The specific technology used to generate electricity is also reported in the survey. The source of energy used to produce electricity is recorded for each of the generators (numbering 19,243 in 2013). There are 36 different codes

¹⁶Plants not covered by this survey can reasonably be ignored as their operation should not impact the wholesale market for electricity.

¹⁷Distinct variables are recorded for summer and winter capacity for two broad sets of reasons. Hydroelectric plants generally have seasonally variant streamflow and reservoir conditions. The temperature of cooling water and ambient air can impact the generating capacity of thermal plants and combustion turbine as well.

describing the primary source of energy used in each of these generators. These codes correspond to 8 broad categories of input fuel and generation technology: coal, hydroelectric, natural gas, nuclear, other, petroleum, solar and wind. The data from the EIA 860 Form is used to construct a measure of hydroelectric reliance: the share of a region's nameplate capacity that is hydro. Denoted SNH_m , this variable is calculated using 2010 data and is not allowed to vary temporally in the sample. The subscript m indexes the region. This measure is intended to reflect the potential for drought to impact hydroelectric facilities in a region rather than the true market share of hydropower. Actual market share is determined by more than nameplate capacity alone, as some plants operate as base load, while others only ramp up when demand is at its peak. Furthermore, the network of transmission lines also constrains the set of firms able to supply power to any given load point.

When taken together, each of these variables helps to describe the state of generating infrastructure in the U.S. market for electricity. Moving beyond the technological state of the wholesale electricity market, other sources must be employed to observe inputs to production and generation as well as market characteristics such as price levels and volatility. This additional information is also made available by the EIA.

1.2.3 Plant and Fuel Level Generation Data

Information on the amount of net generation by plant type is readily available at the state-month level for the duration of the sample period (2001 through

2013). Net generation is the gross quantity of electricity generated by a power plant less the electricity employed in-house for station service and auxiliaries. This data is obtained from the EIA's Electric Power Monthly report. However, data on net generation is also available at the plant level, facilitating aggregation to the climate division level as well as the state and market levels.¹⁸

Data on the type, quantity, quality (heat content) and electrical output of the fuels employed in major power plants around the United States is also gathered by the EIA. The sample includes approximately 1,900 plants every year that report on a monthly basis. Another roughly 4,100 plants report annual figures. Before publication of the data, the EIA imputes monthly data for the annually sampled plants using a method of regression prediction¹⁹. 7,813 unique plants report 123,818 observations over the course of the 2001 to 2013 sample period.²⁰ I aggregate the generation variables of interest by the same 8 fuel groups as described above.

1.2.4 Climate Division and State Level Panels

The first analysis of energy inputs to hydroelectric production uses two panels: one at the level of climate division and one at the state level. In the case of the former panel, plant level data is merged into a monthly panel by means of a

¹⁸The definition of markets used in this chapter is presented in Section 1.5.1

¹⁹Essentially, this method uses the distribution of production exhibited by the monthly sample to establish weights by which annual figures are split into monthly components.

²⁰The EIA consolidated its reporting forms during the sample period examined in this chapter, but the variables of interest at the plant and generator level are available for all years. For years 2001 through 2007, data comes from the EIA-906 form. The agency reports that the EIA-923 superseded the EIA-906 and others in 2008. Other forms also superseded by the EIA-923 include the EIA-920, FERC 423, and EIA-423. All data used in the 2001 to 2013 sample are reported as final on the EIA website.

spatial join in ArcMap. The geographic coordinates of all plants was obtained using Google's geocoding service. Once every plant is matched to its respective climate division, energy inputs for electrical generation are aggregated by fuel type along with other variables of interest. The state panel is readily formed using the street addresses of each plant. The climate division is the baseline level of aggregation for the Palmer drought metrics. The state level series for the drought indices are an area-weighted sum of the values obtained for the constituent divisions. The number of divisions varies with the size and geographic diversity of the state. The effects of drought on net generation, production costs and external damages is also evaluated using this state level panel.

1.3 Drought Shocks and Substitution Patterns

This section presents empirical evidence of drought's effects on hydroelectric and thermal power plants. The analysis begins with a focus on inputs to hydroelectric production and then follows the effects of a drought shock on net generation by other technologies. Afterwards, the impact of drought on the composition of generating technologies is examined.

1.3.1 Drought as an Input Shock

The first question taken to the data is how does drought impact the extent to which hydropower is utilized. More specifically, how does drought impact the

energy content of water resources used in hydroelectric facilities to generate electricity.

The heat content of fuel used for electrical generation is measured in Btus and facilitates the comparison of energy inputs across fuel groups. The heat content of a volume of natural gas is the amount of energy released when that gas is burned. Unlike thermal generators, hydroelectric generators report no fuel inputs as a quantity.²¹ However, the EIA provides estimates of the heat content equivalent of water resources employed in hydroelectric generation to measure the relative quantity of inputs. The energy input to hydroelectric generation is affected by the availability of water, the level of demand for electricity and the cost of alternative generation options. The primary determinant of interest, the availability of water is captured in the drought variable, $\mathbf{D}_{c,t}$, defined in Equation (1.1).²² The demand for electricity is especially susceptible to changes in temperature and the use of cooling infrastructure. The daily average number of degree days over the course of a given month, denoted $CDD_{c,t}$, helps to control for the direct effects of temperature on the energy inputs to hydro as well as the impacts of a major demand shifter. As specified in Equation (1.2), the heat content of hydroelectric inputs is regressed on measures of drought, temperature, and a set of temporal indicators with regional fixed effects.

$$\text{Heat Content}_{f,i,t} = \alpha_c + \beta_1 \cdot \mathbf{D}_{i,t} + \beta_2 \cdot CDD_{i,t} + \lambda_t + \epsilon_{f,i,t} \text{ For } i \in \{c, s\} \quad (1.2)$$

²¹Thermal generators report fuel input quantities in barrels of oil, tons of coal and millions of cubic feet of natural gas.

²²A separate regression is run using each of the three main drought indices.

Let f index the fuel group, i denote the region and t indicate the month within the sample. Regional fixed effects (α_i) as well as temporal indicators, (λ_t), are also included in the regression analysis, but are omitted from the results presented in Table 1.1. Both drought and cooling degree days are standardized within the sample so as to make the coefficients more comparable. As a result, each coefficient indicates the change in the heat content of resources utilized by hydropower that comes with a one standard deviation increase in each independent variable.

The results from estimating equation (1.2) are presented in Table 1.1. To begin, consider the effects of drought on the heat content of fuel. Column (1) in Table 1.1 indicates that one standard deviation increase in the severity of drought, as measured by the PHDI, corresponds with a reduction of more than 94.9 billion Btus of heat content equivalent for hydroelectric producers in a typical climate division. When climate divisions are aggregated to the state level as in Column (4), the effect of a standard drought shock sums to 746.2 billion Btus for the average state. The climate-division and state effects are significant at the one and five percent level respectively. Given average residential consumption and plant efficiency ratings, this quantity of energy inputs could power 79,000 homes in a typical state for a month.

Cooling degree days are insignificant determinants of hydroelectric inputs in the state level sample. However, the impact of cooling degree days on climate division hydroelectric inputs is negative and significant, indicating that higher average temperatures corresponds with fewer inputs to hydropower. Increased

Table 1.1: Heat Content of Hydroelectric Inputs and Drought

	Climate Division			State		
	(1) PHDI	(2) PMDI	(3) ZNDX	(4) PHDI	(5) PMDI	(6) ZNDX
$D_{i,t}$	-94.90*** (19.461)	-97.49*** (19.795)	-51.74*** (10.180)	-746.2** (235.651)	-721.6** (226.057)	-348.6** (109.293)
$CDD_{i,t}$	-54.95* (27.481)	-53.68 (27.302)	-64.36* (28.636)	-388.4 (331.986)	-382.7 (331.259)	-465.1 (342.413)
Baseline	722.9	728.9	698.3	5,180.9	5,200.7	4,819.6
Observations	47,596			6,912		

The energy content of resources used to generate hydropower is the dependent variable in each regression. Each of the drought variables is transformed to have a mean of zero and a standard deviation of one. Cluster robust standard errors are presented in parentheses with significance denoted: *, $p < 0.10$; **, $p < 0.05$; $p < 0.01$, ***. The units for all coefficient estimates are billions of Btus. The sample period is 2002 through 2013. Regressions (1)-(3) are run on the climate division level monthly panel. Regressions (4)-(6) are run on the state level monthly panel.

evaporation in warmer months may explain some of this effect.²³

1.3.2 The Impact of Drought on Net Generation

After analyzing the impact of drought on the inputs to hydroelectric production, attention is turned towards output. Consumers, if they think much about electricity at all, generally think about the number of kilowatt-hours for which they are charged on their utility bills. Borenstein (2009) and Ito (2012) present evidence that consumers do not respond to the marginal price of electricity; instead relying on expectations or more inferior criteria. The next step, is to evaluate the net generation, or output less on-site use, provisioned to the grid by each fuel group and how drought impacts these quantities. As many climate divisions report zero or negative values for net generation by a certain fuel group, the following analysis is conducted using the state-level panel.

²³The technical report, Torcellini et al. (2003), discovers that 18 gallons of water are lost to evaporation per kWh of hydroelectric generation. The average for thermal plants is 0.47 gallons per kWh.

Table 1.2: Drought and Net Generation by Fuel Group

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Hydro	Wind	Nuclear	Coal	Natural Gas	Petroleum	All Fuels
$PHDI_{s,t}$	-78.94*** (24.74)	7.756 (15.94)	-5.008 (5.36)	12.27 (12.69)	51.43** (25.92)	-15.47 (12.83)	-26.33 (25.94)
$CDD_{s,t}$	-41.71 (34.02)	8.012 (6.08)	48.82*** (13.80)	276.1*** (61.96)	600.4*** (220.25)	43.08 (32.73)	936.1*** (279.11)
Baseline	458.4	17.00	1,510.6	3,578.3	1,330.2	157.3	7,189.1
Observations	6,912						

Cluster robust standard errors are presented in parentheses. Clustering is conducted at the state level. The units for all coefficient estimates are billions of Btus. The sample period is 2002 through 2013. All coefficient estimates are in GWh. Regressions are run on the state level monthly panel.

Again it is useful to think of cooling degree days, $CDD_{s,t}$, as a control for demand fluctuations. Equation (1.3) presents the specification used to estimate the impact of drought on net generation.

$$Net\ Generation_{f,s,t} = \alpha_s + \beta_1 \cdot \mathbf{D}_{s,t} + \beta_2 \cdot CDD_{s,t} + \lambda_t + \epsilon_{f,s,t} \quad (1.3)$$

Temporal controls, (λ_t) , and state level fixed effects (α_s) are also included in the regression, but not presented in Table 1.2 with the rest of the results. Net generation from hydroelectric plants falls by 78.94 GWh when a standard drought shock visits the typical state.²⁴

In Table 1.2, the fuel groups other than hydropower are generally presented from left to right in increasing order of marginal generating costs. In this way, the ordering roughly reflects the technological merit order or industry marginal cost curve of generation by fuel group. Nuclear and coal plants operate as base load generation and will likely be dispatched regardless of the state of the water supply. Natural gas plants operate both as base load and peaking plants but

²⁴This sample average effect is equivalent to the amount of electricity consumed by 86,800 typical residential customers in a single month of 2013.

occupy a higher part of the industry marginal cost curve. Depending on the level of demand for power, either of these types of natural gas plants usually constitute the marginal producers. These natural gas plants exhibit a 51.43 GWh increase in net generation and the coefficient estimate is significant at the five percent level. Beyond natural gas plants, as we ascend the marginal cost curve, are petroleum plants. These most expensive and environmentally harmful plants do not exhibit a significant change in net generation quantities, indicating that they do not act as substitutes for lost hydropower. That role appears firmly in the hands of natural gas plants. While total production is negatively impacted by a standard drought shock, this effect is not statistically significant. In summary, if anything, standard drought shock reduces the total quantity of electricity supplied, significantly affects the composition of energy production. We will return to these compositional changes later when discussing the costs of production and environmental damages.

Nuclear, coal and natural gas plants all respond significantly to a standard deviation increase in the average number of cooling degree days. The response to higher temperatures and greater electricity demand for cooling is also concentrated in natural gas technology. Almost two-thirds of the effect of CDD on net generation from all fuels is driven by changes in natural gas generation. This is further evidence that natural gas plants are the primary marginal producers on the grid and are thus well-situated as substitutes for lost hydroelectric production.

1.3.3 Drought and Energy Production Composition

So far, the analysis has focused on the levels of inputs and output at power plants employing different fuel sources. However, current policy initiatives are oriented towards greater utilization of renewable and low-emission power plants as a share of total generation and a shift away from traditional, but dirty generation technologies.²⁵ How does drought impact our ability to meet this major policy goal? This section evaluates the composition of technologies and fuels that are employed to generate power in the contiguous United States and the manner in which this mixture changes when a standard drought shock occurs. Let the share of net generation in state s from fuel f in month t be denoted $SNG_{f,s,t}$. The net generation share variables are regressed on the same covariates that were used in the analysis of net generation levels. Equation (1.4) presents the basic regression specification used in the analysis of generating technology shares.

$$SNG_{f,s,t} = \alpha_s + \beta_1 \cdot \mathbf{D}_{s,t} + \beta_2 \cdot CDD_{s,t} + \lambda_t + \epsilon_{f,i,t} \quad (1.4)$$

Table 1.3 presents the results from estimating Equation (1.4). The two technologies that respond to a standard drought shock are hydroelectric power and natural gas. The baseline row indicates the prevailing average share of net generation for each fuel group. The coefficient on drought is the marginal effect of a standard deviation increase in drought severity in percentage points.

²⁵The Clean Power Plan is a current example of such policy.

Table 1.3: Drought and Share of Net Generation

	(1)	(2)	(3)	(4)	(5)	(6)
	Hydro	Wind	Nuclear	Coal	Natural Gas	Petroleum
$PHDI_{s,t}$	-0.0083*** (0.0018)	-0.0022* (0.0011)	0.0002 (0.0013)	0.0043* (0.0022)	0.0069* (0.0037)	-0.0010 (0.0011)
$CDD_{s,t}$	-0.0092* (0.0050)	0.0025* (0.0014)	-0.0122*** (0.0027)	-0.0040 (0.0048)	0.0209*** (0.0044)	0.0033** (0.0014)
Baseline	0.0866	0.0050	0.1996	0.5060	0.1575	0.0220
Observations	6,912					

Standard Errors are presented in parentheses. Clustering is conducted at the state level.
Regressions are run on the state level monthly panel. The sample period is 2002 through 2013.
The dependent variables are the share of net generation from each fuel group.

Dividing the coefficient for $PHDI_{s,t}$ by its counterpart in the baseline row renders the percent change in the share of net generation from each fuel group. Precisely, the share of net generation that comes from hydropower falls by 9.6 percent when a standard drought shock occurs. Natural gas net generation sees its share increase by 4.5 percent for the same shock. This means that the shares for the two groups move from 0.087 to 0.078 and 0.158 to 0.164 for hydro and natural gas respectively.

Unlike the plain net generation results, when the technology shares of generation are analyzed, several other fuel groups experience statistically significant changes in their share with a standard drought shock. The current penetration of wind power is low, but this is changing as installed wind power is growing rapidly. The baseline share for wind technology is half of one percent. However, the fall in wind generation due to a standard drought shock accounts for 44 percent of the technology's baseline output.²⁶ Effectively, drought shrinks the

²⁶Although it may seem counterintuitive, a technical report, Hodge et al. (2011), indicates that wind and hydropower are complements for operations reasons. Hummon et al. (2013) finds that the cost of maintaining operating reserves is dependent on natural gas prices and the availability of hydroelectric generating capacity.

renewable share of generation, striking at the two most prevalent technologies in the category: hydropower and wind.

Another difference between the raw generation and share analyses is that the latter sees coal generation increase while the former did not. The coefficient on the drought metric for coal is about two-thirds that of natural gas. Both are significant at conventional levels. Furthermore, coal occupies the largest baseline share of any technology in the United States with 50.6 percent of net generation. A standard drought shock pushes up coal's share to 51.0 percent of net generation. Nuclear plants are inframarginal to the standard drought shock. As these typically large plants are slow to ramp up and low in marginal cost, they are almost always operating near their capacity limits and thus unable to increase output when hydropower and other renewable technologies are less productive. Petroleum plants also fail to exhibit significant changes in their share. This is sensible as the drought (exclusive of related heat waves) is unlikely to push the market clearing quantity of electricity up.

The results presented in Table 1.3 are derived using OLS panel regression methods.²⁷ Papke and Wooldridge (1996) provides a brief discussion of why fractional response models are preferable to OLS when confronting a bounded dependent variable such as the share of net generation that is derived from any given fuel group.²⁸ Table 1.4 presents the results of the share regressions using

²⁷A few observations report negative net generation values for nuclear and solar fuel groups. In these rare cases, negative net generation values were recoded as zero to facilitate the analysis of shares.

²⁸A fractional logit model was chosen over a log odd ratio approach as it is possible within any given month that a share variable could obtain a boundary value. In the case of this chapter the lower boundary of zero production coming from a given fuel group is common. Some states have no nuclear plants and thus obtain the boundary value for all observations.

Table 1.4: Fractional Logit Analysis of Technology Shares

	(1)	(2)	(3)	(4)	(5)	(6)
	Hydro	Wind	Nuclear	Coal	Natural Gas	Petroleum
$PHDI_{s,t}$	-0.089*** (0.017)	-0.055 (0.076)	0.003 (0.009)	-0.001 (0.012)	0.050** (0.022)	-0.061 (0.073)
$CDD_{s,t}$	-0.026* (0.014)	-0.182*** (0.028)	-0.058*** (0.008)	-0.035*** (0.009)	0.122*** (0.014)	0.047 (0.034)
Observations	6,912					

Coefficients represent percent changes in the share of net generation derive from each fuel group.
Significance is denoted: *, $p < 0.10$; **, $p < 0.05$; $p < 0.01$, ***.
Robust standard errors are presented in parentheses.

the methodology discussed in Papke and Wooldridge (1996).²⁹ Fixed effects are omitted from the specification used to generate Table 1.4 due to the incidental parameter problem. Discussed in Papke and Wooldridge (2008), the problem arises when regional fixed effects are included as the number of time periods is small and the number of cross sectional observations is large. The panel used for this part of the analysis contains 48 states and 144 months of data. Significant at the one percent level, the coefficient on $PHDI_{s,t}$ in column (1) indicates that a standard drought shock decreases the share of net generation from hydro by 8.9 percent. That same shock increases the natural gas share of generation by 5.0 percent. This second effect of drought is significant at the five percent level. These estimates are close to the OLS estimates, lending additional robustness to the findings.

Another result of interest is found in the effect of cooling degree days on each technology in the merit order ahead of natural gas. Rising temperatures can decrease the efficiency and productivity of thermal plants like large base

Furthermore, the share of net generation from any given fuel group is not a proportion of a discrete set.

²⁹The Stata command `xtgee` is used with the options `family(binomial)` `link(logit)` `vce(robust)` `corr(ar1)` to estimate the share regressions presented in Table 1.4.

load nuclear and coal-fired facilities. The effect of a heat wave on the industry supply curve is similar to that of the drought, only the effect touches more than just hydroelectric dams. Steps in the industry marginal cost curve are narrowed by the heat and thus, holding demand constant, more of the marginal plants are dispatched. These marginal facilities happen to generally be natural gas plants. Petroleum plants realize a slightly higher and statistically significant increase in their share of net generation as well.

In summary, the results in Tables 1.2, 1.3 and 1.4 document a significant change in U.S. electricity production in response to a natural disaster. Drought mitigates the ability of grid operators to rely on renewable technologies like hydropower and wind while increasing reliance on fossil fuel generation like coal and natural gas. Not only are these substitute technologies less environmentally friendly with respect to their emissions profiles, but the cost of their fuel inputs can be considerable and is subject to the fluctuations of fuel markets. The nature of these cost changes is discussed in the following section.

1.4 Regional Cost Analysis

1.4.1 Cost Data

Data on the marginal cost of generating and transmitting electricity is proprietary, strategically valuable information. As a result, readily comparable data on the marginal cost of generating electricity is difficult to obtain for the full duration of the sample used in the study. The Nuclear Energy Institute

publishes average operations and maintenance costs, fuel costs and the sum of the two components for nuclear, coal, natural gas and petroleum plants for the years 1995 through 2014. This data is sourced from the ABB³⁰ Velocity Suite; which draws on raw data collected in the Federal Energy Regulatory Commission (FERC) Form 1. This data source provides sufficient temporal support for the 2001 through 2013 sample over which price data is obtained. Data on the variable operating and maintenance cost of generation, including fuel, is obtained from the EIA's Annual Energy Outlook for 2015 for the hydroelectric, wind, solar and other fuel groups. As the majority of plants in the other category are renewables of one sort or another, the cost value for biomass plants was assigned to this category.

1.4.2 External Damages Data

The primary estimates of environmental damages associated with producing electricity are gross external damages (GED) borrowed from Muller et al. (2011). The estimates of GED are attractive because they arise from an attempt to incorporate the health and climate change impacts of economic activity into the accounting of a wide variety of sectors. The direct impact of six local pollutants on health are calculated and combined with the social cost of carbon to construct an estimate of the environmental damages originating with the production of electricity.³¹ Thermal generating technologies are

³⁰Headquartered in Zurich, Switzerland, ABB or ASEA Brown Boveri, is a multinational corporation operating in the automation, power and robotics sectors.

³¹The list of pollutants includes sulfur dioxide, particulate matter smaller than 2.5 and 10 micrometers, nitrous oxides, volatile organic compounds, and ammonia.

generally shown to contribute gross external damages in excess of their value added per unit of output. Coal plants represent the most damaging technology evaluated as sulfur dioxide emissions contribute extensively to human mortality. Natural gas plants, by comparison, entail considerably fewer mortality risks due to emissions of local air pollution.³² The severity of environmental damages from the substitution to natural gas from hydropower varies with the estimate used for the social cost of carbon. A single agreeable estimate of the social cost of carbon proves elusive for reasons of uncertainty that are discussed in Ackerman and Stanton (2012). The EPA currently reports four distinct estimates of the social cost of carbon, ranging from \$12 to \$120 per ton of CO_2 . A distribution of cost estimates is generated for discount rates of 5 percent, 3 percent and 2.5 percent. The average estimate is taken from each and the 95th percentile estimate is also chosen from the 3 percent discount rate scenario. I will use the estimate of \$40 in 2014 dollars per metric ton of CO_2 , which is the median estimate based on a discount rate of three percent.

1.4.3 Drought and the Marginal Cost of Generation

Switching to natural gas from hydropower fundamentally changes the cost structure of generation. Both technologies require the maintenance of secure, operable generating facilities and a number of fixed costs. As the replacement pattern analyzed in this chapter happens in the short run, only the difference in marginal generating costs matters for estimating the cost of a standard

³²However, any methane lost in the transmission process between the wellhead and the plant also constitutes an emission of a powerful greenhouse gas.

drought shock.

The two main forms of internal marginal costs for power generation are variable operations and maintenance costs and the cost of fuel inputs to production. Hydropower plants generally do not pay an explicit price for the water used to generate power. As such, the fuel costs for hydropower are assumed to equal zero. Natural gas, on the other hand, is a relatively expensive fuel, even in the wake of the domestic natural gas boom that has resulted from the exploration and development of shale gas. If all natural gas generation was conducted at new combined cycle plants with modern specifications, the best case scenario puts the VOM cost for natural gas, inclusive of fuel expenditures, at \$53.6 per MWh. VOM costs for conventional coal plants are \$29.4 per MWh. The same figure for hydroelectric plants, also according to the EIA Annual Energy Outlook for 2015, is \$7.0 per MWh.³³ Substituting natural gas for hydropower entails a difference in VOM costs of \$46.6 per MWh. Variable operating and maintenance costs are also presented in Table 1.5.

Table 1.5: Variable Operating and Maintenance Costs for Select Generation Technologies

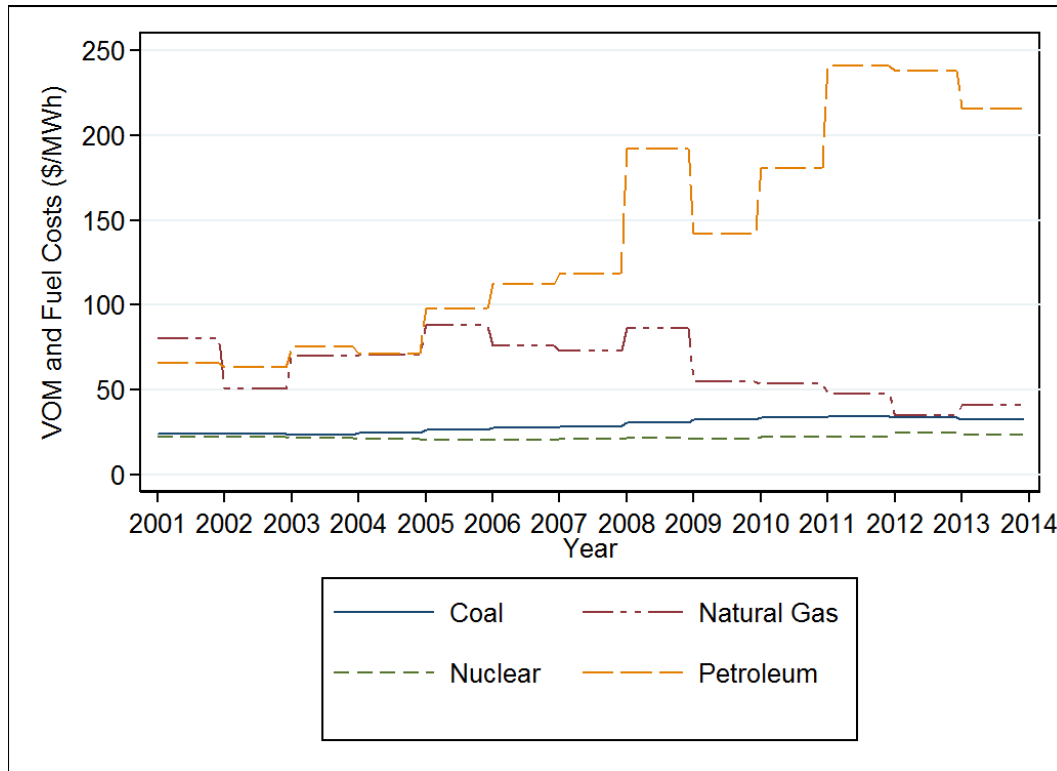
Technology	Nuclear	Hydroelectric	Wind	Solar	Coal	Natural Gas	Petroleum	Other
VOM	24.0	7.0	0.0	0.0	29.4	53.6	224.9	37.6

All cost estimates other than those for nuclear and petroleum are taken from the EIA Annual Energy Outlook (AEO) for 2015. All EIA AEO estimates are presented in terms of 2013 dollars per megawatt hour of generation. These estimates include the cost of fuel. The other category assumes the cost of biomass plants. The nuclear and petroleum cost estimates (in 2014 usD) are taken directly from the NEI data for 2014.

Through these compositional changes, drought may also affect the emissions profile of the energy market. Muller et al. (2011) presents estimates of

³³The EIA classifies hydroelectric power as non-dispatchable in its Annual Energy Outlook. All of the cost figures expressed here are in 2013 dollars.

Figure 1.2: Variable Operating and Maintenance Costs (Including Fuel)



the gross external damages (GED) associated with every major sector in the United States. Special attention is paid to the electrical power sector as it contributes considerably to air pollution and the emission of greenhouse gasses. The paper separates CO_2 emissions from other pollutants as reliable national level data on CO_2 is not available for all sectors, just the electrical power sector. Their focus is on coal, petroleum and natural gas plants. The good news for the substitution patterns examined in Tables 1.2, 1.3 and 1.4 is that natural gas plants have the lowest GED per kWh of the three fuel groups. Coal plants offer the worst damages per unit of output due to extensive SO_2 emissions that contribute to increased mortality. While the GED per kWh is \$0.0280 for coal generation, Muller et al. (2011) find that petroleum and natural gas

contribute \$0.0203 and \$0.0085 worth of damages per kWh. The bad news, however, is that natural gas emits pollutants where hydroelectricity does not. I use the EPA's median estimate for the SCC in 2015 assuming a discount rate of 3 percent (\$40 per tCO_2).³⁴

How much additional power must a typical state generate with natural gas when a standard drought shock occurs? If we take the results directly from Table 1.2, 51.43 additional GWh must be generated by the average state. If we use the estimate of the change in share from Table 1.3 and multiply it by the baseline total (all fuel groups) generation estimate presented in Table 1.2, natural gas net generation increases by 49.46 GWh. In the interest of providing a conservative or lower bound estimate of the additional marginal costs of generation with a standard drought shock, the second, lower estimate is used. The additional VOM and fuel costs for generating 49.46 GWh with natural gas sum to \$2.3 million per month. Assuming the GED per kWh of \$0.0085 an additional \$420,400 per month in damages occurs for the typical state due to worsened air quality. When the climate change impacts of CO_2 and other greenhouse gasses are incorporated into the GED³⁵ estimate, the number rises to \$0.0113 per kWh.³⁶ In this last case the additional marginal GED costs are \$558,900 per month or \$6.7 million per year for the average state.

When VOM costs, fuel costs, and external damages with greenhouse gas

³⁴A discussion of the methodology behind the construction of these estimates Greenstone et al. (2011)

³⁵Muller et al. (2011) indicates this measure as GED*.

³⁶Assuming a social cost of carbon of \$65

impacts are combined, the cost for a typical state facing a standard drought shock is \$2.85 million per month. If the shock persisted in a constant manner for a year, this would amount to \$34.2 million. Next, the concept of a spatially defined wholesale market is developed and explained in detail.

1.4.4 State-level Drought Cost Estimates

The average effect of drought on generation within a state is interesting, but it says little about state-level trends. This section attempts to generate an estimate of the state-level impact of a standard drought shock that lasts a full year. The first step is to estimate the impact of drought on state level hydroelectric and natural gas generation. The presence of hydroelectric dams exposes a region to the impacts of drought. The extent of a state's exposure is measured by the installed nameplate capacity of hydroelectric facilities within its borders. The net generation of each fuel group is regressed on drought and its interaction with hydroelectric capacity as specified in Equation (1.5). The nameplate capacity of hydro is not included in the specification as it is time-invariant and therefore absorbed by the state-level fixed effect.

$$NetGen_{f,s,t} = \alpha_s + \beta_1 \cdot \mathbf{D}_{s,t} + \beta_2 \cdot \mathbf{D}_{s,t} \cdot NP_s^{hydro} + \beta_3 \cdot CDD_{s,t} + \lambda_t + \epsilon_{f,i,t} \quad (1.5)$$

The results from the regressions specified in Equation (1.5) can be found in Table 1.6. Each column in the table contains the regression results with the net generation of a given fuel group as the dependent variable. The coefficient

on the drought variable indicates that there is no effect of drought on the net generation of any fuel group for states without any hydroelectric capacity. The standardized drought measure is interacted with the hydroelectric capacity of a state, measured in GW. The interpretation of the interaction coefficient is the change with a standard drought shock in GWh of net generation experienced by the given fuel group per GW of hydro capacity. In other words, the coefficient informs us of the average change in net generation per GW of installed hydroelectric capacity that comes with a standard drought shock.

Table 1.6: Drought and State-Level Net-Generation by Fuel Group

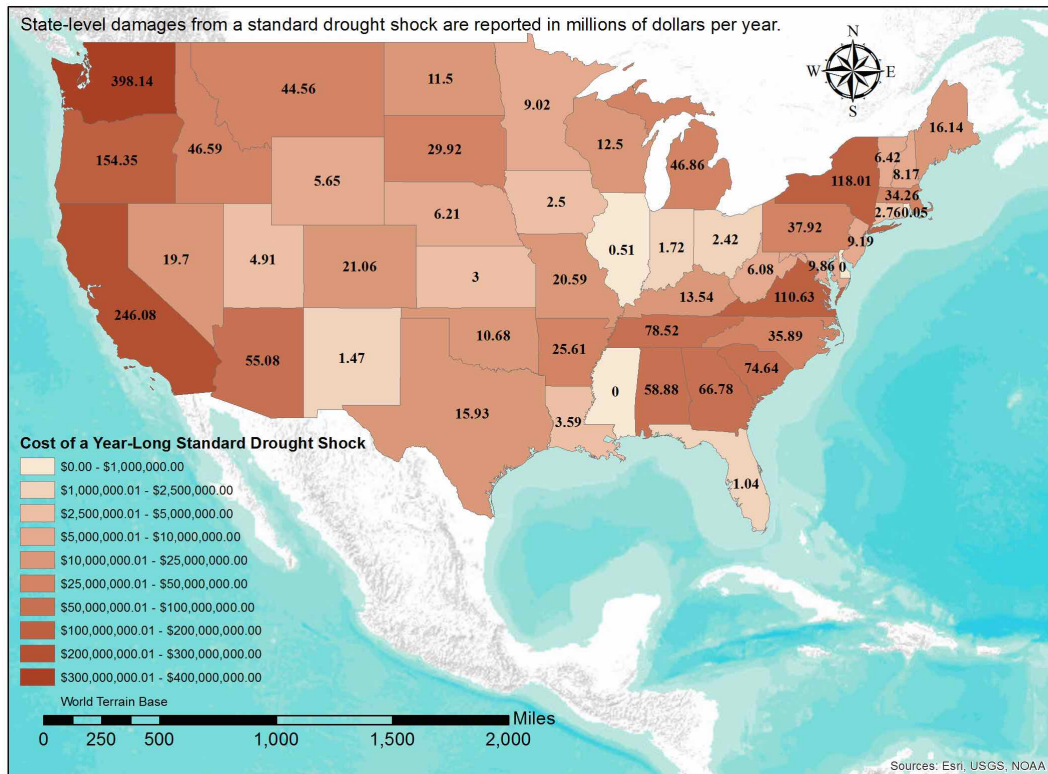
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Hydro	Wind	Solar	Nuclear	Coal	Natural Gas	Petroleum	Other	Total
$PHDI_{s,t}$	0.472 (6.117)	15.30 (17.896)	-0.456 (0.448)	1.802 (9.070)	11.29 (13.957)	7.990 (23.028)	-14.94 (14.982)	1.166 (1.329)	22.63 (26.152)
$PHDI_{s,t} \cdot NP_s^{hydro}$	-40.02*** (3.243)	-3.805 (2.452)	0.421 (0.308)	-3.432 (5.560)	0.490 (2.386)	21.89** (7.576)	-0.268 (1.526)	0.0481 (0.176)	-24.67*** (6.699)
$CDD_{s,t}$	-36.37 (31.670)	8.519 (5.859)	0.479 (0.413)	49.28*** (13.901)	276.1*** (62.076)	597.5** (220.444)	43.11 (32.605)	0.873 (1.496)	939.4** (279.190)
Observations	6,912								

Cluster robust standard errors are presented in parentheses with significance denoted: *, $p < 0.10$; **, $p < 0.05$; $p < 0.01$, ***. Each of the drought variables is transformed to have a mean of zero and a standard deviation of one. All coefficients are in GWh.

The results show that a drought shock leads to less hydropower output and more natural gas output as an increasing function of hydroelectric capacity. As natural gas generation does not entirely offset lost hydroelectric production, total net generation falls with drought in regions with at least some hydroelectric capacity. I estimate the change in net generation by both hydroelectric and natural gas plants for every state. Then I use the VOM costs and environmental damages data to calculate the increased costs of natural gas generation less the savings on lost hydroelectric generation.

Figure 1.3 displays these state-level drought cost estimates. Washington

Figure 1.3: Cost of a Year-Long Standard Drought Shock



state experiences almost 400 million dollars in additional costs and environmental damages with a year-long standard drought shock. The cost of a year-long drought shock for Mississippi is estimated at zero due to the lack of hydroelectric facilities in my sample of generators larger than 1 MW.

As generating electricity with natural gas is relatively low-emission when compared to other fossil fuel choices, the composition of additional generation related costs with drought is mostly operations costs followed by carbon dioxide damages and other gross external damages. Variable operating and maintenance costs, inclusive of fuel, account for 57.3 percent of the additional generation related costs due to drought. With a social cost of carbon set at \$40 per metric ton of CO_2 , damages from carbon dioxide emissions are calcu-

lated to account for 30.8 percent of additional costs in the presence of drought. Lastly, gross external damages to the environment, other than those related to CO_2 , constitute 11.9 percent of additional costs. The composition of additional generating costs induced by drought is likely to change over time as atmospheric CO_2 levels rise and the appropriate rate at which to discount future damages fluctuates. The current low cost of natural gas is not guaranteed to persist in the medium and long run. As plants age, maintenance costs can rise as well.

It is important to note that the costs are those paid by people within each state for electricity regardless of the state of origin. Washington state may buy natural gas generation from another state as a substitute for lost domestic hydropower. Even though the generation costs and damages are not necessarily internal to Washington, entities in the importing state are ultimately responsible for the costs. Rate payers will likely not see the price change in real time, but utilities and other wholesale market participants will.

Sensitivity of Cost Estimates to the Social Cost of Carbon

One source of uncertainty with respect to the baseline estimates of additional generating costs due to drought is that the social cost of carbon takes on a distribution of values rather than a single consensus value. As carbon dioxide is a persistent pollutant, influencing the greenhouse gas effect over decadal time periods, a stream of environmental damages must be estimated to construct a value for the social cost of carbon. The SCC for someone living in coastal

Louisiana is likely to differ from that of an individual living in New York City. Future costs must be discounted at the appropriate rate and geographical and temporal differences in growth and interest rates mean that the social cost of carbon is difficult to pin down with a single value. Instead, a scenario planning approach is used to provide sensitivity analysis in the process of estimating the SCC.

Table 1.7: Sensitivity of Drought Costs Estimates to SCC Choice

Year	Choice of SCC Estimate			
2015	\$12	\$40	\$62	\$120
State	Total Costs (Millions)			
Washington	\$312.3	\$398.1	\$465.6	\$643.5
California	\$193.0	\$246.1	\$287.8	\$397.7
Oregon	\$121.1	154.4	\$180.5	\$249.5
New York	\$92.6	\$118.0	\$138.0	\$190.7
Virginia	\$86.8	\$110.6	\$129.4	\$178.8
Tennessee	\$61.6	\$78.5	\$91.8	\$126.9
South Carolina	\$58.5	\$74.6	\$87.3	\$120.6
Georgia	\$52.4	\$66.8	\$78.1	\$107.9
Alabama	\$46.2	\$58.9	\$68.9	\$95.2
Arizona	\$43.2	\$55.1	\$64.4	\$89.0
Component	Percent of Total Costs			
VOM	73.0	57.3	49.0	35.4
GED	15.2	11.9	10.2	7.4
CO2	11.8	30.8	40.8	57.2

The Social Cost of Carbon is reported in 2014 dollars per metric ton. The drought costs estimates presented in this table reflect the additional cost related to electricity generation and associated emissions with a year-long increase in drought severity of one standard deviation relative to the sample period.

Table 1.7 presents the additional costs from a standard deviation increase in drought severity lasting one year for the ten most-impacted states in different SCC scenarios. With the SCC valued at \$40 per metric ton of CO_2 , damages from the greenhouse gas account for 30.8 percent of the additional generation-related costs. The share of damages climbs to 57.2 percent if the SCC is valued

at \$120 per metric ton of CO_2 and falls to 11.8 percent when the SCC is only \$12.

For California, the difference between the lowest SCC and highest SCC scenario is \$205 million annually. The range in cost estimates is 83.3 percent of the baseline number. The uncertainty associated with the SCC is a limitation complicating the estimation of environmental damages, but as the challenge is not unique to the phenomena of drought, it is beyond the scope of this chapter.

1.4.5 California Drought, Jan. 2012 to Sep. 2015

California was among the states that faced severe drought in the sample period. Since the end of the sample, the California drought has dragged on into the present, becoming more severe, and thus more costly. I use the drought effect estimates from the previous analysis to construct an estimate of the additional electricity generation costs and damages associated with the current drought in California. This requires the development of out-of-sample estimates for sample-standardized PHDI in California between the end of the sample (December 2013) and the present.³⁷ The most recent PHDI data is for September of 2015.

The sample period (2001-2013) was drier on average than the full period of record (1895-2015). The distribution of PHDI has thicker tails in the sample period than it does in the full historical period. This implies that more severe drought is relatively more common in the sample than it is historically. Cali-

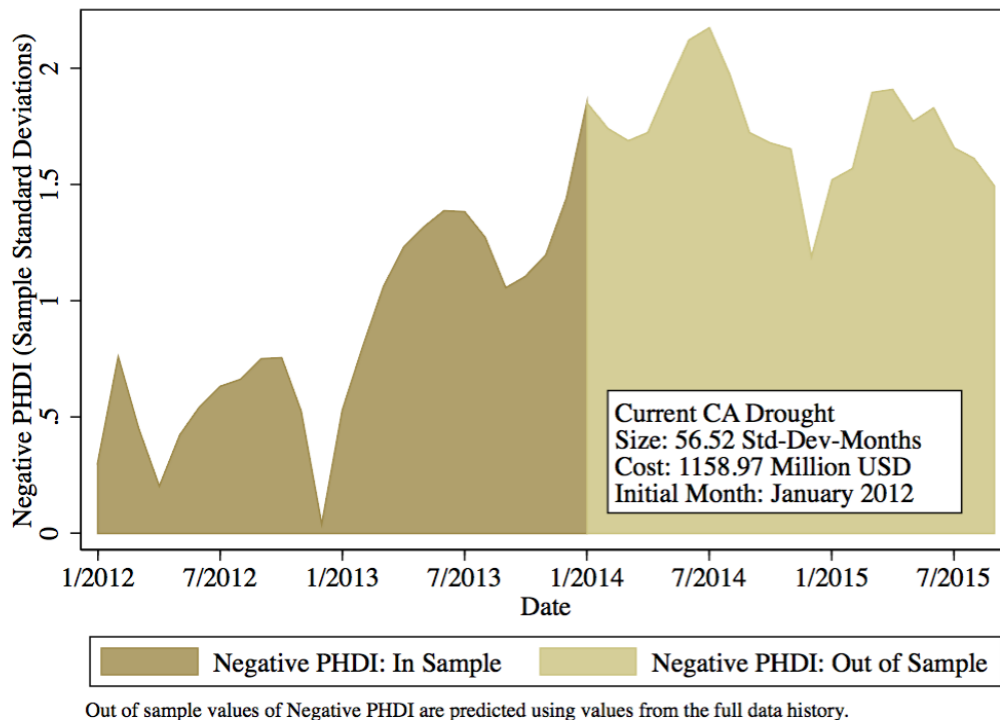
³⁷In all cases, drought variables have been standardized with respect to all values observed in the national sample rather than with respect to values from a given region.

California exhibits a distribution with a considerably lower (drier) mean than the rest of the nation.

The sample standardized values of PHDI are regressed on the raw values from the full historical sample. Then the historical values are used to predict the out-of-sample values for the sample standardized PHDI variables. Figure 1, found in Appendix F, presents the raw, sample standardized, and estimated standardized values of PHDI between the sample outset and the present. The estimated severity of the recent California drought with respect to the sample period is presented in red.

The sample and estimated values of PHDI are combined to create a single standardized series of drought severity for California. Figure 1.4 presents this series and the implied additional costs and damages of generation due to the drought. The cost to California of a single-month standard drought shock, \$20.50 million, is taken from the previous section and multiplied by the cumulative severity of the drought, which is measured in standard-deviation-months. The current drought is 56.5 standard-deviation-months. The estimated undiscounted drought cost of \$1.16 billion since January 2012 assumes a linear extrapolation of effects. If the costs of drought are increasing functions of severity, and not constant, this estimate represents a lower bound of the true costs. These findings are fairly close to those of Gleick (2015), which place the cost to California at \$1.4 billion.

Figure 1.4: Drought and Additional Electricity Costs in California



1.5 Drought, Prices and Mark-ups

So far the additional costs of generation have been calculated at the state level. However, wholesale markets straddle state boundaries. As a result, the analysis next turns to ten wholesale markets located around the United States in order to compare the impacts of drought on the cost and composition of generation with drought's effects on market price and volatility. This comparison facilitates the evaluation of the extent to which the input cost shock of drought is passed through to power purchasers. This section continues the analysis of drought and its impact on the electrical power sector at the level of wholesale markets.

1.5.1 Market Definition

Developing a proper definition of a market is an important first step towards its analysis. Arriving at a physical definition of a wholesale electricity market is complicated by the fact that their spatial boundaries can fluctuate considerably with environmental and technological factors,³⁸ For example, plants from much of the western half of the country may occasionally sell power to be consumed in Southern California, but the plants with the strongest ability to sell power over the SP15 market hub located in the greater Los Angeles region enjoy a higher degree of spatial proximity. The physical complexities of the market structure thus necessitate a heuristic definition of the wholesale markets studied here.

The market data observed for this study concerns power traded at one of a given set of nodes around the contiguous United States. These physical points on the grid are called market hubs. I refer to the broad geographic area in which wholesale market participants are located as the market. A market is defined as the region that is within 500 km of the market hub location. The climate data employed in this chapter is not explicitly available for these constructed regions. The most complex aspect of this market definition scheme is the matching of climate variables that are observed at the level of climate division (sub-state) with the market series. The geographic centroids of each of the 344 climate divisions in the contiguous United States are computed and

³⁸For instance, the market for wholesale electricity on the west coast of the United States can operate as two distinct north and south markets or as one combined market. Power is sold from the north to the south in the summer and in the opposite direction when the north is confronted with winter weather and mild temperatures grip southern California. The north and south markets operate independently when local generating sources can meet the intermediate levels of demand that prevail in the intervening periods.

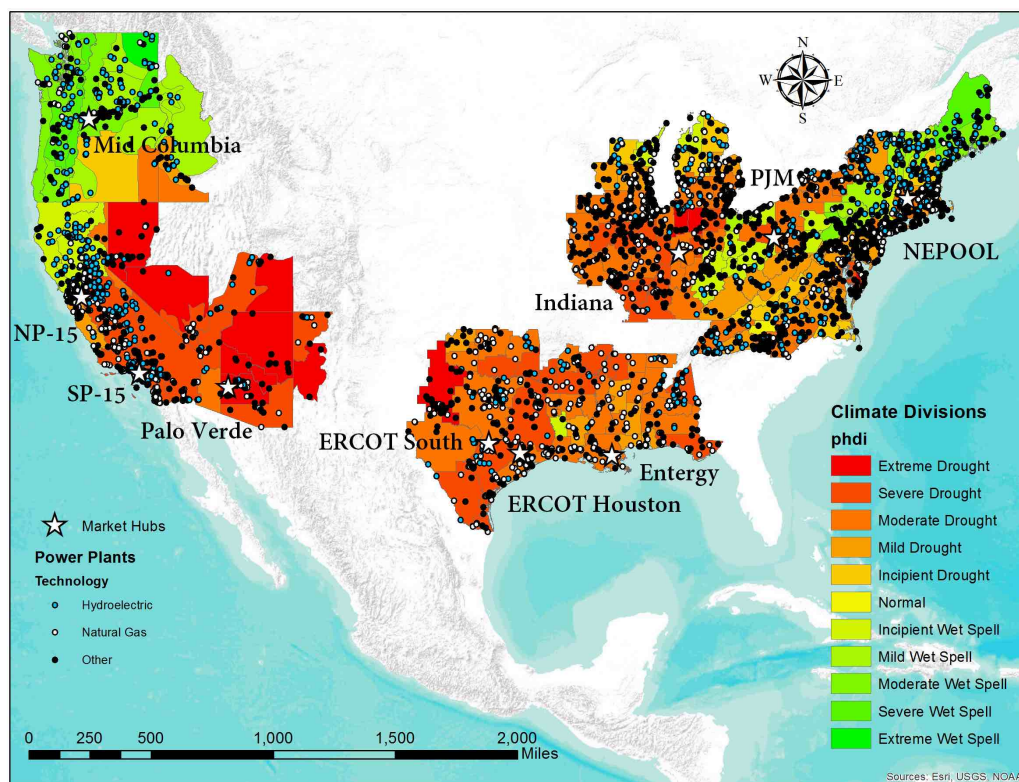
each market hub is paired with the set of climate divisions that have centroids within 500 km. A discussion of the threshold distance chosen for this analysis can be found in the appendix.

The geographic coverage that is obtained with a 500 km radius can be seen in Figure 1.5. In this diagram, only the climate divisions with centroids within 500 km of a market hub are displayed. The climate divisions are coded to reflect the same month as in Figure 1.1 (June 2012). The ten market sample covers most of the country with the exception of the southern Atlantic seaboard, the plains states and the Rocky Mountain region. The west coast, southwest, south, midwest and east coast are all well represented in this sample of wholesale markets. Power plants are coded to highlight the geographic distribution of hydroelectric facilities, the natural gas plants that replace lost hydropower when drought strikes, and all other plants of any fuel group.

1.5.2 Wholesale Electricity Market Model

A model of imperfect competition in the context of a day-ahead wholesale market for electricity can be found in Appendix C. Production is divided between a set of hydroelectric firms and an efficiently dispatched set of thermal generating plants that are modeled with increasing marginal costs. A simple model of Cournot competition is used to model the strategic responses of hydroelectric and thermal technology electricity generation firms to drought. The degree of competition among hydroelectric producers is modulated through the number of identical hydroelectric firms in the market, N .

Figure 1.5: Geography of the 10 Market Sample



Comparative statics motivate several hypotheses for the impact of drought on core market outcome variables. Drought enters the model specification through a low realization of the water resource endowment, R . Drought increases the marginal cost of hydroelectric generation and decreases the collective output of hydroelectric and thermal generation. Market average marginal generating costs therefore rise with drought. The substitution of higher marginal cost thermal generation for lost hydropower is less than complete. Average market prices clearly rise with drought in the model. The effect of drought on markups depends on whether the movement in costs or prices is more rapid. Inter-period price changes are more pronounced when hydroelectric produc-

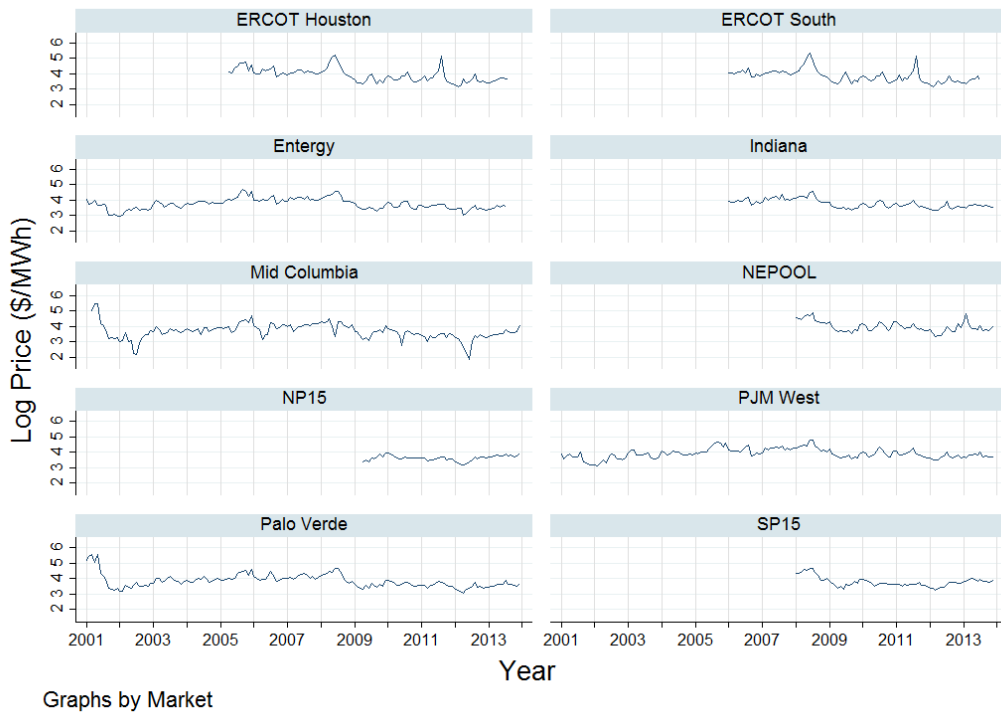
tion is concentrated among relatively few firms (low N scenario). These same fluctuations in price are dampened by either more competition or more severe drought, which acts to reduce market power through reducing inputs to production. Drought should reduce price volatility the most where competition is least present. These theoretical hypotheses are tested in the following sections.

1.5.3 Wholesale Electricity Market Data

The lack of geographic agreement between state boundaries and the modern wholesale market for electricity in the U.S. provides impetus for the search for additional sources of data. The main price data utilized in the following empirical analysis is republished by the EIA with the consent of the Intercontinental Exchange (ICE). This price data entails transactions for bulk power exchange in 10 geographically dispersed markets within the United States, covering years 2001 through 2013. The markets observed in this chapter and their abbreviations are as follows: Entergy Louisiana (Entergy), Electric Reliability Council of Texas - Houston (ERCOT Houston), Southern Texas (ERCOT South), Midwest (Indiana), Oregon-Washington Border (Mid-Columbia), Northeast Pool (NEPOOL), Northern California (NP15), Pennsylvania-New Jersey-Maryland West (PJM West), Southwest (Palo Verde), and Southern California (SP15).

The day ahead electricity price data employed in this analysis comes from the ICE platform for over-the-counter trading. The ICE platform facilitates roughly 70 percent of next day trading activity. Transacting parties in these markets include banks, chemical and transportation companies, hedge funds,

Figure 1.6: Log Wholesale Price Series



refiners, power stations and utility companies, among others. The main series used for each of the ten markets observed is an index of weighted average price for a given day of trading³⁹. Let these series or power indices be denoted $P_{m,\tau}$, where m indexes the specific wholesale market hub (location) and τ indicates the day of interest. Each power index is calculated as $P_{m,\tau} = \sum_{k=1}^{K_{m,\tau}} \frac{P_{m,\tau,k} \cdot V_{m,\tau,k}}{V_{m,\tau}}$, where $K_{m,\tau}$ is the number of transactions occurring on day τ in market m . The price, $P_{m,\tau,k}$, and volume, $V_{m,\tau,k}$, for each transaction, k , are measured in dollars and MWh respectively. The total volume of qualifying transactions is denoted $V_{m,\tau}$. Transactions can be considered “non-qualifying” for several reasons such as when both transacting parties are

³⁹Information regarding the indices was obtained from the EIA’s website, <http://www.eia.gov/electricity/wholesale/>.

owned by the same parent company or when the trade was altered or cancelled between consummation and confirmation of the deal⁴⁰. As the analysis is conducted at the market-month level, log price and volatility variables are constructed from the set of daily values for price. Monthly price variables are constructed as the mean of daily values. Section 1.5.10 describes the construction of monthly volatility series.

Ultimately, the power indices offer a measure of wholesale electricity price level at 10 markets over a considerable amount of time. Figure 1.6 illustrates the temporal support of price data. Summary statistics for the price and volatility series are presented for each market in Table 1.8.

Table 1.8: Summary of Price Data for 10 Markets

Market		Price		Volatility		SNH	N
Name	Number	Mean	Std. Dev.	Mean	Std. Dev.		
Entergy	1	45.679	16.888	0.364	0.167	0.033	139
ERCOT Houston	2	58.450	33.706	0.561	0.420	0.008	96
ERCOT South	3	54.279	35.809	0.552	0.475	0.011	88
Indiana	4	46.060	14.330	0.565	0.243	0.018	96
Mid-Columbia	5	45.589	30.138	0.645	0.797	0.604	153
NEPOOL	6	58.001	22.738	0.669	0.392	0.100	72
NP15	7	38.533	6.757	0.349	0.141	0.258	57
PJM West	8	54.236	18.925	0.676	0.342	0.076	156
Palo Verde	9	52.913	36.337	0.384	0.244	0.085	156
SP15	10	46.717	18.200	0.395	0.200	0.135	69

Volatility is presented as the mean percentage price change that could be expected over the course of a month. The mean volatility of 0.645 for the Mid-Columbia hub indicates that price could fluctuate 64.5 % in a month. Price data is recorded in \$/MWh. Uneven panel of 10 markets over 156 months.

1.5.4 Market-Level Environmental Series

A monthly measure of drought severity is constructed for each market as a weighted average of the values observed for the constituent climate divisions assigned to each market hub. An algebraic representation of the weights is

⁴⁰Some relatively complicated trades, options with specific time frames and deals that are reversed within 2 minutes are also excluded from the calculation of the power indices.

presented in equation (1.6). A set of variables is generated, indicating whether a given climate division is near enough to each market to warrant the inclusion of the division's drought series in the construction of the market's composite drought series. These indicators are multiplied by the nameplate capacity of hydroelectric plants located within the climate division in order to arrive at the weight denoted N_d .⁴¹

$$\mathbf{D}_{m,t} = \frac{\sum_d D_{d,t} \cdot N_d}{\sum_d N_d} \text{ for } d \in m \quad (1.6)$$

As the intent of the chapter is to uncover the drought-affected market mechanisms related specifically to hydroelectric production, weighting individual climate division series by hydroelectric nameplate capacity was more attractive than using population or area-based weighting schemes. These other two methods entail the use of weights that more closely reflect demand conditions than supplier conditions. Regression analysis determined that the 2010 levels of hydroelectric nameplate capacity at the climate division level are orthogonal to the mean values of PMDI, PHDI, and ZNDX that are estimated for the same regions over the period of record (1895-2013).⁴² The resulting weighted sum is then divided by the sum of hydroelectric nameplate capacity in all relevant climate divisions. Fundamentally, the impacts of drought on hydroelectric production should be most pronounced where hydroelectric capacity

⁴¹Alternate weighting regimes were also evaluated. A discussion of these other options can be found in the appendix.

⁴²These regressions were performed using raw drought data that has not been standardized for the sample period explored in the rest of the chapter.

is the most prevalent. The weighted, market-level values for drought are then standardized within sample to exhibit a mean of zero and a standard deviation of one. It is now possible to estimate the impact of a standard drought shock on a representative sample of U.S. wholesale electricity markets.

1.5.5 10 Wholesale Market Panel

Evaluation of the market price data requires the creation of a market level panel for the remainder of the series which were not explicitly observed at the same market level. The definition and details of this market are discussed more completely in section 1.5.1. Each market price series is linked to a set of climate divisions within a threshold distance of the hub location. The climate data for these constituent divisions is aggregated to construct series for each of the 10 markets. All the plants contained within these linked divisions and their output is associated with the adjacent market. The result is that a wholesale market is effectively constructed as a central price node and the set of plants that are sufficiently close to serve the load at that node. The boundaries of these markets are broadly informed by a threshold distance from the node, but the exact demarcation follows the borders of climate divisions in order to closely match data on environmental conditions and generating behavior.

Table 12, located in the appendix D, displays summary statistics for the population of plants of at least 1 MW nameplate capacity in the contiguous United States as well as for the sample of plants located within proximity of the ten wholesale market hubs. 207 of the 344 climate divisions have a centroid

within 500 km of at least one market hub in the sample. Of the 5,793 plants for which I observe primary energy source data, 3,902 or 67.3 percent are in the ten market sample.⁴³ Roughly 72.6 percent of all plants by nameplate capacity are in the ten market sample. Hydroelectric plants account for 26.7 percent of the plants in 10 market sample and 9.8 percent of that sample's nameplate capacity. The same figures for the national sample are 24.9 and 9.0, indicating that hydroelectric facilities are fairly well-represented in the 10 market sample. The largest generating group by primary fuel source is Natural Gas, which accounts for 44.0 percent of nameplate capacity in the sample. At 19.9 percent of the 10 market sample capacity, coal is the second most prevalent technology. The historically low cost of coal has meant that it is used far more often to meet base load demand than is natural gas. The capacity factor for many natural gas plants is relatively low as the facilities are only dispatched to meet demand during the peak conditions.

1.5.6 Cluster Robust Inference with Few Markets

The use of data from only ten markets presents an empirical complication that requires the estimation of standard errors that are robust to the problem of too 'few' clusters. Generally, the use of cluster robust standard errors would be an acceptable method for contending with heteroskedasticity and correlated errors within clusters. However, as noted in Cameron et al. (2008), there is considerable risk of over-rejection of null hypotheses by asymptotic tests when

⁴³Another 1020 plants report no fuel source or nameplate capacity data and are thus omitted from the ten market sample.

so few clusters are utilized. To correct for this, a wild cluster bootstrap-t method is employed as it does not entail the restrictions of i.i.d. errors or a balanced panel. The error structure in the panel constructed for this study is serially correlated and the clusters are not of equivalent size as some markets report price data for only a sub-sample of the months between 2001 and 2013. Wild bootstrapping the t-statistics is also the favored method advanced by Cameron and Miller (2015) when contending with few, unbalanced clusters. Through this method, detailed in the following paragraph, more accurate p-values are estimated.⁴⁴ The analysis in this section presents p-values in tables rather than standard errors. Following the advice of Cameron and Miller (2015), a wild bootstrap is conducted with 999 resamples for each regression and Rademacher weights are employed.

The bootstrapping procedure has several steps and can be computationally intensive. What follows draws extensively on Cameron and Miller (2015). using the cost analysis as an example, the first step to implementing the Wild Cluster Bootstrap is to estimate the model specified in Equation (1.8) while imposing the null hypothesis that drought has no effect on cost either directly or through an interaction with the hydroelectric capacity share. In order to test the significance of drought as a determinant of price, log price is regressed on all components of the covariates matrix except drought. The resulting residual values are turned into pseudo-residuals equal to the actual residual multiplied by either one or negative one. The probability that either weight

⁴⁴The wild bootstrap procedure is implemented in the following regression results using the `gcmwildboot` command, written for Stata by Judson Caskey of UCLA.

is assigned is one half and all observations within a given cluster are assigned the same weights. These pseudo-residuals are used to construct new values for the dependent variable within each resample. Next, the coefficient estimates of interest are obtained with OLS for the current resample. Then the Wald t-statistic is calculated by taking the difference of the resample coefficient estimate and the original sample estimate divided by the cluster-robust standard error of the coefficient. The p-value for the coefficient on drought in equation (1.8) is equal to the proportion of times that the absolute value of the Wald statistic estimated with the original sample exceeds the Wald statistics from the 999 resamples. If 10 of the resampled test statistics are greater in absolute value than the original sample statistic, the corresponding p-value is around 0.01.⁴⁵

1.5.7 Market-Level Cost Analysis

How does drought impact the cost of generating electricity in the ten markets under investigation? To begin, a definition of generating cost must be developed. Let $C_{m,t}$, defined in Equation (1.7), be the average variable cost of electricity generated by plants within market m in month t . The variable cost and quantity of generation with fuel $f = 1, 2, \dots, F$ in month t is denoted $c_{f,t}$ and $q_{f,m,t}$ respectively.

$$C_{m,t} = \frac{\sum_{f=1}^F (c_{f,t} \cdot q_{f,m,t})}{\sum_{f=1}^F q_{f,m,t}} \quad (1.7)$$

⁴⁵As noted in Webb (2013), with only G groups there are only 2^{G-1} possible values for the t-statistics. For ten groups the t-statistics can obtain 512 distinct values.

This average variable unit cost of production is regressed on measures of drought severity and the interaction of drought severity with the share of nameplate capacity that is derived from hydroelectric power within each market. The more hydroelectric nameplate capacity in a given market region the greater the potential for a standard drought shock to impact the wholesale power market. For this reason, the specification presented in equation (1.8) allows the impact of drought to interact with the nameplate share variable. The hydroelectric share of nameplate capacity in each market, denoted SNH_m , is calculated based on 2010 generator level EIA data. The hydroelectric share variable is time invariant in this analysis, and is thus absorbed by the market level fixed effects, denoted α_m .⁴⁶ The panel is unbalanced and contains a set of monthly indicator variables, λ_t , to account for national time trends. In all cases, m indexes the market and t indexes the time period (month).

$$\log(C_{m,t}) = \alpha_m + \beta_1 \cdot \mathbf{D}_{m,t} + \beta_2 \cdot \mathbf{D}_{m,t} \times SNH_m + \lambda_t + \epsilon_{m,t} \quad (1.8)$$

The baseline cost and price regressions in this section and the immediately following one do not control for cooling degree days. The most basic specification possible is used in order to focus on the the bootstrapping procedure and its impact on inference. Section 1.5.9 on markups presents cost and price regression results that do control for cooling degree days. This difference-in-difference strategy is implemented with the baseline cost results presented in

⁴⁶A fixed-effects model was chosen over a random effects model as a cluster robust Hausman test rejected the null of equivalent coefficient estimates with a Sargan-Hansen χ^2 test statistic of 27.925.

Table 1.9: Baseline Log Cost Regression Results

Dep. Var.	PHDI		PMDI		ZNDX	
	CRVE	WBST	CRVE	WBST	CRVE	WBST
D_t	-0.0115 [0.314]	-0.0115 [0.404]	-0.0110 [0.296]	-0.0110 [0.344]	-0.0095 [0.287]	-0.0095 [0.326]
$D_t \times SNH$	0.2534*** [0.001]	0.2533*** [0.000]	0.2596*** [0.000]	0.2596*** [0.000]	0.1707*** [0.000]	0.1707*** [0.000]
Observations	1095					

P-values are presented in square brackets. Clustering is conducted at the market level.
CRVE indicates that cluster robust standard errors were estimated.
WBSE denotes the wild bootstrap method used to contend with the “few” clusters problem.

Table 1.9. A standard drought shock has no significant direct effect on market cost, regardless of the choice of drought metric. Instead the impact of drought is mediated by the degree to which each market relies on hydroelectric capacity. For the hypothetical market with the sample mean share of hydroelectric nameplate capacity, a standard drought shock leads to an average cost shock of 3.35 percent when drought is measured with PHDI. The effect of a standard drought shock is 3.45 percent and 2.27 percent when the PMDI and ZNDX are used respectively. As is ZNDX measures short-term deviations from normal water conditions rather than the longer-term hydrological conditions that matter for hydroelectric facilities, the impact of drought appears smaller when using the former measure. For moderately hydro-reliant markets, a standard drought shock pushes up costs by roughly one-fourth. Attention now turns to the impact of drought on market prices.

1.5.8 Market-Level Price Analysis

What happens to the wholesale price of electricity as drought gets more severe? Drought is shown to act as a straightforward supply shock for hydroelectric producers in Table 1.1. The effect of drought on the average variable cost of generating a MWh in wholesale markets is shown in Table 1.9. Equation (1.9) presents the specification used to evaluate the impact of drought on market prices. The right-hand side of the equation is identical to that of Equation (1.8). The continuity in specification is intended to facilitate a close comparison of the magnitude of cost and price effects from drought.

$$\log(\text{Price}_{m,t}) = \alpha_m + \beta_1 \cdot \mathbf{D}_{m,t} + \beta_2 \cdot \mathbf{D}_{m,t} \times \text{SNH}_m + \lambda_t + \epsilon_{m,t} \quad (1.9)$$

The results from regressing the log of wholesale price on a measure of drought severity, $D_{m,t}$, and its interaction with SNH_m are presented in Table 1.10. Columns labeled as CRVE employ a cluster robust estimate of the variance matrix for improved inference. P-values are presented in square brackets. The set of columns labeled as WBST use the Wild Bootstrap t-statistic procedure to generate more accurate p-values. Column one suggests that a one standard deviation increase in the severity of drought corresponds with prices rising 2.9 percent for a hypothetical market without any hydroelectric nameplate capacity. The magnitude of the price shock is amplified by the reliance of a market on hydroelectric power. For a hypothetical market with hydroelectric nameplate share equal to the mean value observed for the ten markets

Table 1.10: Baseline Log Price Regression Results

Dep. Var. Log $Price_{m,t}$	PHDI		PMDI		ZNDX	
	CRVE	WBST	CRVE	WBST	CRVE	WBST
D_t	0.0286** [0.022]	0.0286** [0.040]	0.0285** [0.041]	0.0285** [0.046]	0.0298** [0.015]	0.0344** [0.044]
$D_t \times SNH$	0.1519** [0.050]	0.1579 [0.2142]	0.1579** [0.036]	0.1579 [0.196]	0.1885** [0.009]	0.0676 [0.246]
Observations	1095					

P-values are presented in square brackets. Clustering is conducted at the market level.
CRVE indicates that cluster robust standard errors were estimated.
WBSE denotes the wild bootstrap method used to contend with the “few” clusters problem.

(13.3 percent), that same one standard deviation increase in drought severity is associated with a 4.9 percent increase in price. The implementation of the bootstrapping procedure appears to have little effect on the significance of the effect of drought when the hydroelectric share of capacity is zero. However, the interaction term ceases to be significant when the Wild Bootstrap is conducted. It is worth noting that the coefficient on the interaction term is very similar with and without the bootstrap procedure for the two long-term drought metrics. Only the monthly rain index indicates a pronounced difference in point estimates with and without the bootstrap procedure.

1.5.9 Markups

With price and an estimate of average variable cost for each market-month pair in the sample, it is possible to calculate a basic measure of markups. Let $M_{m,t}$, the average markup for market m in period t be defined as in Equation (1.10).

$$M_{m,t} = \log \left(\frac{P_{m,t}}{C_{m,t}} \right) \quad (1.10)$$

An increase in $M_{m,t}$ indicates a widening gap between the average variable cost of production and the wholesale market price for electricity. The physical network of the grid and behavior of competitors are important determinants of the degree of competition in wholesale electricity markets. In markets that rely heavily on hydropower, such producers will have significant market power, and therefore contribute to the mark-ups exhibited. Equation (1.11) presents the specification used to evaluate the impact of drought on markups. The right-hand side differs from the two previous specifications used for market analysis in that it includes cooling degree days. The inclusion of $CDD_{m,t}$ enables the decomposition of drought's impact into heat and water components.

$$M_{m,t} = \alpha_m + \beta_1 \cdot \mathbf{D}_{m,t} + \beta_2 \cdot \mathbf{D}_{m,t} \times SNH_m + \beta_3 \cdot CDD_{m,t} + \lambda_t + \epsilon_{m,t} \quad (1.11)$$

Table 1.11 presents evidence on the impact of drought on costs, prices and markups with each panel utilizing a different drought measure. The log ratio of price to cost increases 3.1 percent with a standard drought shock and this effect is significant at the one percent level. This may mean that it is now relatively costlier to get power from the point of generation to the market hub. Drought increases the average variable cost of generating electricity by 3.4 percent for the market with average hydro-reliance. For this average market, the standard drought shock implies a rise in markups of 1.8 percent. The number of cooling degree days is important to both market costs and market prices. A standard deviation increase in the quantity of cooling degree days

is associated with a 4.5 percent increase in market costs. However, as market prices rise 16.4 percent with the same shock, heat waves tend to increase the markup over generating costs paid on wholesale power markets. Markups rise 11.9 percent with a standard deviation increase in cooling degree days and this effect is significant at the ten percent level. While the data used for this study cannot determine the exact composition of factors responsible for rising markups, it is possible to discern from the findings above that drought leads to a less cost effective utilization of the power grid in delivering power to wholesale customers.

Panel B of Table 1.11 shows that the results are robust to the use of an alternate drought measure. Panel C of the same table shows the impacts of anomalous rainfall on costs, prices and markups. As the log price cost ratio increases, the effective degree of competition among generators is decreasing. Some market power held by operators of large hydroelectric plants may be lost to drought, but the substitute plants gain some market power as they replace the production of their diminished competitors. This is one explanation for why the positive effect of drought on markups is mitigated in the presence of hydroelectric capacity. Rising prices and markups are both attractive to potential investors, but what effect does drought have on market price stability. A high price signal is only as attractive as its likelihood of persisting over a plant's productive lifetime. The next section presents evidence concerning the impact of drought on price volatility.

Table 1.12 presents estimates of the effect of drought on costs and markups

Table 1.11: Impact of Drought on Costs, Prices and Markups

	Cost	Price	Mark-ups
	(1)	(2)	(3)
Panel A	$\log C_{m,t}$	$\log P_{m,t}$	$M_{m,t} = \log \frac{P_{m,t}}{C_{m,t}}$
$PHDI_{m,t}$	-0.0148 [0.206]	0.0166 [0.116]	0.0314* * * [0.000]
$PHDI_{m,t} \times SNH_m$	0.254* * * [0.000]	0.154 [0.182]	-0.100** [0.016]
$CDD_{m,t}$	0.0446* [0.068]	0.164* * * [0.000]	0.119* * * [0.008]
Baseline	3.536	4.522	0.986
Panel B	$\log C_{m,t}$	$\log P_{m,t}$	$M_{m,t} = \log \frac{P_{m,t}}{C_{m,t}}$
$PMDI_{m,t}$	-0.0145 [0.158]	0.0157 [0.214]	0.0302*** [0.000]
$PMDI_{m,t} \times SNH$	0.262*** [0.000]	0.165 [0.132]	-0.0964** [0.024]
$CDD_{m,t}$	0.0450* [0.070]	0.164*** [0.000]	0.119*** [0.008]
Baseline	3.538	4.528	0.990
Panel C	$\log C_{m,t}$	$\log P_{m,t}$	$M_{m,t} = \log \frac{P_{m,t}}{C_{m,t}}$
$ZNDX_{m,t}$	-0.0144 [0.116]	0.0189 [0.122]	0.0333*** [0.000]
$ZNDX_{m,t} \times SNH$	0.181*** [0.000]	0.102** [0.032]	-0.0795*** [0.004]
$CDD_{m,t}$	0.0527* [0.096]	0.169*** [0.000]	0.116*** [0.008]
Baseline	3.567	4.562	0.995
Observations	1095		

P-values are presented in square brackets with significance denoted: *, $p < 0.10$; **, $p < 0.05$; $p < 0.01$, * * *.
The wild bootstrap method for inference with few clusters is used in all regressions.
Clustering is conducted at the market level.

in each individual wholesale market. The strength of the impact is mediated by the presence of hydroelectric resources.

Table 1.12: Market Specific Drought Effects

	Effect of an (X) standard deviation increase in Drought Severity	Costs			Mark-ups		
		$C_{m,t}$	$C_{m,t}$	$C_{m,t}$	$M_{m,t}$	$M_{m,t}$	$M_{m,t}$
	$SNH_m(\%)$	($X = 1$)	(2)	(3)	(1)	(2)	(3)
ERCOT Houston	0.81	0.21	0.41	0.62	3.06	6.12	9.18
ERCOT South Texas	1.09	0.28	0.55	0.83	3.03	6.06	9.09
Indiana	1.78	0.45	0.90	1.36	2.96	5.92	8.89
Entergy	3.30	0.84	1.68	2.51	2.81	5.62	8.43
PJM West	7.60	1.93	3.86	5.79	2.38	4.76	7.14
Palo Verde	8.45	2.15	4.29	6.44	2.30	4.59	6.89
NEPOOL	9.95	2.53	5.05	7.58	2.15	4.29	6.44
SP 15	13.52	3.43	6.87	10.30	1.79	3.58	5.36
NP 15	25.84	6.56	13.13	19.69	0.56	1.11	1.67
Mid Columbia	60.43	15.35	30.70	46.05	-2.90	-5.81	-8.71
Threshold Market	31.4	7.98	15.95	23.93	0.00	0.00	0.00

All estimates are in percent. Effects are assumed to scale linearly with the severity of drought.
Each estimate is constructed from the marginal effect of drought on the variable of interest presented in Table 1.11.
The threshold market is a hypothetical market with hydroshare such that mark-ups stay constant with a drought shock.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.010$

Arrayed in ascending order of hydroelectric nameplate share, the markets exhibit cost effects that increase in magnitude while the effect on markups declines and then goes strongly negative for the Mid Columbia market. A two standard deviation drought shock for the market surrounding the NP-15 hub in northern California is estimated to entail a 13.1 percent increase in average variable costs and a 1.1 percent increase in the log price-cost markup. The northern Californian market has the second highest value of SNH_m . The Mid Columbia market exhibits the most striking pattern of effects for the various severities of drought shock. For the northwest market, costs are estimated to rise 46.1 percent while markups fall 8.7 percent. Let the threshold market be defined as a market with hydroelectric capacity share such that the positive and negative effects of drought on mark-ups exactly cancel out. Markets

with hydroelectric capacity shares greater than 31.4 percent will experience falling mark-ups with drought shocks. Most markets, those deriving less than 31.4 percent of capacity from hydroelectricity, will see mark-ups rise when confronted with a drought shock.

1.5.10 Drought and Volatility

As volatility can be influenced by anything that impacts price, through supply or demand, numerous mechanisms could be simultaneously engaged. Fundamentally, whether drought acts a dampener or amplifier of volatility is an empirical question that can be answered using the data from our ten U.S. market price series.

It is useful to define a measure of price volatility with which to compare the relative stability of each market as well as the stability within markets over time. The methodology used in this chapter to calculate and evaluate price volatility in wholesale electricity markets is drawn from (Mastrangelo, 2007), which evaluates the natural gas price volatility at the Henry Hub in Louisiana.

The natural-log-transformed daily relative price change is denoted ΔP_t . For Equations (1.12) and (1.13), let τ index days within month t .

$$\Delta P_\tau = \ln \left(\frac{P_\tau}{P_{\tau-1}} \right) \quad (1.12)$$

Equation (1.13) defines price volatility, $V_{m,t}$, for market m and month t as the product of the standard deviation of ΔP_τ and the square root of the number

of trading days, denoted N_T . Not all months have the same number of trading days due to holidays and the presence of days without trades in some markets.

$$V_{m,t} = \sqrt{\frac{\sum_{\tau=1}^{N_T} (\Delta P_{\tau} - \Delta \bar{P})^2}{N_T - 1}} \cdot \sqrt{N_T} \quad (1.13)$$

The resulting variable, $V_{m,t}$, will obtain a value that indicates the distance the price might move over the course of a month as a percentage of its current value. That is, a monthly volatility value of 0.5 indicates that for the month of interest, the sum of daily price movements (in absolute values) over all days is equal to half the price level. In reality, price does not move uniformly up or down for any sufficiently long period of time, but another way to think of volatility equal to 0.5 is to realize that the price could have fallen or appreciated by half of its prevailing value in a matter of a month.

1.5.11 Volatility Regressions

Theory is less unified and clear regarding the effects of drought on price volatility. To reiterate, the price data comes from power purchases on day-ahead markets and values reflect the volume-weighted average price of electricity transacted. These price indices are constructed daily. Therefore any volatility detected in this study is reflecting movement in interday average price. That is, hourly determinants of volatility are beyond the scope of this analysis.

Fundamentally, we are interested in the sign and magnitude of the effect that drought has on price volatility. The theoretical mechanisms through which

volatility actually rises or falls are difficult to separate a priori from those other mechanisms that are not at work. As a consequence the impact of drought is left as an empirical question.

Equation (1.14) presents the baseline specification used to examine the impacts of drought on price volatility. Drought is still interacted with the market hydro share variable, SNH_m , in order to see how hydroelectric facilities mediate the impact of the disaster on market price volatility. The level of cooling degree days has no discernible effect on the degree of market price volatility and is thus omitted from the specification.⁴⁷ Market level fixed effects, α_m , and temporal controls, λ_t , are also included in the specification.

$$V_{m,t} = \alpha_m + \beta_1 \cdot \mathbf{D}_{m,t} + \beta_2 \cdot \mathbf{D}_{m,t} \times SNH_m + \lambda_t + \epsilon_{m,t} \quad (1.14)$$

The results of running the regressions specified in (1.14) are presented in Table 1.13. The direct effect of drought on volatility for a hypothetical market with no hydroelectric capacity is on the order of 3.8 percent increase in volatility for a single standard deviation increase in drought severity. This effect is just outside the threshold for significance at the the ten percent level. Most of the action is encapsulated in the coefficient on the interaction term. Markets with considerable hydroelectric reliance, see a decline in volatility that can be considerably larger than the insignificant direct effect of drought. For a hypothetical market with the average SNH observed in sample, a standard drought shock corresponds with a 4.2 percent fall in volatility. Unlike the

⁴⁷Other specifications were investigated to confirm this lack of association.

direct effect, the interaction effect is highly significant, even when correcting for downward-biased variance estimates through the bootstrapping procedure. For the most hydro-reliant markets the impact of a standard drought shock on volatility is even more pronounced.

Table 1.13: Baseline Volatility Regression Results

Dep. Var. Volatility	PHDI		PMDI		ZNDX	
	CRVE	WBSE	CRVE	WBSE	CRVE	WBSE
D_t	0.0378 [0.118]	0.0378 [0.110]	0.0389* [0.098]	0.0389 [0.110]	0.0156 [0.617]	0.0575*** [0.000]
$D_t \times SNH$	-0.3139*** [0.000]	-0.3139*** [0.002]	-0.3305*** [0.000]	-0.3305*** [0.002]	-0.2292*** [0.000]	-0.4224*** [0.002]
Observations	1082					

P-values are presented in square brackets. Clustering is conducted at the market level.
CRVE indicates that cluster robust standard errors were estimated.
WBSE denotes the wild bootstrap method used to contend with the “few” clusters problem.

The evidence from U.S. markets suggests that volatility in hydro-reliant markets falls when drought reduces the inputs to hydroelectric production. Costs rise with the severity of drought and prices are generally increased by the accompanying heat waves. As more power is generated (as a share) with regularly scheduled thermal generation, water resources employed in hydroelectric production account for less of the power that clears in regional markets. Consistently high demand and a truncated supply curve imply that prices are high and relatively stable. The shock of drought to the industry supply curve drags the market clearing point up along the linear demand curve, where demand is more elastic. The demand curve itself may be shifted out by the heat that comes with the drought and may fall as less electricity is required to service irrigation needs. Regardless of the dominant effect, if the market clears at a point with more elastic demand, the movements in price that result from

idiosyncratic shifts in demand should be less pronounced. That is, latent price volatility should fall when drought pushes equilibrium back along the demand curve. The extent of the supply curve shift is determined by the prevalence of hydroelectric facilities. Drought has the potential to shift the market supply curve further when more hydropower plants are competing. This reconciles well with the results that show only the interaction term and not the simple effect to be a significant determinant of volatility.

1.5.12 Robustness of Results to Mid Columbia Outlier

A robustness check was conducted to evaluate the effects of extreme price movements in the early summer of 2012. June of that year exhibits the highest volatility spike present in the complete ten market sample. The Mid Columbia market has the highest hydroelectric share of nameplate capacity (60.4 percent) among the ten in sample. This volatility spike is driven by a number of factors. Unseasonably heavy precipitation and low demand for power coupled to force spilling by hydroelectric power plants in the Northwest. Environmental considerations restrict the ability of dams to divert water (spill) even when there is insufficient demand for the product that would be generated in the absence of spilling. These environmental considerations were binding in June of 2012. As a result, large quantities of cheap hydropower were dispatched, causing a precipitous fall in the prevailing wholesale price. This large and rapid price movement contributes to the high volatility observed in that month. No other volatility spike comes even close in magnitude. It is necessary to investigate

the extent to which the main results of the chapter hinge on or are resilient to changes in sample period that exclude this outlier month. The robustness check involves shortening the sample to cover January 2001 through the end of May in 2012, just before the anomalous volatility spike⁴⁸.

Each of the four main market variables is regressed on the same set of covariates presented in Equation (1.8). The only difference between the results in Table 1.14 and those in Table 1.11 is the sample period over which the analysis is conducted.⁴⁹ The Wild Bootstrap t-procedure is used for all regressions in this robustness check. Table 1.14 presents results with the same pattern of sign and significance as was presented in the main analysis. However, the coefficients obtained through the sensitivity analysis are generally attenuated by comparison. Drought represents the far end of the water availability spectrum compared to the deluge that sent volatility up in this outlier event. It is also important to recognize that too much water can lead to the uneconomic dispatch of hydropower. The constraints forcing such inefficient generation are less likely to bind as the Palmer Indices indicate weakening wet spells and more severe droughts. Hydroelectric facilities are only as powerful in wholesale markets as their disposable resources are large. A few bad years of drought can limit the market power of hydroelectric plants considerably.

When markups are regressed on the interaction of drought and the hy-

⁴⁸By curtailing the sample period for the unbalanced panel, the composition of the data set changes in favor of the early-reporting market hubs. Hubs such as those found in California only report data for the later years. Therefore these markets are poorly represented by the curtailed sample.

⁴⁹All standardized variables such as drought and its interactions were restandardized within the curtailed sample for this robustness check.

Table 1.14: Baseline Results with Alternate Sample Period (Jan 2001 - May 2012)

	Costs	Prices	Mark-ups	Volatility
	$C_{m,t}$	$P_{m,t}$	$M_{m,t}$	$V_{m,t}$
$PHDI_{m,t}$	-0.00643 [0.539]	0.0155* [0.068]	0.0220*** [0.000]	0.0346** [0.030]
$PHDI_{m,t} \times SNH_m$	0.253*** [0.000]	0.137 [0.218]	-0.117* [0.086]	-0.183** [0.014]
$CDD_{m,t}$	0.0501*** [0.000]	0.162*** [0.000]	0.112** [0.030]	-0.00277 [0.969]
Baseline	3.591	4.503	0.912	0.425
Observations	925	925	925	920

P-values are presented in square brackets with significance denoted: *, $p < 0.10$; **, $p < 0.05$; $p < 0.01$, ***. The wild bootstrap method for inference with “few” clusters is used in all regressions. Clustering is conducted at the market level.

droelectric share of capacity the negative effect observed is greater in absolute value when the most hydro-dependent market (Mid-Columbia) is omitted from the sample. As this market contains some of the largest dams in the country and a single entity controls many of these assets, the finding of an attenuated effect is consistent with the presence of market power in wholesale power markets.

1.6 Policy Discussion

Having demonstrated the technological substitution associated with drought in the electrical power sector, attention turns to the impacts of these findings on energy policy. Hydroelectric plants may not account for a large share of net generation at the national level, but the operational flexibility that such facilities can lend to grid managers is of considerable value. The value of flex-

ible renewable generating options is clarified in scenarios with high penetration of variable generation technology like wind and solar. van Kooten (2010) explains that fluctuations in the output from wind generation requires the rapid ramping of substitute generating options and inefficient operation of thermal facilities. These less than optimal operating practices push up operating and maintenance costs. In the absence of grid scale electricity storage, hydroelectric plants offer the best technology for temporal smoothing of the output from renewables. Jacobson (2009) ranks hydroelectric power higher than nuclear with respect to its climate and health impacts and refers to the technology as “an excellent load balancer”. Benitez et al. (2008) finds that the “cost effectiveness of intermittent sources is related to the share of hydropower in the grid”. In simulations for the Los Angeles area, Jacobson (1999) demonstrates that lower initial soil moisture levels increase wind speeds relative to the baseline scenario. Drought may increase potential wind power generation, but without hydroelectric power to act as a buffer the dispatch of wind power could negatively impact operating and maintenance costs at thermal plants. Some wind generation may have to be curtailed if reliability concerns cannot be alleviated.

While wind power represents only one of a number of renewable, low-pollution generating technologies currently competing with natural gas and the rest of the traditional generating fleet, by many accounts, wind power is the leading option. The 2015 Annual Energy Outlook published by the EIA estimates the levelized cost of electricity generated over the lifetime of wind power built in 2020 to be \$73.6 per MWh. This figure rises only slightly by

2040 to \$75.1 per MWh. Geothermal power is the only group that is considerably less expensive. Advanced combined cycle natural gas plants built in 2020 and 2040 are estimated to generate electricity at a rate of \$72.6 and \$79.3 per MWh.⁵⁰ Wind power should be competitive with natural gas generation when fuel costs are high and environmental conditions are favorable. A price on carbon emissions would also improve the competitiveness of wind power. It is the variable nature of wind generation, however, that causes concern and has driven research into how best to integrate the renewable technology into the grid.

If hydropower cannot balance increasing wind power generation to a sufficient extent, alternate energy storage technologies become more attractive. Cleary et al. (2015) evaluates the ability of compressed air energy storage (CAES) technology to mitigate the prevalence of wind generation curtailment in the common synchronous power system operated by the Republic of Ireland and Northern Ireland. The integration of CAES technology into the grid is shown to increase revenue with more wind generation as curtailment is reduced. The economic viability of investment in wind technology is more certain with reliable energy storage infrastructure. As geographic realities limit the locations in which CAES is viable, other energy storage technology will be needed to balance variable generation. Battery and hydrogen storage technology is a component of one vision of the future power grid.⁵¹ Sioshansi et al. (2009)

⁵⁰All cost estimates are in 2013 dollars.

⁵¹Khouri (2015) reports the installation of Tesla battery systems in Irvine and Newport Beach, California to provide Southern California Edison with 10 MWs of reserve capacity. The California Public Utilities Commission has set 2024 as the target year by which to have brought online 1,325 megawatts of additional storage.

found that energy storage could offer gains from arbitrage and increased consumer surplus from lower prices in the PJM region. In simulations matching data on system load and environmental drivers of wind and solar generation, Budischak et al. (2013) found it possible to meet demand in the PJM region with renewables and electrochemical storage as much as 99.9 percent of the time. The three storage technologies evaluated were grid-integrated electric vehicles, centralized batteries and a centralized hydrogen system. Even in this simulation, almost 9 hours a year require some generation from thermal power plants. At present, the national electric grid is far from such fossil fuel independence.

The natural gas boom experienced in the U.S. presents a tremendous opportunity to replace the most environmentally damaging plants with more efficient, and recently, more cost effective natural gas plants. Drought offers an example of natural gas acting as a substitute for losses in the renewable share of generation. Natural gas generation is environmentally preferable to many of the alternatives in the short run as the sector responds to drought, but in the long run, renewable sources may replace such substitute thermal generation. If the full potential of natural gas generation to lower emissions from the power sector is to be realized, the extent to which it crowds out renewable generation must be limited. New natural gas generation is most beneficial where it replaces the most damaging existing plants.

The benefits and environmental costs of using natural gas to generate electricity are not limited to the site of the power plant. Feyrer et al. (2015)

estimates that the natural gas boom in the United States has increased aggregate employment by 750,000. Some important potential sources of damage were not well documented when the gross external damage values used in this chapter were estimated back in 2011. The collection of technologies and techniques that have come to go by the colloquial name ‘fracking’ have enabled the extraction of natural gas from previously unprofitable shale formations. Rapid development of these formations has brought down the cost of natural gas, created large sums of wealth for some in the extraction industry and led to public concern around the effects of fracking on water quality. Vidic et al. (2013) reviews the evidence on the impact of the industry behavior on water quality in the Marcellus shale-gas deposit. For this formation, a single well can take 2 to 7 million gallons of water to drill and 18.7 million gallons of water per day were used for fracking in 2013. About 3.4 percent of wells in the Marcellus formation received notice of well construction violations from the Pennsylvania Department of Environmental Protection (DEP) from 2008 to 2013. Failure rates of any type of infrastructure increase with age. The effective long-term durability of well casings and their ability to prevent gas migration remain an open questions that may not receive satisfactory answers. Natural gas lost to leakages between the well head and the final consumer constitutes a greenhouse gas emission in its own right.

Vidic et al. (2013) notes the existence of “substantial impediments to peer-reviewed research into environmental impacts” for shale gas development. Effective science on the subject is stymied by a lack of pre-drilling baseline data.

As the activity is conducted in many remote places simultaneously with most of the infrastructure located underground, observing operations is challenging. Presently, using natural gas to generate electricity offers a promising option for reducing power plant emissions. However, the full effects of the natural gas boom on long term environmental quality cannot be known immediately. Therefore, the full environmental costs of drought-induced natural gas generation are subject to some uncertainty.

Considerable domestic natural gas resources have led to the decline in the cost of generating electricity with the fuel here in the United States. However, there are no guarantees that the cost will remain low. While stocks of natural gas are largely stranded in the domestic market, the development of LNG hubs promises to open these supplies to international markets and related pressures. Of course, if other countries also develop their shale gas resources, upward movement in international prices may be tempered. Either way, as the nation becomes more reliant on natural gas for electricity generation, volatility in the commodity's price may pass back through to power purchasers.

1.7 Conclusion

The drought currently afflicting millions of Americans on the west coast has increased the salience of drought for people working in all sectors. One sector of importance to all others, electrical power, has been significantly impacted by the drought through changes to hydroelectric generation. This chapter

contributes to the literature on the water-energy nexus by developing a novel way to incorporate environmental data into panels of electricity production and price data. This task is complicated by the mercurial market boundaries of wholesale electricity and the lack of accessible, high definition data on the transmission network servicing power producers and consumers. Like a plant's marginal costs, the structure of the network to which a plant is connected is also proprietary, strategically important information. This chapter has managed to assess the impact of drought along the electrical power value chain and on wholesale markets while leveraging all publicly available data.

Drought reduces the energy content of the water resources used to generate power at hydroelectric facilities. Natural gas plants are the substitute technology revealed in the regression analysis presented in Table 1.2. As hydroelectric production falls and natural gas generation rises, drought is associated with an increase in the average variable cost of generation for the ten wholesale markets in sample. Some of these additional costs are explicit while others take the form of gross external damages. Electricity production with fossil fuels also entails the emission of greenhouse gasses, which contributes to fossil fuel emissions.

Hydroelectric power is a mainstay of renewable, low emission power generation, but the potential of this useful technology to help meet renewable portfolio standards and emission targets is threatened by drought. As climates change, drought is likely to become a more common and severe environmental disaster in much of the hydro-reliant western half of the United States. Future

plans for reducing the carbon footprint of our grid or increasing the proportion of generation from renewable sources should recognize the diminished generating role that hydropower will be able to play in the presence of drought. Other technologies such as energy storage may need to be developed and used to ensure grid reliability with high penetration of variable generating technologies. Drought may have the effect of returning hydroelectric dams to an era in which their water control capabilities are far more important and useful than their generating capacities.

Climate change is likely to impact a wide variety of sectors as all industries require inputs that ultimately come from the environment. As the availability of inputs change, so too can the dynamics of the markets that employ these inputs. The water-energy nexus provides fertile ground for the study of such sectoral interactions with a changing environment as data on water conditions and energy markets is plentiful and accurate in a developed setting. Further research on the reaction of power markets to environmental disasters like drought should focus on the behavioral response of firms and customers. While the findings of this chapter point to rising prices and markups as volatility falls with drought, the relative degree to which transmission losses, congestion, and strategic behavior are responsible is still undetermined. A changing climate will influence our operating constraints and how and when they bind, but humans will decide which strategies to employ in meeting our needs for electricity while mitigating the negative externalities of supplying power to the market.

Chapter 2

Lobbying on Nuclear Power

after Fukushima: An Empirical

Study of US Lobbying Activity

2.1 Introduction

Firms compete within and across industry boundaries in a multidimensional strategy space. In addition to prices, costs, product attributes and brand image, firms can employ lobbying as part of their broader competitive strategy. The US energy sector, and the electrical power industry in particular are no exception to this tendency of firms to lobby for beneficial rules and regulations and against those political endeavors that may benefit their rivals. Lobbying itself is multifaceted and may be conducted with a variety of objectives in mind. Richter et al. (2009) asserts, “Lobbyists conduct research on firms’ prob-

lems and all impacted parties including the relevant political constituencies. They then coordinate meetings with the relevant bureaucratic and legislative agencies to argue their case for mutually beneficial changes in enforcement or in legislation”.

This chapter documents the lobbying activity of the U.S. nuclear power industry after the meltdown at the Fukushima Daiichi plant in Japan. It is thus an effort to examine the industry’s lobbying response to disaster. The organization of this chapter is as follows.

Section 2.2 details the disaster and subsequent changes in the regulatory setting. I exploit a plausibly exogenous shock to uncertainty regarding the future costs to U.S. nuclear firms. The uncertainty in costs works primarily through the channel of costs related to safety measures. This fact is conducive to the analysis presented in this chapter for several reasons. The lobbying data employed in the empirical section of this work covers only lobbying at the federal level. Issues of nuclear power safety are handled at the federal level, while questions concerning the economic viability of the industry are left to the states to determine. While the requirement to install additional safety measures on some nuclear plants has the potential to change their economic viability, the costs of the measures recommended by the nuclear regulators are relatively well known. Some of the plants in operation have already installed these measures.

The event study background section also discusses the importance of energy issues and the role of lobbying in the development of energy policy. This

section motivates the choice of the energy sector for event study of lobbying activity. Energy is an important input to all production processes. Even manual labor requires energy from food to be expended by workers. The market for electricity is also central to the cost structures of many industries and fluctuations in electricity prices and production can have major impacts on most sectors of the economy. The central questions of how the lobbying strategies of nuclear power and other energy firms changed in the aftermath of the Fukushima disaster are discussed in section two.

Section 2.3 covers related literature on lobbying, investment, and the nuclear industry. This collection of literature is rather eclectic. First, I discuss a sample of the numerous studies on lobbying that have been conducted. Many of these studies ask questions that have been of interest for decades if not centuries. Advances in data collection have opened the door for more nuanced, organization level studies of lobbying phenomena.

Section 2.4 describes the novel data that I use in my analysis and outlines the basic empirical strategy employed. Cleaning the messy and information-rich data on lobbying from the Senate Office of Public Records required the use of fuzzy matching algorithms. Spelling variations and duplicate responses are accounted for using the open source software known as Google Refine.¹ More details regarding the specific cleaning algorithms used in this research are contained in Appendix L.

Results are analyzed in Section 2.5. In the quarter immediately following

¹Support for this program has changed significantly since the original research was conducted.

the Fukushima meltdown, the energy sector as a whole does not seem to respond in terms of changing its expenditure levels. However, disaggregating the sector into seven constituent industries allows us to see that the nuclear industry does change its activity along at least two key dimensions, and possibly a third. First, the nuclear industry responds to the disaster by increasing its expenditure levels by between 14.8 and 19.2 percent relative to the rest of the economy. Relative to the wildlife industry (a reference category within the energy and natural resource sector) firms in the nuclear industry increased lobbying expenditures by 12.9 to 16.5 percent.

The number of issues actively lobbied declines amongst actors in the nuclear industry. Relative to the non-energy sectors the number of issues lobbied by the nuclear industry falls to around 73 percent the pre-disaster level. There is some evidence to suggest the nuclear industry increased the number of government agencies contacted relative to the rest of the economy after the disaster. This finding, however, is small and not robust to changes in the sample from which it is estimated.

Section 2.6 concludes and discusses possible directions for future research. The empirical exercises suggest that the nuclear industry abandoned some fringe issues after the disaster and focused on core concerns with its lobbying effort. Expenditures increased while the number of lobbyists hired and agencies contacted appear not to change when compared with other sectors of the economy.

2.2 Event Study Background

On March 11, 2011 an earthquake off the northeast coast of Japan triggered a tsunami that had devastating effects on the island nation's population and economy. What followed had profound impacts upon every-day life across Japan as whole communities were displaced, entire villages were devoured by the seismically-induced wave, and a confluence of worst case scenarios cultivated one of the worst nuclear power disasters ever seen in the OECD.

The Fukushima Daiichi Nuclear Disaster became a focal point around which concerned citizens, policy makers, and industry gathered. Regulators of the U.S. nuclear power industry were quick to react to the disaster in Japan. On March 29th 2011, the NRC's Executive Director for Operations, R. William Borchardt, stated in congressional testimony that,

[N]otwithstanding the very high level of support being provided to respond to events in Japan, we continue to maintain our focus on our domestic responsibilities. Borchardt (2011)

Nuclear accidents concern the international community since radioactive material released into the environment on one side of the globe can be cause for concern to people living half the world away. Regulators have an interest in learning from disasters in other parts of the world in order to prevent similar occurrences locally.

Regulators are well aware that the nuclear power industry is not the sole other stakeholder concerned with issues of electricity generation and safety.

Revenue from retail sales of electricity to U.S. customers was just above \$388 billion in 2015. The largest customer by sales was the residential sector (\$177 billion), while commercial (\$143 billion) and industrial (\$66 billion) activities also require large sums of the commodity.² Whenever sizable amounts of money are at play, so too are lobbyists in Washington. Public and private sectors are each vested in the issues of energy. Testifying about his organization, Borchardt reminds the observer of the breadth of stakeholder interest before outlining the NRC regulatory response to the Fukushima disaster,

[W]e have an extensive range of stakeholders with whom we have ongoing interaction, including the White House, Congressional staff, our state regulatory counterparts, a number of other federal agencies, and international regulatory bodies around the world... The Chairman, with the full support of the Commission, directed the NRC staff to establish a senior level agency task force to conduct a methodical and systematic review of our processes and regulations to determine whether the agency should make additional improvements to our regulatory system and make recommendations to the Commission for its policy direction... The task force will evaluate all technical and policy issues related to the event to identify additional potential research, generic issues, changes to the reactor oversight process, rulemakings, and adjustments to the regulatory framework that should be pursued by the NRC. Borchardt (2011)

The task force ultimately made twelve recommendations in Miller et al. (2011), including: “requiring reliable hardened vent designs in [Boiling Water Reactor] facilities with Mark I and Mark II containments” and requiring “licensees to reevaluate and upgrade as necessary the design-basis seismic and flooding protection of SSCs for each operating reactor”.³ These recommen-

²Retail sales data comes from the Electric Power Monthly published by the U.S. Energy Information Administration

³SSC abbreviates structures, systems, and components. Miller et al. (2011).

dations entail significant cost increases for operators of BWR nuclear plants. Lobbying expenditures by firms in the nuclear power industry increased in the aftermath of the meltdown at Fukushima. Producers of electricity that employ nuclear reactors reasonably feared an increase in regulation that could put a dampening force on the returns to their plants, both current and future.

Why should one care about lobbying of the Federal Government on behalf of nuclear and other power producers? Simply put, lobbying costs must be covered by revenues accruing to a firm from one source or another. A central source of revenue in the electricity generation industry comes from the electricity rates charged to industry and residential consumers. The energy industry is one in which natural monopolies often arise, limiting the ability of customers to switch to the product of competitors. While every industry lobbies the government for advantageous (or at least against disadvantageous) policies, consumers of electricity have very little ability to restrict their consumption to electricity generated by organizations that pursue agreeable business and lobbying strategies. The high costs of nuclear mishaps create an incentive for the firms operating nuclear power plants to pursue strategies that allow them to share costs over as many people as possible.

That a utility would use some of its revenue stream to communicate with regulators and legislators concerning the challenges facing its industry is nothing new or inherently malevolent. In fact, the flow of information through lobbying channels may reveal important insights on the state of the world to policy makers. This is perhaps especially important for technologically com-

plex sectors like energy, where an uninitiated observer does not necessarily know where to begin. However, the state (and society more generally) does have an interest in preventing utilities from translating their market power into undue political power.

Hypothetically speaking, an established technology in the electricity-generating industry could use its lobbying clout to prevent the internalization some marginal environmental costs. Such an effort could hinder the emergence of other generation technologies due to the false cost advantages enjoyed by the incumbent. If nuclear power requires the implementation of extra risk mitigating technologies to be conducted safely, these additional outlays should put upward pressure on the prices of electricity in the future (if not presently). Such an occurrence would weaken the competitive position of the industry vis-à-vis other industries in the electric utility sector.

Disasters such as the one at Fukushima Daiichi become focal points for policy reform and public opinion. Historical trends in electricity generation safety might suggest the relative safety of the industry, but people form views immediately upon encountering pictures and footage of faltering nuclear plants. Perhaps no other generating technology conjures up such vivid mental images of disaster as does nuclear power. The general populace often conflates nuclear power with nuclear weapons in terms of the prospective risks. Understandably, public opinion of nuclear power changed rapidly around the globe in the wake of the Fukushima disaster. The shifting macro-political environment in which the nuclear power industry found itself became the playing field for a massive

increase in lobbying by proponents and opponents of the technology. At the same time, we must be careful not to assign any and all occurrences that arrive in the wake of a disaster as being an effect of said disaster. While no nuclear power plants were built in the U.S. after Three Mile Island, this trend owes more to the vast cost overruns and high interest rates the industry experienced in the lead up to the event than the event itself.

2.3 Literature Review

2.3.1 Lobbying

It is instructive to think about lobbying as an investment undertaken by an organization. There are several ways in which lobbying is analogous to other enterprise investments. Firms often improve their ability to track information that is pertinent to the competent and savvy execution of strategic plans. Arrow (1974) discusses the subject of organizations and information gathering, noting that a “key characteristic of information costs is that they are in part capital costs; more specifically, they typically represent an irreversible investment”.

Lobbying is an information channel spanning the government and private sectors. At any given point in time, there will be asymmetries in the information that each group has on the future of the other’s actions. Lobbying is a way through which interested and affected parties can learn about the effects of future regulation or an emergent disruptive technology.

Grossman and Helpman (2001) develop a series of models of lobbying where interest groups and policy makers exchange signals regarding their view of the state of the world. Policy makers must determine whether signals are truthful and what weights to attach to different informational channels. Other political activities within the strategy set of special interests are voter mobilization and contributions to political campaigns. Discussion of the role of various interest groups in the United States goes back at least until the time of the Federalist Papers.⁴

Congressional hearings send relatively convincing signals to interest groups that convey an issue's readiness for political action. Furthermore, presidential involvement on an issue is another key indicator that legislative changes are in store within the near future. Baumgartner et al. (2009) finds evidence that congressional hearings and presidential involvement in policy formation provide a stronger determinant of changes in lobbying demand than do government expenditures. While discussing several possible motives for interest group mobilization, the authors argue that not only do such groups have to overcome a collective action problem in order to form, they must carefully decide the appropriate time to lobby the government as well. The government is likely more eager to get interest group input on nuclear power safety in the wake of a disaster like Fukushima than it would under normal conditions.

Clearly, interest groups would prefer to expend resources on bills they are

⁴James Madison wrote in 1787 that, "The regulation of these various and interfering interests forms the principal task of modern Legislation, and involves the spirit of party and faction in the necessary and ordinary operations of Government".

likely to have a relatively high probability of influencing. Furthermore, political activity is more enticing for the firm when the political climate is favorable. Drawing on an analogous example from the financial sector, Representative Frank discussed the issue of timing and the banking lobby's power.

The greatest power doesn't come from the most money... now as the political climate has shifted to other issues, that's when [banking lobbyists] thrive. They thrive when there is no attention on them.

The more people talk about Benghazi, or immigration or anything else the better they can do. Dodd et al. (2013)

Thinking about this relationship in terms of how it would apply to the case of the Fukushima meltdown leads to some intuitive results. In the immediate wake of the disaster, government regulators such as the NRC want answers from industry regarding the nature of the event. If significant flaws are found in the previous regulatory environment, the NRC likely finds itself in a political climate that is favorable to change. At the same time, the nuclear industry is in a weak position regarding public opinion of their enterprise. Along these lines of reasoning, increases in lobbying expenditures in the aftermath of a crisis are more plausibly attributable to damage control or compensating a negative shock to lobbyist productivity than an increased effort to push for improved policy (for the firm). This would mean that the marginal productivity of a lobbyist is declining in the level of scrutiny applied to his or her client.

An alternative framework through which to view the lobbying response is similar to the trapped factors model of innovation advanced by Bloom et al.

(2013). In this model, a shock reduces the expected return on a firm's product, possibly through increased cost. Some of the firm's resources are trapped. That is, firm specific human capital pertaining to its business model, brand capital, or proprietary production techniques cannot be transferred to other firms in a frictionless manner. Lobbying resources certainly fit this description. As the opportunity cost of these inputs to lobbying production decreases with the shock, firms are more willing to employ these inputs in new, innovative lobbying strategies.

Damania (2001) investigates the notion that firms employing older technology are often rather adept at securing relatively weak regulatory constraints on their operations. As an extension of Grossman and Helpman (1992) framework, Damania (2001) incorporates investment in technology as a credible commitment device. Firms are modeled as producing a good that pollutes. A pollution abatement technology is chosen with technologies that have the lowest cost of abatement also having the highest fixed cost up front. By underinvesting in abatement technology, firms ensure that any rise in the government tax on emissions will hurt firms' profitability to a greater degree. Given that firms make political contributions out of their profits, the government will tax emissions to a less than socially optimal level if policy makers value such contributions. Within the firm's profit function, investment in pollution abatement technology and lobbying expenditures aimed at resisting higher emissions taxes are strategic substitutes.

The effect of lobbying on the probability that a specific policy is enacted is

small according to an analysis of U.S. energy policies Kang (2015). However, the payoff from successful lobbying by the energy sector is so great that the average returns on lobbying expenditures are around 130 percent. This estimate lends extra weight to the notion that energy firms see opportunities in the establishment of informational channels with Washington.

The best lobbyists have core competencies in the collection, analysis and conveyance of information. These skills are scarce, and their employment in the service of lobbying can improve the information of specific officials. In this sense, lobbying can be thought of as a subsidy to Legislators. Hall and Deardorff (2006) argues that firm lobbying relaxes the budget constraint of natural congressional allies through the contribution of additional labor, information, and strategic thinking.⁵ In this framework, lobbying will distort congressional attention in favor of the best-funded constituents if the lobbying is modeled as an issue-specific grant of information.

The presence of significant fixed costs to political organization has broad support within the literature on lobbying and campaign contributions.⁶ Kerr et al. (2011) finds evidence supporting the presence of fixed costs to organization and a high degree of persistence in whether or not a firm lobbies. Furthermore, firm size is positively related with deciding to lobby and relatively

⁵Hall and Deardorff (2006) open their investigation into lobbying as a subsidy with one of the best assessments of the literature, asserting, “Empirical research on interest group influence has accumulated for decades, but this literature is noteworthy for the noncumulative, frequently inconsistent nature of its findings”.

⁶Firm size heterogeneity can be used to model why some industries exhibit higher degrees of political activity than others Bombardini (2008). The concentration and competitiveness of an industry also has implications for the mode of lobbying activity, with more competitive industries tending to lobby in a relatively cohesive manner Bombardini and Trebbi (2012).

few firms actually decide to become politically active. The intensive margin of lobbying also exhibits a positive relationship with firm size. Intuitively, larger firms possess more resources to apply to the tasks of identifying natural congressional allies, learning lobbying laws, and studying the strategic moves of allied and opposing interest groups or firms. For a discussion of how lobbying relates to other forms of communication between government and industry, Mayda et al. (2010) establishes that solicited feedback from firms appears to have a greater impact than lobbying expenditures on the probability of a tariff suspension being enacted.

2.3.2 Investments and Uncertainty

As discussed briefly in the introduction, lobbying can be reasonably modeled using the framework of investment under uncertainty. Pindyck (1993) finds that uncertainty arising from technical issues or fluctuating input costs change the optimal investment rules for firms. Technical uncertainty is the uncertainty that firms face when they do not know how much investment is necessary to achieve progress on a specific project. Imagine for instance that an electricity producer wishes to expand capacity through the construction of a new type of nuclear reactor. Given that design and construction firms are treading in untested territory, the exact costs of engineering and building a new piece of technology will not be perfectly foreseeable. In fact, it is only through the process of investing in developing the new plant that such technical uncertainty can be overcome.

Even when the technical details of a project are well understood, uncertainty can arise as the costs and availability of key inputs to production fluctuate with time and geography. Furthermore, “unpredictable changes in government regulations can change the required quantities of one or more inputs” Pindyck (1993). A plant that formerly required the installation of one battery of sensors, might find itself being forced by government regulations to install a secondary monitoring unit to promote defense-in-depth strategies. In effect, we can model the rise in costs from having to buy two components as opposed to one in the same manner as a doubling of the price of said input.

Pindyck’s model allows the expected cost of completing a project (such as a nuclear plant) to evolve over time with the remaining cost that must be paid for a project to reach fruition defined to follow a controlled diffusion process. The functional form of depends on the presence of each type of uncertainty discussed above. The value of the opportunity to invest in the project evolves with the remaining costs. The firm will decide whether to invest at the maximum rate or not invest at all.

Pindyck evaluates situations of pure technical and input cost uncertainty separately before allowing their coexistence in the model. The irreversible nature of these investments is a central feature of the model. In the case of pure technical uncertainty, the value of the investment opportunity and the upper bound on cost for which initiating investment is profitable are increasing in uncertainty. That is, if input costs and government regulation were static,

more investment should follow in the face of greater technical uncertainty.⁷ Intuitively, there is a value to investment in that it uncovers the true costs of a project. For projects that rely intensively on cutting edge research and development efforts, investment is an opportunity for learning and improving production processes.

Increasing uncertainty depresses investment in the pure input cost case. In this case, as the input cost uncertainty rises, “a correct net present value rule would require the payoff from the investment to be about twice as large as the expected cost before the investment is undertaken” Pindyck (1993).

If we view lobbying as a type of investment, the evolution of costs as a function of lobbying activity should exhibit qualities of technical and input cost uncertainty. Input costs are subject to change as a result of the political process, with or without a positive amount of lobbying on behalf of the electric utility. However, through investment in the political process (lobbying expenditure) a firm may (hope to) impact future costs. Even if the lobbying activity conducted by the utility does not sway policy formation, it may provide an information-gathering channel through which the firm could resolve uncertainty. Being close to the policy formation process allows the firm to understand the direction of legislation and regulatory activity earlier and in greater detail than would be possible without political engagement. Irreversibility of lobbying as an investment is also sensible. Most money invested

⁷Given the international competition for the scarce resources that are inputs for power plant construction, the assumption of static input costs is questionable. Lobbying skills are also scarce leaving their wage rates prone to fluctuations in demand.

in communicating with the government cannot be liquefied as other typical assets owned by a firm. Once spent, that money is no longer recoverable.

Bloom et al. (2007) develops a model of partially irreversible investment in the presence of uncertainty. Firms operate multiple production units according to a supermodular revenue function that is derived from a Cobb-Douglas production function. Two types of capital are employed with labor to produce. Demand conditions are represented by a single index so that the revenue function can be homogeneous of degree one in the normalized demand condition index and the two capital stocks. A firm-specific and plant-specific element of demand conditions both evolve with the passing of time as augmented geometric random walks with stochastic volatility. Uncertainty is modeled using these random walks.

Adjustment costs are incorporated into the model in two forms. The first form of adjustment costs is that of fixed disruption costs. Such fixed costs do not depend on the size of the adjustment and are readily applicable to up-rates in the electrical utility industry.⁸ In order for new capital stock to be brought online, a plant must be shutdown for some amount of time. This shutdown period is time in which production and therefore sales are not occurring. Nuclear power plants could prove especially prone to such costs as it takes considerable time to mitigate the heat generated by the core's chain reaction. Downtime is money lost for firms operating nuclear reactors. A firm anticipating the introduction of new safety requirements may find that expending resources to

⁸Up-rates is a term for the incorporation of newer technology or greater capacity into an existing electricity generation plant.

lobby against such proposals is less costly in expectation than agreeing to the new terms. Using simulated data, Bloom and coauthors find that uncertainty in the presence of only fixed adjustment costs has a positive effect on the investment response to demand shocks. Plants that do invest, invest more in the face of uncertainty. This effect dominates the effect of uncertainty that leads to fewer of a firm's individual plants investing.

The second type of adjustment cost is quadratic in nature, allowing for the response to be convex with respect to the level of investment. Larger changes to the capital stock incur larger costs of adjustment. Bringing on a new reactor core incurs higher costs than simply installing a new piece of monitoring equipment. With respect to the simulation, the game is changed when the included adjustment costs take the quadratic form. Now greater uncertainty has a chilling effect on the investment response to demand shocks. The long-run capital stock is eroded in a statistically significant manner by the presence of uncertainty in this specification.

The model in Bloom et al. (2007) is applied to an unbalanced panel of 672 firms over 20 years. The authors find no significant evidence of the long-run effect obtained in the simulation with quadratic adjustment costs. However, they conclude that, "the only effect of uncertainty on company investment behavior that we can detect with a high degree of statistical confidence is the interaction with the impact effect of current real sales growth" (Bloom et al. page 408). Given two otherwise identical firms, the investment response to a demand shock of the firm at the 25th percentile of uncertainty will be twice

that of the firm at the 75th percentile. One implication of this finding is that in times of heightened uncertainty, such as during the oil crisis of the 1970's or after September 11th, 2001, firms will be less responsive to policy-induced shocks. Fukushima provides yet another opportunity for a case study of these theorized effects.

Stein and Stone (2013) develop a novel instrumental variables approach to identify the effects of uncertainty on investment decisions. The volatility of a firm's stock price as implied by stock options is the proxy employed for firm level uncertainty. Examining almost 4000 firms for ten years, uncertainty is established to have a negative and significant effect on capital investment and a positive and significant effect on research and development. Technical uncertainty is a key factor in research and development investment.

Baker and Bloom (2013) grapples with endogenous uncertainty in their study of its effects on growth. Uncertainty exhibits strong counter cyclical tendencies. Natural disasters, terrorist attacks and political shocks such as coups are plausibly exogenous shocks. The unanticipated nature of shocks is measured by comparing the incidence of related words in newspapers before and after the event. The frequency of the word "Japan" in the newspaper sample gathered by Baker and Bloom increased 322 percent between the five days preceding and following the Fukushima disaster.⁹us

⁹The methodology used to gauge media coverage of an event focus on the U.S. national print media. The jump in U.S. media coverage of Japan after the nuclear disaster is consistent with the view that meltdown can be viewed as an exogenous shock to U.S. regulatory uncertainty.

2.3.3 The Centrality of Energy

The implications of energy policy are wide ranging in nature. Energy is a central component to the production processes of firms in all industries. For heavy industrial processes, energy is as necessary a factor of production as capital or labor. The production of aluminum for instance requires large sums of electricity to smelt ore into aluminum that can be used as an input in numerous manufacturing applications. Aluminum provides an illustrative if not representative example of the centrality of energy to economic activity.

Shocks to energy prices, especially electricity prices, can have massive implications for industries that use the input intensively. Choate and Green (2003) reports a steep increase in the cost to firms of electricity in the summer of 2001 had the effect of closing down primary (non-recycled) aluminum producers in the Pacific Northwest. Heat waves on the East Coast coupled with low hydroelectric output in the Northwest led demand to increase relative to supply, pushing up prices. As many aluminum producers have long-term low-cost electricity contracts, some of these firms found it profitable to forego use of contractually cheap electricity in production and instead opted to sell the input back into the electricity market at the high rates. The summer spike in prices shuttered 43 percent of production in the aluminum industry. When one considers how many other industries employ aluminum as an input, the potential reach of energy policy becomes clarion.

While the economic viability of aluminum production is plainly tied to the energy sector, even industries that use energy in a much less intensive manner

can be affected. Typical retailers of consumer goods use electricity to run lights, operate heating and cooling systems, and power sales terminals. With the exception of the interior climate control systems, these other sources of electricity demand are not massive. However, while the total draw on the electrical grid may be relatively small for retailers, electrical devices occupy a crucial position within such firms' ability to do business. Processing payment cards without electricity is not feasible. Increasing use of cloud based services located on distant servers means that local economic activity may have impacts on energy use in far off locations.

2.3.4 Nuclear Power

In a recent analysis of the nuclear power industry, Davis (2011) details the central economic determinants of the technology's viability. At different times in the last half-century nuclear power plants have enjoyed periods of unremitting optimism and suffered seemingly overwhelming obstacles to continued construction and operation. The two biggest factors to consider when deciding whether to build a power plant that employs a nuclear reactor or other electricity generation technology are the cost of capital and the cost of alternative fuel sources. The construction of nuclear plants is an inherently complicated endeavor. Highly technical in design and requiring a great degree of redundancy in safety mechanisms, nuclear plants usually take longer to build than either coal or natural gas generation plants. This redundancy often goes by the name of defense-in-depth "in which consecutive and independent levels of protection

would all have to fail before harmful effects could be caused to people or to the environment” Cameron and Gordelier (2010).

Furthermore, the potential for catastrophic nuclear disaster occupies the concerns of the public and regulators in a way that is simply not present in alternate technologies. Consequentially, long delays to construction resulting from an involved permitting process stretches out construction time, pushing up the cost of capital necessary to complete such a project. These delays are not entirely without merit. While all electricity producing activities result in casualties, the structure of risks associated with nuclear power lead to relatively high political costs.¹⁰

The expected value of casualties associated with each technology can be compared to determine which option minimizes risk of death or other ill consequences.¹¹ However, two technologies with the same expected value of casualties might face very different political costs in mobilizing public support. Nuclear power results in very few deaths as a result of standard operation. However, the minuscule probability of catastrophic failure of a nuclear plant is often insufficient to quell public anxiety regarding the widespread effects of such an event. Were a radioactive plume to be released into the atmosphere, wind currents and other environmental factors would determine the spread of effects. The potentially large subset of the voting public that could be affected

¹⁰Cameron and Gordelier (2010) argues that the latent fatalities attributed to the nuclear energy chain are likely dwarfed by the ill effects of particulate matter coming from electricity generated with fossil fuel.

¹¹Estimates of deaths from various generation technologies vary with time and between studies. Nuclear power looked safer on paper before March 11th 2011 than it did afterwards. An estimate from the late 70's placed the number of deaths associated with one standard plant-year of electricity generation at 3.3—107 for coal and 0.17—1 for nuclear Peirce (1996).

by such an event complicates the politics of expanding nuclear power.¹²

Almost all traditional power generation technologies consist of a means for boiling water and employing the attendant steam to move a turbine. The electrical company cares mainly about the respective costs of each fuel type and the systems necessary to convert fuel into steam. Revenue from the power plants production is determined largely by the price on the wholesale electricity market. Generally speaking there is little room for differentiating a plant's product in the eyes of the end consumer.¹³ Most people do not think deeply about the source of the electricity whenever they flip a light switch. Beyond knowing the general composition of a local utility's energy portfolio, it is difficult to determine the origin of the electrons illuminating your lights at any given time. At off-peak times, it is probable that the electricity is coming from the lowest marginal cost options such as nuclear.

The specific cost structure of nuclear makes it both intriguing and risky for firms that wish to expand capacity. Nuclear plants often have the highest up front capital costs of any generation technology and are thus susceptible to changes in financing rates.¹⁴ The median levelized cost estimates of nuclear plants in Europe rise around \$40 per Megawatt hour (\$0.04 per kWh) when the discount rate doubles to ten percent from five. However, once the facilities are

¹² Using 2010 Census data, Dedman (2011) reports that 116 million people in the United States live within a 50-mile radius of a nuclear plant. U.S. officials encouraged evacuation of Americans living within this radius of the Fukushima plant after the disaster.

¹³One counter example is the Eugene Water and Electric Board, which offers its customers the option to pay one cent per kilowatt hour in excess of typical rates to use "greenpower". The additional revenue from this source is used to expand generation from renewable sources and fund grants to non-profits EWEB (2013).

¹⁴The International Energy Agency estimates that investment costs account for 60 or 75 percent of total levelized generation costs under scenarios with five and ten percent discount rates Sicilia and Keppler (2010).

built, the variable costs of operation are relatively small compared to natural gas and far less prone to price fluctuations.

Security of supply concerns that are associated with the sourcing of fossil fuels from conflict-ridden regions of the globe are largely avoided by the nuclear industry at present. Canada, Australia, and the United States are all major producers of uranium.¹⁵ Nuclear power generation as well as the extraction and refining of nuclear fuel are highly geographically concentrated and often vertically integrated. National security concerns around anti-proliferation have reinforced these trends. Government regulation of the nuclear industry has also largely dictated its structure.

Regulation of the nuclear power industry has been the subject of intense debate in the courts.¹⁶ The regulation of radiation hazards falls under the purview of the Nuclear Regulatory Commission (NRC).¹⁷ A complex dual regulatory framework means that firms operating nuclear reactors face uncertainty regarding the future actions of a multitude of actors. The NRC maintains on-site inspectors at the nuclear reactors currently producing electricity in the United States.

¹⁵For a summary of the geographic concentration of the Nuclear energy chain see Garcier (2009).

¹⁶Pacific Gas and Electric sued the State Energy Resources Conservation and Development Commission of California, alleging that the State's ability to regulate the nuclear industry was pre-empted by the 1954 Atomic Energy Act. The Supreme Court held that "the Federal Government maintains complete control of the safety and 'nuclear' aspects of energy generation, whereas the States exercise their traditional authority over economic questions such as the need for additional generating capacity, the type of generating facilities to be licensed, land use, and ratemaking" *Pacific Gas & Elec. Co. v. State Energy Resources Conservation and Development Comm'n* (1983).

¹⁷The NRC's predecessor was the U.S. Atomic Energy Commission, an organization tasked with the conflicting interests of promotion and regulation of activities involving radioactive materials.

2.4 Data Description

2.4.1 Lobbying Data

The data employed in this research project comes from the Senate Office of Public Records. The 1995 Lobbying Disclosure Act and the subsequent 2007 Honest Leadership and Open Governance Act require the Secretary of the Senate to make available the disclosure filings of all organizations that spend above the *de minimis* levels. Firms conducting lobbying activities are referred to as registrants. Registrants that earn less than \$3,000 from a given client in a quarter are not required to file a disclosure of their efforts for that client. As the total lobbying expenditure in 2012 was \$3.3 billion, amounts under the threshold cannot reasonably be seen to have an economically significant impact on the outcome of policy. Testifying before congress does not require filing a disclosure. However, repeated contact between an agent of an organization and a covered member of congress or the executive branch for the purpose of informing policy does initiate the filing requirement.¹⁸

Organizations that pay lobbyists or conduct advocacy on their own are referred to as clients in the filings. The presence of client names and states of operation make it possible to identify the industry and regions represented by lobbyists.¹⁹

Lobbying activity can be measured in many ways. Each metric offers a

¹⁸Covered in this sense indicates that an individual is covered by the disclosure laws.

¹⁹The Center for Responsive Politics (CRP) has created its own categorization system for clients based originally on the 1988 SIC code system. The “catcodes” created by the CRP are used to identify the industry in which an organization operates.

different perspective on the extent and intent of these efforts. The scope of lobbying is indicated in the data through the identity and number of government entities contacted by the filer. With this element of the picture, we can address the breadth of a firm or organization's efforts to interface with the policy formation process. More nuanced approaches can identify specific government entities that are targeted for contact. The House of Representatives and the Senate are the two most commonly disclosed contacts.²⁰

Total lobbying expenditures and the identity of lobbyists hired to contact the government are also observable. Clearly, larger levels of expenditure should correspond with greater efforts to inform policy. Firms with larger cadres of lobbyists should be thought to possess a larger capacity to produce lobbying product than a firm employing only one or two people. Even among organizations with a similar number of lobbyists under their employ, quality can differ. Some individual lobbyists, are simply more prolific in the disclosure records. A precise conception of what it means to be more frequently encountered is elusive. On one hand, more frequent listings seems to be indicative of higher productivity. Perhaps some lobbyists are really that much more effective and thus capable of taking on larger work loads than their peers. A competing (but not mutually exclusive) hypothesis is that these individuals play a supervisory role to other lobbyists making them present on many cases without necessarily accounting for the majority share of the labor hours for any given client.²¹ In

²⁰According to the Center for Responsive Politics' count, contact with the Senate was disclosed in 551,181 reports while the number for the House is at 550,737 during the period of 1998 to the first quarter of 2013 (Center for Responsive Politics 2013).

²¹Upon examination of the most commonly encountered lobbyist names in the data, it is not uncommon for these individuals to own or operate eponymous registrants.

any event, these individuals are constrained by time and thus there will be some negative relationship between the number of clients represented and the lobbyists' product per client.

The issues on which the lobbying efforts have been directed are enumerated on separate pages in the filings. The dispersion of these lobbying resources over the set of 76 general issue areas can be viewed to assess the concentration of a firm's efforts. Client firms that lobby on a wide array of issues are often large and utilize sizable budgets. Some small lobbies exist only to address a single topic of interest. Analogous to the situation of the time-constrained lobbyist, a budget constraint on lobbying efforts would imply that the depth of lobbying on a given issue is inversely proportional to the number of issues addressed. Such a relationship ignores the real possibility for complementarities from lobbying on related issues. Many firms are wagering profits on the strategic inclusion of both their industry-specific issue and the issue of taxes. Shifts in the size and composition of a firm's issue portfolio over time can signal changes in lobbying strategies. In any given year, an organization may judge it prudent to either double down on core issues, divesting it of fringe issues, or diversify its portfolio through expanded political endeavors.

For the purpose of the analysis that follows, firms are grouped into industries and sectors according to the classification scheme established by the Center for Responsive Politics (CRP). The set of lobbying organizations are divided into broad sectors, of which, energy and natural resources will be the focus. I will generally refer to this sector simply as energy, while still speaking

inclusively of natural resources and wildlife. Within the energy sector, I have assigned all organizations to one of seven groups. Organizations involved in the construction and operation of nuclear plants are grouped into the nuclear industry. The remaining industry groups are oil and gas, alternative energy, electricity generation, natural resources and extraction, waste and wildlife. The assignment of specific firms is subject to several possible schemes. The exploration and extraction of natural gas and oil utilize much of the same technology and skilled labor. Furthermore the resources are often colocated. Classification of the electricity generation group is made more complex by the fact that some firms straddle the line that demarcates them from oil and gas. Regardless of the exact assignment of other industries, the nuclear industry firms are well defined by the classification.

All lobbying filings for the years 2009 to 2012 are included in the sample.²² These filings are then collapsed at the firm-quarter level so as to create an unbalanced panel of organization-level lobbying activity. The panel is balanced for some of the analysis as well.

There is a life cycle of sorts for the paper trail that comes with lobbying. First, organizations that wish to lobby must file a registration detailing their firm, the registrant, and the identities of individual lobbyists working for them. Next, a report is filed for every quarter that the expenditure threshold is crossed. These reports describe the general and specific issues being lobbied as well as the identities of government agencies contacted. Once an organization

²²The fourth quarter of 2012 is omitted from the following analysis as not all filings for the period were recorded at the time the data was pulled from SOPR.

no longer wishes to lobby, a termination is filed. Inaccurate filings may be amended in separate filings. Firms that retain lobbyists (that is, firms that do not terminate their representation in Washington), but do not actively lobby in a given quarter, may file a “no activity” report for which I observe a report with an expenditure of zero. In the data, such reports are distinct from an absence of filings in a period. About a third of the filings in sample report zero expenditures.

Both sources of zeros present empirical issues when trying to estimate the change in lobbying activity after the Fukushima disaster. Silva et al. (2006) examines the viability of OLS and other estimators for application to the gravity model of trade. No trade between two countries such as Lesotho and Afghanistan is recorded as a zero for bilateral exports. Similarly, there is not necessarily any lobbying contact between all lobbying client and government agency pairs. It is not very surprising that the “I Have A Dream” Foundation did not lobby the Federal Emergency Management Agency in 2008. Furthermore, organizations that lobby regularly occasionally sit out a quarter for one reason or another.

Log-linearization does not work in the presence of zero values for the dependent variable. Furthermore, heteroskedasticity leads to inconsistent estimates when the model is transformed in a nonlinear fashion. Following Silva et al. (2006), I employ a variation of the Poisson pseudo maximum likelihood estimator to achieve consistent estimates of the change in lobbying after Fukushima.

The core dependent variables of interest in my analysis of the lobbying

response to the Fukushima meltdown are all pulled from the original filings. The primary dependent variable is the sum of the expenditures disclosed for a given client and quarter. Constructing this variable involves aggregating the lobbying efforts of firms across the registrants that they employ. The minimum for this variable is of course zero and the maximum observed is \$100 million. The mean total filing amount per organization-quarter is \$32,375. When the sample is restricted to strictly positive expenditures, the average rises to around \$81,000 per organization-quarter.

The next three variables of interest get at the scope and scale of lobbying along several important margins. The lobbyist count, is a variable that takes integer values for the number of people (not registrants) hired to be political agents for a firm or trade association. The government entity count numbers the federal agencies and chambers of congress contacted on the client's behalf. Issue count is the number of distinct issue areas on which a client lobbies. The first count variable is a measure of scale while the later two relay more information about the scope of the lobbying effort. High values for the scope count variables may indicate a more complex lobbying effort, but they also suggest a greater level of dispersion. On the other hand, organizations that lobby on fewer issues or talk to a more select group of government agencies might evince a higher degree of focus or importance for their efforts. Another possibility is that simpler lobbying strategies are matched to simpler policy efforts. Summary statistics for the 2009-2012 sample are listed in Table 2.1.

Table 2.1 exhibits several measures of the distribution of values taken by

Table 2.1: Summary of Filing Count Data

Group	Obs	Sum of Client Filing Amounts (\$)			# of Lobbyists Hired		
		Average	Total	Max	Average	Total	Max
All Sectors	396,859	32,375	12,848,480,774	100,000,000	1.502	596,247	99
Non-Energy Sectors	389,810	32,168	12,539,591,291	100,000,000	1.493	581,827	99
Energy Sectors	7,049	43,820	308,887,039	4,660,000	2.046	14,420	76
Alternatives	1,237	22,573	27,922,727	668,948	1.765	2,183	23
Electricity	1,456	72,302	105,272,396	4,660,000	2.159	3,144	76
Nuclear	154	108,982	16,783,197	1,000,000	4.838	745	34
Oil and Gas	1,161	78,698	91,367,960	2,920,000	2.842	3,299	62
Resources	993	21,891	21,738,150	890,000	1.415	1,405	22
Waste	330	36,270	11,969,054	770,000	2.070	683	21
Wildlife	1,718	19,694	33,833,588	480,000	1.724	2,961	14
Group	Obs	# of Agencies Contacted			# of Issues Lobbied		
		Average	Total	Max	Average	Total	Max
All Sectors	396,859	1.778	705,484	77	1.241	492,606	69
Non-Energy Sectors	389,810	1.765	688,186	77	1.233	480,493	69
Energy Sectors	7,049	2.454	17,298	51	1.718	12,113	57
Alternatives	1,237	1.861	2,302	21	1.385	1,713	33
Electricity	1,456	2.280	3,319	51	1.761	2,564	57
Nuclear	154	6.805	1,048	42	4.844	746	25
Oil and Gas	1,161	2.629	3,052	30	1.929	2,239	34
Resources	993	2.066	2,052	29	1.491	1,481	27
Waste	330	2.452	809	21	1.615	533	16
Wildlife	1,718	2.745	4,716	19	1.651	2,837	28

Each variable of interest has a minimum value of zero. The sample from which these summary statistics are drawn is restricted to the clients-quarter pairs in which no amendments were filed.

the four central variables of interest. Given the presence of zeros discussed earlier the minimum values each variable is trivial and therefore withheld from the table. The average sum of filing amounts is greater for firms in the energy sector than it is for the non-energy sector. The energy sector is also relatively more prolific in Washington as it hires more lobbyists per client, talks to more agencies and enters the discussion of more issues than other sectors on a per firm basis. Within the energy sector, much of this higher level of political involvement is driven by the above average activity of the nuclear industry. Even with the zero values in the sample, the average sum of filing amounts for

a firm in the nuclear industry is almost \$109,000 each quarter. The average nuclear industry firm hires roughly 140 percent more lobbyists than the energy sector average. The two measures of lobbyist scope are similarly higher for the nuclear industry than they are for the larger energy sector.

2.4.2 Electricity Firm Data

The plant level industry data on the physical generating infrastructure, used extensively in the earlier analysis of drought, is also employed in the lobbying analysis to link lobbying clients to their productive assets. With this information, it is possible to categorize lobbying clients with respect to the technologies that they employ to produce electrical power.

Table 2.2 summarizes key characteristics of the four main firm types in the data. Firms employing only a single type of generating technology are defined as pure firms. If that technology is nuclear, I will refer to such firms as pure nuclear firms. Firms employing a variety of technologies including nuclear are defined as diversified nuclear firms while their nuclear-free counterparts are simply defined as diversified firms.

The five columns on the right of the table indicate the mean value and standard deviation for each variable. The first and most glaring aspect of the data is that pure nuclear firms do not lobby under their own name. Seventeen of twenty-one pure nuclear firms are members of the Nuclear Energy Institute (NEI), an industry trade association. Eleven of the pure nuclear firms are members of the American Nuclear Society (ANS), which is concerned with

the promotion of nuclear science and technology. Pure nuclear firms have a more specific set of lobbying interests than their diversified rival firms. This encourages the pure nuclear firms to form an effective trade association that can lobby for policies that would benefit all firms in the nuclear industry.

When compared to the other strategic groups diversified nuclear firms tend to own the largest number of plants. Non-nuclear diversified firms appear to constitute the middle of the firm-size distribution, while the smallest firms operate only one type of technology. On average, diversified firms spend about \$1,000 more each filing period than pure firms. The ranking of lobbying effort across strategic groups is consistent for the three primary count variables. Diversified firms are the most active with respect to their employment of lobbyists, the number of issues they lobby and the number of government agencies contacted.

Table 2.2: Lobbying by Firm Competitive Group

Group	Firms	Percent of Filings	Plants	<i>FilAmt_{c,t}</i>	<i>GovtCount_{c,t}</i>	<i>IssCount_{c,t}</i>	<i>LobCount_{c,t}</i>
Pure Nuclear	21	0.0079	1.5714 (1.9530)	\$ 0 (0)	0 (0)	0 (0)	0 (0)
Diversified Nuclear	22	0.0083	22.7727 (17.3416)	\$ 3,159 (10,907)	0.2045 (0.6094)	0.1591 (0.5227)	0.25 (0.8743)
Diversified	325	0.1237	6.0246 (6.2517)	\$ 18,618 (232,134)	0.5454 (2.0051)	0.5254 (2.4962)	0.4715 (1.7455)
Pure	2259	0.8599	1.4478 (2.7039)	\$ 17,544 (308,243)	0.3095 (2.0880)	0.2830 (1.9175)	0.2885 (1.9727)

The five columns on the right of the table indicate the mean value and standard deviation for each variable.

2.5 Empirics

To begin the analysis, I document the trends in lobbying activity that occurred after the Fukushima meltdown on March 11, 2011. Two conceivable frames of

reference present themselves to the investigator. First amongst these is that of the firm or organization's perspective. In this sense, we are looking at the decision of an organization to expend resources in support of pursuing political objectives. An organization-centric approach would look at all the different strategies and channels through which a specific organization or group thereof might work to affect any tangent policies. A policy-centric approach would focus on the collection of strategies and channels through which any actors work to inform or instruct the policy formation process pertaining to an issue of interest. Most of the following analysis is concerned with the former of the two perspectives. The policy-centric approach is left for future research.

In the lobbying reports filed with the Senate Office of Public Records, the organizations conducting the lobbying must produce record of all the activities they conduct, irrespective of the specific issue. In this sense, the data can be readily applied to the first framework just described. The organization, as the unit of analysis, is perhaps of most interest to the individual actors and regulators in the lobbying industry. The American public, however, will face not the effects of any one player in the game of lobbying, but rather the aggregate of their actions manifested in current policy. It is in this sense that the frame of reference through which the public's interest is most central is that of the issue-based approach.

Both of these lenses provide for insights into the effects of post-Fukushima lobbying on legislative uncertainty. As organizations in the nuclear industry (as well as the larger energy sector) ramp up lobbying activities, uncertainty

can change in several distinct ways. Early in the post-disaster period, the eventual product of the legislative and regulatory processes is fairly uncertain. As fact-finding missions (such as the one discussed in the introduction) produce reports and stakeholders express their-own interests, general uncertainty can rise or fall. If regulators find that the preexisting deterrents to further disasters are sufficient, uncertainty regarding the effects of future government activity should decline. On the other hand, a report of systemic problems with a technology choice or regulatory system would probably leave organizations less sure about the future of their industry.

It should be made clear that lobbying is seemingly at times both the cause and effect of uncertainty for organizations. Therefore the functional form of the relationship is of interest on its own. For example, were an environmental interest group (or any other) to push for more stringent environmental impact studies on natural-gas extraction facilities, this would induce uncertainty in the minds of electric utility operators regarding the future price of natural gas. The degree of uncertainty would be determined by the probability of the environmental group's success. Guaranteed success or failure would have less of an effect on uncertainty by definition. Now consider the position of the natural gas firm. Faced with the uncertain prospect of higher costs imposed by outside actors, the natural gas firm has an incentive to counter-lobby. The counter effort allows the energy firm to update its beliefs on future government action and is a channel through which the outcome of the policy debate could ostensibly be altered favorably.

Changes in the levels and variance of lobbying expenditures and actions can help proxy for changes in uncertainty. Given that many lobbyists are simply retained by clients at a near constant pay rate, the variance in expenditure likely holds much more valuable information pertaining to fluctuations in uncertainty. As described in the Pindyck (1993) model, uncertainty can have a positive or negative effect on the optimal investment rules of organizations, depending on the model specification. In other words, payoff uncertainty may induce an organization to continue to pursue a venture that it might not otherwise consider prudent. When the sums at stake are large, and the public is stuck paying the bill for such a gamble, the causes of such misallocation merit analysis.

2.5.1 Results and Analysis

This chapter uses the 2nd quarter reports from 2011 as the group that constitutes lobbying activity in the post-disaster period. This window of time was selected for several reasons. First, the second quarter filing period begins about 20 days after the disaster began. Twenty days is also the time allotted to registrants to finish filing for previous quarters. There is some delay between when an event occurs and when a client could effectively start implementing its lobbying strategy. Second, while the Fukushima meltdown was a major event, congress does not remain focused on a single topic for long. Issues of nuclear energy safety fade from the public's concern over time. Longer post-event periods would likely muddle the response by including filings from periods that

are less affected by the disaster.²³ A third reason supporting the choice of the second quarter of 2011 as the appropriate post-event period is contained in the testimony of William Borchardt discussed earlier. The NRC initiated a 90-day (one quarter) review of the regulatory environment that coincided very closely with the second quarter.

In answering the broad question of what happened to energy-sector lobbying activity after the Fukushima meltdown, we can begin with the level of expenditure. Equation 2.1 presents the specification used to test for sector-wide expenditure changes after the disaster in Japan.

$$FilAmt_{c,t} = \beta_0 + \beta_1 \cdot Dis_t + \beta_2 \cdot Dis_t \times Energy_c + \beta_c + \beta_y + \beta_q + \varepsilon \quad (2.1)$$

The dependent variable, $FilAmt_{c,t}$, is the sum of all lobbying expenditures made by a client c in a given time period t . The specification includes a dummy variable for the second quarter of 2011, denoted Dis_t . The energy sector and the disaster are interacted and represented as $Dis_t \times Energy_c$. Congress is not uniformly active throughout the course of the year. To counter the evident seasonality present in the data, quarterly indicator variables, β_q , are included with the reference category being the first quarter of the year. Yearly controls, β_y , are also included to account for shifts in lobbying that can be attributed to election years or other general conditions. The omitted category is 2009. Table 2.3 suggests that the sector wide increase in energy lobbying expenditure barely

²³As a robustness check, several other disaster time windows were tested. Two quarter and year-long post disaster dummies were both insignificant statistically.

fails to be significant at the ten percent level. The nuclear industry does exhibit a larger response in spending relative to all other industries. Without more controls, this difference is not significant relative to other industries within the energy sector. Next, we must disaggregate the sector into its constituent industries to get finer detail of the post-disaster period.

Table 2.3: Energy Sector Lobbying Expenditures after Fukushima

Dis_t	0.006 (0.019)	0.007 (0.019)	0.011 (0.050)
$Dis_t \times Energy_c$	0.057 (0.038)		
$Dis_t \times Nuclear_c$		0.147*** (0.039)	0.099 (0.053)
Observations	309,794	309,794	5,915
Number of Clients	21,363	21,363	408
Only Energy Sector	N	N	Y
Robust standard errors are in parentheses. Client, quarter, and year fixed effects are included in all regressions. Significance is denoted: *, $p < 0.10$; **, $p < 0.05$; $p < 0.01$, ***.			

The basic specification for investigating individual industry lobbies is presented in equation (2.2). Each industry within the energy sector also has an indicator variable and these indicators are interacted with Dis_t to identify changes in expenditure occurring after Fukushima. The excluded category for the industry dummies is all sectors other than energy and the resource extraction industry. Client fixed effects, denoted β_c , absorb the industry indicators

in the specification below.

$$\begin{aligned}
FilAmt_{c,t} = & \beta_0 + \beta_1 \cdot Dis_t + \beta_2 \cdot Dis_t \times Nuclear_c + \beta_3 \cdot Dis_t \times Oil\ and\ Gas_c \\
& + \beta_4 \cdot Dis_t \times Alternatives_c + \beta_5 \cdot Dis_t \times Electricity_c \\
& + \beta_6 \cdot Dis_t \times Waste_c + \beta_7 \cdot Dis_t \times Resources_c \\
& + \beta_c + \beta_y + \beta_q + \varepsilon
\end{aligned} \tag{2.2}$$

The next four tables examine the responses of lobbying expenditures and the three main count variables to the disaster within the energy sector. Six model variations are employed. Odd-numbered models utilize a sample of firms from all sectors. Even-numbered models leverage a sample that excludes all organizations outside of the energy sector. This has implications for the reference group in each regression. The reference group in even numbered specifications is the wildlife industry. In odd numbered specifications all the non-energy sector organizations form the reference group.

Model 1 includes a balanced panel of all lobbying organizations for the 15 quarters of interest between 2009 and 2012. Model 2 restricts the sample to only the energy sector, but is otherwise identical in specification to the first model. Model 3 uses an unbalanced panel that only considers observations for which an organization filed disclosures. Model 4 does the same thing for the energy sector sub sample. Models 5 and 6 follow the pattern described above, using an unbalanced panel in which only observations with strictly positive filing amounts are included. Client level fixed effects are included in

all specifications in Tables 2.4 through 2.7.

Table 2.4: Filing Amounts by Industry

Dependent Variable: $FilAmt_{c,t}$ (\$)	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)
Dis_t	0.006 (0.019)	-0.043 (0.075)	0.009 (0.022)	-0.028 (0.073)	0.024 (0.031)	-0.021 (0.067)
$Dis_t \times Alternatives_c$	-0.033 (0.106)	-0.033 (0.120)	0.036 (0.084)	0.007 (0.096)	0.007 (0.072)	-0.007 (0.085)
$Dis_t \times Electricity_c$	0.072 (0.070)	0.071 (0.090)	0.090 (0.074)	0.061 (0.087)	0.057 (0.072)	0.040 (0.084)
$Dis_t \times Nuclear_c$	0.149*** (0.039)	0.153* (0.069)	0.176*** (0.044)	0.149* (0.065)	0.138*** (0.041)	0.122* (0.062)
$Dis_t \times Oil\ and\ Gas_c$	0.090 (0.051)	0.104 (0.075)	0.079 (0.045)	0.065 (0.064)	0.047 (0.039)	0.045 (0.059)
$Dis_t \times Resources_c$	-0.131 (0.118)	-0.128 (0.131)	-0.184 (0.127)	-0.203 (0.134)	-0.092 (0.071)	-0.101 (0.083)
$Dis_t \times Waste_c$	0.067 (0.117)	0.067 (0.131)	0.114 (0.122)	0.085 (0.132)	0.040 (0.096)	0.026 (0.108)
$Dis_t \times Wildlife_c$	0.000 (0.062)		0.029 (0.061)		0.016 (0.052)	
Observations	309,794	5,915	190,333	4,326	155,670	3,683
Number of Clients	21,363	408	20,218	398	18,421	384
Balanced Panel	Y	Y	N	N	N	N
Only $FilAmt_{c,t} > 0$	N	N	N	N	Y	Y
Only Energy Sector	N	Y	N	Y	N	Y

Robust standard errors are in parentheses. Client, quarter, and year fixed effects are included in all regressions. Significance is denoted: *, $p < 0.10$; **, $p < 0.05$; ***, $p < 0.01$, ***.

The disaster-nuclear industry interaction term in Table 2.4 suggests that lobbying expenditures in the post-disaster period are between 14.8 and 19.2 percent higher than they are for all non-energy sectors. Restricting the sample to only the energy sector changes the reference category to include only the wildlife industry. Nuclear power firms exhibit a 12.9 to 16.5 percent higher post-Fukushima response compared to the wildlife reference group. These second results are less significant as the estimators only leverage two percent of the full sample of observations. Over longer post-disaster time periods, this

jump declines in size and significance. The oil and gas industry also seems to have increased its expenditures in the wake of the nuclear disaster, but these findings are statistically insignificant.

The number of lobbyists employed, $LobCount_{c,t}$, by firms in the nuclear industry and its energy sector cohort is flat after the disaster once we take into account the slight decline in lobbyist employment evinced by the aggregate of sectors. Table 2.5 shows this flat trend. One possible explanation for this is simply that sufficiently knowledgeable lobbyists are scarce and of fixed supply in the short run. It seems reasonable that the human capital necessary to be an effective lobbyist for the nuclear industry takes more than 3 months to accumulate. The experience of researching this project is certainly consistent with this narrative. The specifications used in Tables 2.5 through 2.7 all contain the same independent variables as detailed above. Each of these tables offers a look at a different dependent variable measuring lobbying strategy.

Only model 3 in Table 2.6 suggests an even borderline significant change in the nuclear industry's strategy with respect to the number of agencies being contacted, $GovCount_{c,t}$. This effect is positive, and has an incidence rate ratio of 1.087. That is, this lone result would suggest nuclear industry firms appear to contact 8.7 percent more government agencies immediately after the disaster. No new regulators come into existence during the post-disaster period. There are no obvious priors with respect to the direction of change in the number of agencies contacted. Given that the structures and responsibilities of government institutions are persistent, this absence of change may be the

Table 2.5: Lobbyists Employed by Industry

Dependent Variable: <i>LobCount_{c,t}</i>	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)
<i>Dis_t</i>	-0.015*** (0.004)	-0.016 (0.043)	-0.017*** (0.004)	0.013 (0.031)	-0.012** (0.004)	0.006 (0.030)
<i>Dis_t × Alternatives_c</i>	-0.091 (0.122)	-0.120 (0.128)	-0.162 (0.129)	-0.210 (0.133)	-0.220 (0.135)	-0.240 (0.138)
<i>Dis_t × Electricity_c</i>	-0.020 (0.044)	-0.051 (0.060)	-0.008 (0.033)	-0.054 (0.043)	-0.047 (0.037)	-0.067 (0.046)
<i>Dis_t × Nuclear_c</i>	0.037 (0.045)	0.009 (0.063)	0.048 (0.045)	0.002 (0.053)	0.018 (0.044)	0.001 (0.051)
<i>Dis_t × Oil and Gas_c</i>	0.120 (0.080)	0.095 (0.089)	0.046 (0.059)	0.002 (0.065)	0.015 (0.060)	-0.003 (0.065)
<i>Dis_t × Resources_c</i>	-0.027 (0.090)	-0.056 (0.099)	-0.086 (0.068)	-0.130 (0.074)	-0.077 (0.071)	-0.097 (0.076)
<i>Dis_t × Waste_c</i>	0.105 (0.087)	0.076 (0.096)	0.125 (0.075)	0.079 (0.081)	0.135* (0.053)	0.116* (0.059)
<i>Dis_t × Wildlife_c</i>	0.029 (0.042)		0.047 (0.029)		0.019 (0.028)	
Observations	365,120	6,636	215,456	4,696	155,186	3,681
Number of Clients	25,125	457	23,529	443	18,319	383
Balanced Panel	Y	Y	N	N	N	N
Only <i>FilAmt_{c,t}</i> > 0	N	N	N	N	Y	Y
Only Energy Sector	N	Y	N	Y	N	Y

Robust standard errors are in parentheses. Client, quarter, and year fixed effects are included in all regressions. Significance is denoted: *, $p < 0.10$; **, $p < 0.05$; $p < 0.01$, ***.

most expected possible outcome.

The largest strategic change in lobbying activity by the nuclear industry can be seen in Table 2.7. While the number of lobbyists and government agencies contacted do not seem to change much, the number of issues lobbied, *IssCount_{c,t}*, declines significantly in all specifications. The estimates from Table 2.7 suggest that nuclear industry organizations and firms lobbied on between 72.6 and 74.0 percent as many issues as they did before the disaster. This finding describes an industry that immediately ramps up spending on lobbying and cuts out activities that do not serve to further its core goals in

Table 2.6: Government Agencies Contacted by Industry

Dependent Variable: <i>GovCount</i> _{c,t}	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)
<i>Dis</i> _t	0.005 (0.004)	-0.026 (0.038)	0.001 (0.004)	-0.004 (0.030)	0.005 (0.004)	-0.007 (0.030)
<i>Dis</i> _t × <i>Alternatives</i> _c	0.035 (0.070)	0.035 (0.079)	0.002 (0.051)	-0.002 (0.058)	-0.043 (0.052)	-0.035 (0.059)
<i>Dis</i> _t × <i>Electricity</i> _c	-0.024 (0.056)	-0.024 (0.067)	-0.012 (0.045)	-0.016 (0.052)	-0.075 (0.044)	-0.066 (0.052)
<i>Dis</i> _t × <i>Nuclear</i> _c	0.074 (0.043)	0.073 (0.057)	0.084* (0.043)	0.080 (0.050)	0.051 (0.040)	0.060 (0.048)
<i>Dis</i> _t × <i>Oil and Gas</i> _c	0.051 (0.071)	0.052 (0.079)	-0.005 (0.061)	-0.010 (0.066)	-0.030 (0.060)	-0.023 (0.066)
<i>Dis</i> _t × <i>Resources</i> _c	0.077 (0.103)	0.077 (0.110)	-0.051 (0.098)	-0.054 (0.102)	0.052 (0.058)	0.060 (0.064)
<i>Dis</i> _t × <i>Waste</i> _c	0.099 (0.085)	0.099 (0.093)	0.103 (0.075)	0.098 (0.080)	0.105 (0.071)	0.113 (0.076)
<i>Dis</i> _t × <i>Wildlife</i> _c	-0.000 (0.037)		0.004 (0.028)		-0.008 (0.028)	
Observations	357,687	6,532	212,644	4,623	154,714	3,678
Number of Clients	24,619	450	23,129	436	18,228	382
Balanced Panel	Y	Y	N	N	N	N
Only <i>FilAmt</i> _{c,t} > 0	N	N	N	N	Y	Y
Only Energy Sector	N	Y	N	Y	N	Y

Robust standard errors are in parentheses. Client, quarter, and year fixed effects are included in all regressions. Significance is denoted: *, $p < 0.10$; **, $p < 0.05$; $p < 0.01$, ***.

the wake of the meltdown. Changes to the individual issues within the nuclear industry's lobbying portfolio are not detailed in the current analysis.

As a robustness check, one of the industry-disaster interactions is dropped in each of the specifications in Table 2.8. The task of selecting the best reference category is thus left to the reader's discretion. In order to more readily interpret the coefficients in Table 2.8, taking the exponential function of the values renders the incident rate ratios. Table 2.8 shows the expenditure responses of the nuclear industry relative to other industries in the energy sector. The response is most pronounced when compared to the natural resource and

Table 2.7: Issues Lobbied by Industry

Dependent Variable: $IssCount_{c,t}$	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)
Dis_t	-0.002 (0.012)	-0.028 (0.122)	-0.006 (0.011)	0.009 (0.120)	-0.007 (0.013)	0.018 (0.134)
$Dis_t \times Alternatives_c$	-0.155 (0.132)	-0.100 (0.176)	-0.083 (0.125)	-0.062 (0.168)	-0.210 (0.109)	-0.185 (0.166)
$Dis_t \times Electricity_c$	-0.105 (0.111)	-0.050 (0.161)	-0.122 (0.106)	-0.096 (0.155)	-0.160 (0.101)	-0.130 (0.161)
$Dis_t \times Nuclear_c$	-0.320** (0.108)	-0.264 (0.158)	-0.301** (0.102)	-0.277 (0.151)	-0.311** (0.101)	-0.283 (0.158)
$Dis_t \times Oil\ and\ Gas_c$	-0.054 (0.104)	0.001 (0.156)	-0.088 (0.102)	-0.062 (0.153)	-0.128 (0.111)	-0.099 (0.168)
$Dis_t \times Resources_c$	0.189 (0.122)	0.245 (0.169)	0.143 (0.114)	0.168 (0.161)	0.198 (0.110)	0.228 (0.167)
$Dis_t \times Waste_c$	0.143 (0.167)	0.199 (0.204)	0.149 (0.164)	0.174 (0.200)	0.221 (0.162)	0.253 (0.204)
$Dis_t \times Wildlife_c$	-0.055 (0.117)		-0.023 (0.114)		-0.027 (0.126)	
Observations	391,637	7,021	222,201	4,791	155,666	3,683
Number of Clients	26,912	483	24,624	457	18,419	384
Balanced Panel	Y	Y	N	N	N	N
Only $FilAmt_{c,t} > 0$	N	N	N	N	Y	Y
Only Energy Sector	N	Y	N	Y	N	Y

Robust standard errors are in parentheses. Client, quarter, and year fixed effects are included in all regressions. Significance is denoted: *, $p < 0.10$; **, $p < 0.05$; $p < 0.01$, ***.

wildlife industries. Relative to the waste and electric industries, the nuclear industry's response is insignificant. Given that there is potential for overlap between nuclear and these two industries, the lack of a difference is perhaps not surprising. Many electricity-generating firms operate nuclear reactors and must make plans for how to deal with the attendant radioactive waste. While not as significant as the other coefficients, nuclear power does increase its expenditure relative to the oil and gas industry and the alternative energy industries.

Table 2.8: Lobbying Expenditures by Industries in Energy Sector

Dependent Variable: <i>FilAmt_{c,t}</i>	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)	Model (7)
<i>Dis_t</i>	-0.184* (0.080)	-0.032 (0.140)	-0.377*** (0.103)	-0.146* (0.060)	0.026 (0.070)	-0.100 (0.054)	-0.236 (0.122)
<i>Dis_t × Alternatives_c</i>	-0.052 (0.138)	-0.204 (0.180)	0.141 (0.150)	-0.090 (0.134)	-0.262* (0.130)	-0.135 (0.134)	
<i>Dis_t × Electricity_c</i>	0.083 (0.084)	-0.068 (0.143)	0.277** (0.102)	0.046 (0.077)	-0.126 (0.070)		0.135 (0.134)
<i>Dis_t × Nuclear_c</i>	0.209** (0.078)	0.058 (0.140)	0.403*** (0.097)	0.172* (0.071)		0.126 (0.070)	0.262* (0.130)
<i>Dis_t × Oil and Gas_c</i>	0.037 (0.084)	-0.114 (0.143)	0.231* (0.102)		-0.172* (0.071)	-0.046 (0.077)	0.090 (0.134)
<i>Dis_t × Resources_c</i>	-0.193 (0.108)	-0.345* (0.158)		-0.231* (0.102)	-0.403*** (0.097)	-0.277** (0.102)	-0.141 (0.150)
<i>Dis_t × Waste_c</i>	0.152 (0.147)		0.345* (0.158)	0.114 (0.143)	-0.058 (0.140)	0.068 (0.143)	0.204 (0.180)
<i>Dis_t × Wildlife_c</i>		-0.152 (0.147)	0.193 (0.108)	-0.037 (0.084)	-0.209** (0.078)	-0.083 (0.084)	0.052 (0.138)

Robust standard errors are in parentheses. Client, quarter, and year fixed effects are included in all regressions. Significance is denoted: *, $p < 0.10$; **, $p < 0.05$; p < 0.01, ***. Every column in Table 2.8 was estimated on the 6,576 observations from 411 clients in the energy sector.

2.5.2 Lobbying Response by Firm Type

The full sample of firms with generating assets includes municipalities and cities. Table 2.9 shows that the estimates of the interactions of diversified nuclear firms and the disaster period do not change significantly when municipalities and cities are excluded from the sample as in Model 2.

The degree of exposure to competition from nuclear generation should determine the potential for the nuclear disaster in Japan to matter to local electricity producers. A firm that owns any nuclear capacity realizes a value of one for an indicator variable, $Nuclear_f$. Firms that do not own any nuclear assets realize a zero value for this variable. For the four year sample used in this study, $Nuclear_f$ is time invariant.

Measuring the degree of a firm's exposure to competition from nuclear

assets, $ShareRivalNuclear_f$ is the firm level average of the share of local rival nameplate capacity that is derived from nuclear power at each of the plants it owns. In Table 2.9, the negative sign on the coefficient for the $ShareRivalNuclear_f$ interacted with the disaster period is consistent with the notion that firms exposed to more nuclear competition feel less inclined to counter lobby their nuclear rivals after the disaster. The public relations fiasco of the disaster does the work that would normally have required paying lawyers.

The concentration of a firm's nuclear assets is measured by $ShareSisterNuclear_f$, which is equal to the firm-level average of the share of local sister nameplate capacity that comes from nuclear fuel. Higher values for this variable represent more concentration amongst the nuclear assets held by firm.²⁴ Firms with high concentrations of nuclear assets appear to have responded to the disaster with a massive decrease in lobbying expenditure.

Firms with a greater share of rival capacity that is derived from nuclear power appear to lobby less in the disaster period. Firms with a high level of neighboring sister capacity that is nuclear exhibit a lower level of lobbying expenditure.

When nuclear firms are excluded from the sample, diversified and pure firms display no significant difference in lobbying expenditures during the disaster period. This lack of differences is shown in Table 2.10. Non-nuclear firms appear to be maintaining their strategic course after the nuclear disaster in

²⁴Firms that own several nuclear power plants in close proximity of each other may be able to realize additional operations savings by sharing maintenance functions.

Table 2.9: Lobbying Expenditures by Competition Type

Variable	Model 1 (Std. Err.)	Model 2 (Std. Err.)
Dis_t	-0.235* (0.140)	-0.236* (0.143)
$Dis_t \times Nuclear_f$	0.002** (0.001)	0.002** (0.001)
$Dis_t \times ShareRivalNuclear_f$	-0.821** (0.257)	-0.853** (0.261)
$Dis_t \times ShareSisterNuclear_f$	-1.788** (0.638)	-1.775** (0.643)
N	3,152	2,336

Model 1 contains observations for all entities that lobby at least once in the sample and own at least one asset with a nameplate capacity of 10 MW or greater. Model 2 is run on a subset of the sample employed in Model 1 with cities and municipalities excluded. Client, quarter and year fixed effects are included in the regressions. Significance is denoted: *, $p < 0.10$; **, $p < 0.05$; $p < 0.01$, ***.

Japan.

Table 2.11 includes diversified nuclear firms in the analysis as the reference category and interacts each of the non-nuclear strategic groups with the disaster and share of rival capacity that is nuclear. All pure nuclear firms are dropped from the sample as all filing amounts for 2009 through 2012 are equal to zero.

The strong negative trend in expenditures attributable to the time period is still present when the additional interactions are considered. Diversified non-nuclear firms exhibit no significant change in expenditures during the period immediately following the disaster relative to diversified firms with nuclear assets in their portfolio. The share of rival capacity that is nuclear also fails

Table 2.10: Lobbying Expenditures by Firm Type

Variable	Coefficient (Std. Err.)
Dis_t	-0.547*** (0.206)
$Dis_t \times Diversified_f$	0.123 (0.168)
$Dis_t \times Diversified_f \times ShareRivalNuclear_f$	0.205 (0.296)
N	2,288

Client, quarter and year fixed effects are included in the regressions.
Significance is denoted: *, $p < 0.10$; **, $p < 0.05$; $p < 0.01$, ***.

to factor significantly into the strategic expenditure of resources for lobbying by these non-nuclear diversified firms.

Single technology, non-nuclear firms (Pure) can be seen increasing expenditures relative to diversified firms with nuclear assets after the disaster. However, for the pure firms that are most exposed to competition from nuclear plants, expenditures can instead fall after the disaster. These firms may be reducing their competitive efforts against nuclear power while the regulatory environment is undergoing review.

The lobbying strategies of firms in the electrical power industry respond to the nuclear disaster in a manner that is broadly consistent with the nature of competition between their assets and nuclear power plants. Firms that compete most extensively with nuclear power on the grounds of geographic location exhibit the largest declines in lobbying expenditures after the disaster in Japan.

Table 2.11: Lobbying Expenditures by Firm Type

Variable	Coefficient (Std. Err.)
Dis_t	-0.655*** (0.236)
$Dis_t \times Diversified_f$	0.232 (0.224)
$Dis_t \times Diversified_f \times ShareRivalNuclear_f$	0.205 (0.296)
$Dis_t \times Pure_f$	0.414* (0.238)
$Dis_t \times Pure_f \times ShareRivalNuclear_f$	-0.940*** (0.259)
N	2,336
Client, quarter and year fixed effects are included in the regressions.	
Significance is denoted: *, $p < 0.10$; **, $p < 0.05$; $p < 0.01$, ***.	

2.6 Conclusion and Discussion

This chapter documents the response of energy sector lobbying activity after the Fukushima Daiichi nuclear disaster using public data from the Senate Office of Public Records. Organization level data is leveraged to establish a rise in expenditure and a decrease in the breadth of issues lobbied by the nuclear industry in the second quarter of 2011. That is, the nuclear power industry clearly responds to the threats presented by the meltdown by both honing in on pertinent issues and increasing its efforts overall. The nuclear industry has increased its effective lobbying presence in energy policy through the use of these two levers.

Can the increase in lobbying expenditure by the nuclear industry be ex-

plained simply by a rise in the hours billed by lobbyists already on retainer? Or is the nuclear industry spending more because it is upgrading the quality of the lobbyists it employs? Such a trend could exhibit flat employment numbers while costs rise. The relatively more difficult political climate for nuclear power could necessitate bringing in more experienced or better-connected lobbyists. Which issues are dropped from the docket by nuclear firms as they focus on their core business? The number of agencies contacted may not change, but again, the composition of the government actors contacted could change with the disaster. Lobbying behavior is highly persistent. Therefore any changes in the contacts made between industry and government might signal the emergence of new political strategies by firms.

Ultimately, how is the uncertainty faced by a firm impacted by the narrowing of lobbying focus? It seems plausible that some of the issues dropped from the nuclear lobbying agenda might have been directed by more long-sighted strategies. If the nuclear industry feared that competing technologies would seize the opportunity to improve their standing relative to fission, the response we see in lobbying activity may be driven by the strategic interaction of the industries' players. As organizations reallocate lobbying resources to deal with the shock of the day or quarter, uncertainty from other aspects of the business may be allowed to grow.

Using the SOPR data, it is possible to extract the history of any lobbying firm's activity over the last decade. From this information, one could measure the experience that a registrant has with lobbying on a certain issue or

contacting a specific government agency. Registrants with more experience lobbying the Department of Energy could plausibly find the billable rate for their services increasing in the wake of an energy related disaster. With the development of experience, a lobbying firm could reasonably expect to be able to charge more for their product. Specific knowledge regarding the inner-workings of a specific agency could prove invaluable to a client that must make its resources go further in an unfavorable political climate.

This information can be accumulated but is also prone to depreciate with time like many assets. Furthermore, lobbying expenditures represent a partially irreversible investment in that lobbying strategies and the efforts to implement them are not easily transferable between two trading parties. Once Pacific Gas & Electric pays a registrant to conduct the necessary research and contact the right people to execute a chosen political strategy, there is no guarantee that the resulting blueprint can be transferred to Southern California Edison at a price that recuperates cost. This stems from client specific elements of lobbying strategy. Industries with highly differentiated products have been shown to lobby more as individual firms than as trade associations Bombardini and Trebbi (2012). Intuitively, one might expect firms in such industries to find relatively larger portions of their investments as irreversible. Even if we set aside the notion that political knowledge gained from lobbying could be sold, once you pay a lawyer, you would be better off attempting to draw blood from a turnip than trying to get a refund on their consulting fees. The investment under uncertainty framework is even better suited for modeling

lobbying when we consider that political climate can change in unforeseeable ways, and swiftly at that. In a sense there is always technical uncertainty associated with achieving a set political goal such as securing the passage of a given bill or defeating a rival piece of legislation. The cost remaining to achieve a goal can jump with or without lobbying. A few days before the Fukushima disaster, H.R. 909 “A Roadmap for America’s Energy Future” was introduced to Congress calling for large increases in the use of nuclear power generation. It seems fair to suggest that the bill’s sponsor, Representative Devin Nunes of California, did not expect a massive disaster to cloud the political climate into which he jumped. The bill has made little progress.

A registrant that lobbied the NRC last year is likely of higher quality in some senses than an otherwise identical firm that has not made contact with that agency for five or ten years. Congress has regular turnover amongst its membership. Lobbying firms with strong ties to influential Senators lose some of their quality when those very politicians leave office or no longer sit on specific committees. With these temporal considerations in mind, a registrant’s quality with respect to a certain agency can be modeled as a weighted average of the number of filings it has made disclosing contact with the agency of interest in the previous four, eight, or more quarters. Experience on a given issue could be modeled similarly, though the number of lags included in the measure need not be the same as the variable measuring a registrant’s familiarity with an agency. Future work may profitably investigate the importance of lobbying experience and quality.

Appendices

Appendices

A A Brief Primer on Drought

Drought does not impart the violent shock of an earthquake or impress upon us the same immediate fear as does a large tornado. The physical, biological and economic symptoms of drought are often more pernicious by comparison, but no less severe. This relatively subtle manifestation of drought symptoms complicates efforts to define and describe the phenomena. Given enough time, the ill-effects of drought become visible from space in satellite images of exposed reservoir beds, and fallow crop lands.

A single definition of drought and metric with which to measure its severity will not be suitable for all studies of water scarcity. Gregory (1986) discusses the tradeoffs between measuring drought in a relative versus absolute manner. One may compare current water prevalence to some absolute value, establishing the presence of drought when water levels drop below a specific fractional threshold. However, the choice of threshold values will be subject to geographic and climatic considerations. What is normal for the prairies of the North American interior differs extensively from that of New England. It is desirable

that any measure of drought facilitate the comparison of relative scarcity across geographic regions. Furthermore, the comparison of conditions intertemporally is also of interest. The search to meet both criteria brings us to a second definition.

Palmer (1965) develops the basic metric through which drought will be observed and measured for the purposes of chapter 1. In the foreword for Palmer's research for the U.S. Weather Bureau's Office of Climatology, Helmut Landsberg described drought as "an unconquered ill". After a discussion of the shortcomings of other possible metrics, Palmer writes, "A drought period may now be defined as an interval of time, generally of the order of months or years in duration, during which the actual moisture supply at a given place rather consistently falls short of the climatically expected or climatically appropriate moisture supply. Further, the severity of drought may be considered as being a function of both the duration and magnitude of the moisture deficiency." Droughts entail large moisture anomalies that inflict damage over considerable lengths of time. Both the temporal and anomalous aspects of the definition are necessary.

Causes of Drought

In a study of severe drought in what was then recent history, Namias (1980) "consider[s] drought as an extended period of deficient precipitation relative to normal". This definition of the climatic phenomena is simple but similar to that employed in Palmer (1965). Namias goes on to assert that the atmospheric

conditions that cause drought are often systems spread over large distances. Namias (1980) concludes that “most cases of drought in temperate latitudes are associated with persistent upper level anticyclonic²⁵ flow patterns and concomitant subsidence²⁶ with warm dry conditions in the lower atmosphere”²⁷. What is most important for the purpose of chapter 1 is that drought can be viewed as plausibly exogenous with respect to the actions of the electricity generating industry. Operators of hydroelectric facilities may have some discretion over their reservoir holdings, but the amount of water available for use within a given hydrological system is far from under the control of any single firm.

Impacts of Drought

As the severity of drought increases the amount of energy input available to hydroelectric facility managers can decrease significantly. As detailed in Appendix B, a lower water level means decreased potential energy within the reservoir. In this way, drought entails implications for a hydroelectric producer’s effective capacity. Those firms with a degree of market power in peri-

²⁵An anticyclone is defined by the National Weather Service (NWS) of the National Oceanic and Atmospheric Administration (NOAA) as “A large-scale circulation of winds around a central region of high atmospheric pressure, clockwise in the Northern Hemisphere, counterclockwise in the Southern Hemisphere”.

²⁶Subsidence has two distinct meanings that are both relevant to the study of drought. The NWS defines subsidence as “A descending motion of air in the atmosphere occurring over a rather broad area.” This descending motion of air is associated with adiabatic heating of the air at lower altitudes as air pressure rises. Low relative humidity couples with the adiabatic heating to inhibit precipitation.

²⁷Alternatively, the NWS defines subsidence as the “sinking down of part of the earth’s crust due to underground excavation, such as the removal of groundwater.” The second phenomena can be exacerbated by drought as people replace lost supplies of surface water with groundwater sources. Subsidence is a familiar occurrence in regions that rely heavily on groundwater resources for human use such as Mexico City where maximum subsidence rates were 300 mm per year between 2004 and 2006 Osmanoglu et al. (2011).

ods flush with water may find themselves unable to exercise that same power when confronted with drought conditions. The marginal cost of hydroelectric generation is effectively the shadow value on the water constraint. Therefore, drought constitutes a cost shock to hydroelectric producers. The supply of water is exogenous to the hydroelectric generation firms, implying that the hydroelectric firm's productivity is at least partially exogenous.

While drought has real effects on both the supply and demand side of electricity markets the strength of the supply effects is correlated with the presence of hydroelectric facilities. The degree to which economic activity is curtailed or increased for lack of water as well as the water and energy intensity of any given enterprise are the basic arguments that determine drought's effect on the demand for electricity and other energy products.

Drought reduces available water supplies and can cause conflict between parties with competing claims on the resource.²⁸ For reservoir-based hydroelectric plants, the opportunity cost of allowing water to pass through a turbine is the value of the foregone uses of that water.²⁹ The opportunity cost of hydroelectric production generally rises with drought.

B Simple Physical Model of Hydroelectric Generation

A detailed engineering model of the generating technology employed in a hydroelectric plant is beyond the scope of chapter 1. However, it is useful to

²⁸Further discussion on efficiency and the nature of water rights in America can be found in Burness and Quirk (1979).

²⁹See Figure 2 in Appendix K showing the effect of low reservoir levels on summer recreational facilities at Lake Shasta, CA.

establish a simple model for the power that a hydroelectric dam can generate as a function of several fundamental variables and parameters. For the sake of this model, the head, denoted h , of a given hydroelectric facility is the vertical difference between the elevation of the reservoir and that of the tailrace. Let δ be the density of water (kg/m^3). The acceleration constant of gravity ($9.81m/s^2$) is denoted as g . The final determinant of available power at a dam is γ , the rate of water flow (m^3/s). Assuming perfect efficiency, a dam with a head of h generates power of P such that,

$$P = \delta \gamma g h \quad (3)$$

If we know the head of the dam and the rate of flow through the turbine, we can find an estimate of the plant's generating capacity. In reality, hydroelectric plants do not operate at 100 percent efficiency. Let $\theta \in [0, 1]$ denote the efficiency coefficient for a given dam. The actual amount of power generated, measured in watts, is \hat{P}

$$\hat{P} = \theta \delta \gamma g h \quad (4)$$

From the equation above, we can estimate the nameplate capacity of a 90 percent efficient dam with a 200 meter head and a stream flow over the turbines of $1,000 m^3/s$ to be approximately 1.765 GW. If such a plant existed, it would be the seventh largest hydroelectric plant in the country.

It is immediately apparent that the capacity of a hydroelectric plant to produce power is reduced by both low streamflow and lower reservoir levels.

When inputs run low at a thermal plant, production levels can be maintained until fuel sources are exhausted. Hydroelectric plants facing diminishing input of water resources into their reservoirs may be forced to make a tradeoff between maintaining reservoir levels and output in the short run. Given the same streamflow over the turbine, a plant's capacity to generate power will be greater when the head is higher. Allowing the reservoir levels to drop considerably can prove especially bad as significant potential energy is lost. Fundamentally, a lack of water resources such as occurs in drought can inhibit the ability of hydroelectric generators to produce at their design capacity.

C Imperfect Competition in Electricity Generation

The fundamental purpose of this model is to build intuition about how market power impacts wholesale electricity markets. The following appendix will show how hydroelectric market power is dependent on the availability of water resources for the generation of electricity. Drought is a common blight in much of the world, especially the hydroelectric-rich American west. With this in mind, the model is presented so as to highlight the expected channels through which drought will impact production in the electricity generating industry. The manner in which drought impacts market outcomes is dependent on the nature of competition in the wholesale electricity market. I will show in the empirical section that the findings are consistent with imperfect competition. My model will demonstrate that drought can actually lead to lower levels of wholesale price volatility.

In this model, the electricity generating industry is comprised of N hydroelectric firms and a single thermal generating firm with increasing marginal costs. The thermal firm can be thought of as a system operator allocating production among the most efficient producers. The thermal and hydroelectric firms can sell their product at regional market hubs. Let the quantity of electricity produced by the hydroelectric firm k in period t be denoted q_{kt}^{Hy} . The thermal generation firm produces q_t^{Th} in each period t .

In reality, single firms can operate both hydroelectric and thermal plants. The two types of generating assets are split in this manner due to the differing operational constraints and mandates of each set of plants. While the dispatch of thermal plants responds to changes in residual demand, the hydroelectric plants may choose operational strategies that are relatively more informed by the hydrological needs of the local economy.

Demand

Wholesale electricity markets in the United States facilitate the sale of high voltage electricity between independent power producers, integrated utilities and associated marketers. Independent marketers of power can also participate in trades on wholesale markets much as they can in other commodity markets. Prices in efficient wholesale markets should reflect the marginal cost of generating and transmitting electricity given the prevailing demand and supply conditions. Let inverse demand for wholesale electricity be linear.

$$P_t = A_t - bQ_t \quad \text{with} \quad Q_t = \sum_{i=1}^N q_{it}^{Hy} + q_t^{Th}$$

The Water Resource

The primary constraint on the generating activity of firms in this model is that of the water resources available for use within a given time horizon of T periods. The thermal firm is assumed to be able to purchase as much fuel as is necessary to generate its optimal output. Managers at the hydroelectric firms have an expectation of the total water resources that will be available over the coming time horizon. It is in this individual's interest to schedule firm output to maximize profit or net social benefits over the planning horizon. Hydroelectric output in each period must sum up to the total water resource quantity denoted R ³⁰. Assume that each of the N firms has access to an equal share of the water resources.

$$\sum_{t=1}^T q_{kt}^{Hy} = R_k = \frac{R}{N} \quad (5)$$

Firms

In classic Cournot fashion each firm will maximize its profit taking the output of its rival firms as given. A typical hydroelectric firm $k \in \{1, \dots, N\}$ chooses a series of output quantities so as to maximize its profits over the planning horizon of T periods.

³⁰The resource quantity is effectively measured in units of energy.

$$\Pi_k^{Hy} = \max_{q_{kt}^{Hy}} \sum_{t=1}^T \left[P_t(Q_t) q_{kt}^{Hy} - \sigma_k \left(\sum_{t=1}^T q_{kt}^{Hy} - R_k \right) \right] \quad (6)$$

The first order condition with respect to the hydroelectric output in period t can be solved for the best response function of the hydroelectric firm.

$$q_{kt}^{Hy} = \frac{A_t - b \left(\sum_{i \neq k}^N q_{it}^{Hy} + q_t^{Th} \right) - \sigma_k}{2b} \quad (7)$$

The best response function for the thermal firm can be obtained in analogous fashion from that firm's optimization problem. The thermal firm chooses output to maximize profits according to the following expression.

$$\Pi^{Th} = \max_{q_t^{Th}} \sum_{t=1}^T \left[P_t(Q_t) q_t^{Th} - c q_t^{Th} - \frac{\alpha}{2} (q_t^{Th})^2 \right] \quad (8)$$

The thermal firm's marginal generating costs increase with output to reflect the fact that grid operators must dispatch decreasingly efficient power plants as demand rises. The best response function for the thermal firm takes on a similar form to those of the hydroelectric rivals.

$$q_t^{Th} = \frac{A_t - b \sum_{i=1}^N q_{it}^{Hy} - c}{2b + \alpha} \quad (9)$$

Equilibrium

In order to determine the impact of drought on market outcomes I need to construct an expression for the market price as a function of water conditions. Price is simply a function of total output on the market. Total output is the

sum of hydroelectric and thermal output and both components depend on the realization of water resources.

In the interest of simplicity, all hydroelectric firms are assumed to be identical. Imposing this symmetry on the model and finding the intersection of the response curves gives us the optimal outputs of each firm. Hydroelectric output is a function of the shadow value of water for typical firm k , σ_k .

$$q_{kt}^{*Hy} = \frac{(\alpha + b)A_t - (\alpha + 2b)\sigma_k + bc}{b[(\alpha + b)N + (\alpha + 2b)]} \quad (10)$$

$$q_t^{*Th} = \frac{A_t - bNq_{kt}^{*Hy} - c}{\alpha + 2b} \quad (11)$$

The equilibrium market quantity, Q_t , is the sum of each firm's output. With an expression for market output as a function of demand and marginal costs, the market clearing price can be obtained as a function of the same variables and parameters.

$$Q_t = \frac{(\alpha + b)Nq_{kt}^{*Hy} + A_t - c}{(\alpha + 2b)}$$

$$Q_t = \frac{(\alpha + b)N \left(\frac{(\alpha + b)A_t - (\alpha + 2b)\sigma_k + bc}{b[(\alpha + b)N + (\alpha + 2b)]} \right) + A_t - c}{\alpha + 2b} \quad (12)$$

Lemma 1 *The total output of the dual technology electricity market is inversely related to the shadow value of water. Total output will fall in periods*

of drought.

$$\frac{\partial Q_t}{\partial \sigma_k} = -\frac{(\alpha + b)N}{b[(\alpha + b)N + (\alpha + 2b)]} < 0 \quad (13)$$

The cross partial of market output with respect to the marginal cost of hydroelectric production and the number of hydroelectric firms is negative and can be expressed as follows.

$$\frac{\partial^2 Q_t}{\partial \sigma_k \partial N} = -\frac{(\alpha^2 + 3\alpha b + 2b^2)}{b[(\alpha + b)N + (\alpha + 2b)]^2} < 0$$

The extent to which drought applies downward pressure on the market quantity varies with the number of hydroelectric firms. The cross partial derivative above indicates that the the dip in total quantity will be more negative (larger in magnitude) as the number of hydroelectric firms grows. In other words, quantities should fluctuate less as a result of drought when the hydroelectric industry is relatively concentrated (N is small). In the presence of few firms with implicit market power, market quantities change little, driving less movement in the equilibrium price.

Market price is a function of the total quantity generated and can be written as follows.

$$P_t(Q_t) = A_t - b \left(\frac{(\alpha + b)N \left(\frac{(\alpha + b)A_t - (\alpha + 2b)\sigma_k + bc}{b[(\alpha + b)N + (\alpha + 2b)]} \right) + A_t - c}{\alpha + 2b} \right)$$

With the above function for price, P_t , its elasticity with respect to the demand shifter, A_t , can be obtained simply. However, the shadow value of water, σ , is a function of A_t . Next, I will obtain an expression for water's

shadow value as a function of the water resource, the number of firms, the choke price and several parameters.

The Shadow Value of Water

The shadow value of water to hydroelectric producers or the marginal cost of hydroelectric production is found by solving for the optimal output of a typical hydroelectric producer and substituting that expression into the constraint on the water resource.

$$\sum_{t=1}^T q_{kt}^{Hy} = R_k = \frac{R}{N}$$

$$\sum_{t=1}^T \frac{(\alpha + b)A_t - (\alpha + 2b)\sigma_k + bc}{b[(\alpha + b)N + (\alpha + 2b)]} = R_k = \frac{R}{N}$$

Solving for the producer's shadow value of water, σ_k , gives us the relationship between water resources and hydroelectric marginal costs.

$$\sigma_k = \frac{1}{T} \frac{(\alpha + b)}{(\alpha + 2b)} \sum_{t=1}^T A_t - \frac{bc}{\alpha + 2b} - \frac{Rb[(\alpha + b)N + (\alpha + 2b)]}{T(\alpha + 2b)N}$$

Lemma 2 *The shadow value of water is negatively related to the stock of water resources. That is, drought raises the marginal cost of hydroelectric generation.*

$$\frac{\partial \sigma_k}{\partial R} = -\frac{b[(\alpha + b)N + (\alpha + 2b)]}{T(\alpha + 2b)N} < 0$$

Taking the cross partial derivative of σ_k with respect to both the water

resource and the number of firms offers information on the degree to which the marginal cost of hydro changes with drought for markets with different degrees of market power.

Proposition 1 *The impact of drought on hydroelectric marginal costs is relatively small when production is concentrated among few firms.*

$$\frac{\partial^2 \sigma_k}{\partial R \partial N} = -\frac{b[(\alpha + b)(2N) + (\alpha + 2b)]}{T(\alpha + 2b)N^2} < 0$$

The marginal cost of hydroelectric generation not only declines as water resources rise, but the decline is more pronounced when the number of firms is large. Hydroelectric industries with implicit market power thus experience dampened cost shocks from drought. That is, drought will be impactful on the marginal cost of hydropower when production is relatively competitive.

Price Comparative Statics

Price can be fully expanded as an expression of the choke price, A_t , the number of firms, N , the water resource, R , and a collection of other demand and cost parameters.

$$P_t = A_t - b \left(\left(\frac{(\alpha + b)^2 N A_t}{(\alpha + 2b)G} \right) - \left(\frac{(\alpha + b)Nbc}{(\alpha + 2b)G} \right) + \left(\frac{A_t - c}{\alpha + 2b} \right) - \left(\frac{(\alpha + b)N}{G} \right) \left(\frac{1}{T} \frac{(\alpha + b)}{(\alpha + 2b)} \sum_{s=1}^T A_s - \left(\frac{bc}{\alpha + 2b} \right) \left(\frac{G}{TN(\alpha + 2b)} \right) R \right) \right) \quad (14)$$

Where $G = b[(\alpha + b)N + (\alpha + 2b)]$ is employed to simplify notation. The expanded version of the price expression facilitates evaluating the partial derivative of price with respect to the water resource. Through this derivative one can see that prices vary inversely with the size of the water resources at the disposal of the hydroelectric industry.

$$\frac{\partial P_t}{\partial R} = -\frac{b(\alpha + b)}{T(\alpha + 2b)} < 0 \quad (15)$$

Equation (15) takes the intuitive sign considering that changes in the water resources fundamentally constitute cost shocks. The hydroelectric marginal cost curve, which is constant for a given level of water resources, rises when drought occurs and falls when water is plentiful.

Equilibrium price also depends on the structure of the hydroelectric industry. Taking the partial derivative of price with respect to the number of firms lets us know how pricing varies with industry structure. An interesting feature of the following derivative is that its sign is dependent on whether present demand, A_t , is greater or less than the average level for a given planning horizon. This feature renders the following derivative especially informative. When demand is above average, the second term in parentheses obtains a negative value. As the first term in parentheses is always positive, the partial derivative of price with respect to the number of firms will obtain a negative value when demand is high. This implies that peak prices will be lower when the hydroelectric industry is comprised of more firms. When demand is relatively low, the second term in parentheses obtains a positive value and the partial deriva-

tive of price with respect to the firm count will be positive. Off peak prices are higher with a competitive hydroelectric industry than with a concentrated one.

$$\frac{\partial P_t}{\partial N} = \left(\frac{(\alpha + b)^2}{[(\alpha + b)N + (\alpha + 2b)]^2} \right) \left(\frac{1}{T} \sum_{s=1}^T A_s - A_t \right) \quad (16)$$

Equation (16) suggests that concentration of hydroelectric facilities among relatively few firms should lead prices to higher highs and lower lows than would be realized if the industry were comprised of many smaller competitive firms. This theoretical finding is also suggestive of hydroelectric market power as a contributor to price volatility.

Volatility is experienced as prices change from period to period. Electricity demand fluctuates with the time of day, season of the year, temperature, weather and numerous other factors. An exhaustive study of all things contributing to wholesale electricity price volatility is beyond the scope of chapter 1. For the purpose of this chapter, all these potential drivers of demand are represented in a single demand variable, A_t , or the choke price of the linear demand curve. Inter-period price changes are affected by fluctuations in this singular demand variable. The extent to which these demand fluctuations are passed on to the market price is determined by the structure of and resources available to the hydroelectric industry. The simplest measure of inter-period price movement is the first difference of prices between periods $t - 1$ and t .

Price Movements

Let ΔP_t denote the absolute price change experienced into period t . Before obtaining the first difference in price it is useful to decompose the expression for price into time variant and constant components. The first term in Equation (17) varies with the demand shifter, A_t , but the second term does not. Therefore the second term will drop out of the first difference of prices.

$$P_t = \left(1 - \frac{b}{\alpha + 2b} - \frac{b(\alpha + b)^2 N}{(\alpha + 2b)G}\right) A_t + \left(\frac{b}{G}\sigma_k - \frac{b^2 c}{(\alpha + 2b)^2 G} - \frac{bc}{(\alpha + 2b)}\right) \quad (17)$$

where again, $G = b[(\alpha + b)N + (\alpha + 2b)]$ is employed as a notational simplification. The shadow value of water only figures into the second term on the right-hand side of the price expression. This is important because it implies that the impact of water's marginal cost on inter-period price fluctuations is constant over a given planning horizon. The salience of industry concentration to price movements is implied by the presence of N in the time variant component of price. I take the first difference in prices between periods $t - 1$ and t and simplify to arrive at the following expression for absolute inter period price change.

$$\Delta P_t \equiv P_t - P_{t-1} = (A_t - A_{t-1}) \frac{(\alpha + b)}{(\alpha + b)N + (\alpha + 2b)} \quad (18)$$

Equation (18) demonstrates that prices will move proportionally with demand. The degree of proportionality is determined by one parameter each from the demand and marginal thermal cost curves as well as the number of hydroelectric firms operating in a given market.

It is now possible to explore the impact of market concentration on inter period price movements. Taking the partial derivative of the first difference of price with respect to the number of firms offers insight into the role of market power in driving price volatility. The sign of this derivative is once again dependent on the direction of the demand (and thus price) movement.

$$\frac{\partial \Delta P_t}{\partial N} = -(A_t - A_{t-1}) \frac{(\alpha + b)^2}{((\alpha + b)N + (\alpha + 2b))^2} \quad (19)$$

Ignoring for a minute the change in the demand shifter, the rest of the above expression is always negative. This implies that the partial derivative will obtain a sign opposite that of the demand movement. As demand shifts out towards conditions of peak load the concomitant upward movement in price should be more pronounced in the presence of hydroelectric market power. Upward price movements will be smaller when hydroelectric production is spread between many firms. On the other hand, falls in demand will lead to less negative movement in price when the hydroelectric industry is more competitive. This finding motivates the hypothesis that hydroelectric market power drives some volatility seen in wholesale electricity markets.

Proposition 2 *Competition in the form of more firms, a higher N , acts to*

dampen the inter-period price changes that are induced by fluctuations in demand. This means that the concentration of hydroelectric production among few producers with implicit market power should increase price volatility, all else equal.

$$\frac{\partial \Delta P_t}{\partial N} = \begin{cases} > 0, & \text{if } (A_t - A_{t-1}) < 0, \text{ indicating that demand is falling from its peak} \\ < 0, & \text{if } (A_t - A_{t-1}) > 0, \text{ indicating that demand is rising towards its peak} \end{cases}$$

The relationship between industry structure and volatility can be explored using other measures of price change as well. Let the log change in inter-period prices be the backwards difference denoted $\log \Delta P_t$, where

$$\log \Delta P_t = \log \left(\frac{P_t}{P_{t-1}} \right) \quad (20)$$

How will log inter-period price changes be impacted by drought? I take the partial derivative of log price change with respect to the water resource, R . The product of prices from both periods will always be positive, as will the the expression within the first set of parentheses. Again the sign of the derivative will depend on the movements in price driven by underlying demand fluctuations. When price is falling, the partial derivative displayed in equation (21) will obtain a negative sign. Having plentiful water resources should lead downward price shifts to be more negative. When price is increasing towards peak conditions, the derivative is positive and increases in the water resources at the disposal of hydroelectric firms lead the price rise to be larger.

$$\frac{\partial \log \Delta P_t(R)}{\partial R} = - \left(\frac{b(\alpha + b)}{T(\alpha + 2b)} \right) \left(\frac{P_{t-1}(R) - P_t(R)}{(P_t(R))(P_{t-1}(R))} \right) \quad (21)$$

I expand the numerator of the second term of equation (21), substituting the equation (18) to get the response of log price change to water availability as a function of fluctuating demand. Note that the negative sign is internalized by switching the order of the price first difference.

Proposition 3 *Drought will act to dampen the inter-period log price changes that are induced by fluctuations in the level of demand. This means that drought should render both price rises and drops less pronounced, consequently reducing price volatility.*

$$\frac{\partial \log \Delta P_t(R)}{\partial R} = \left(\frac{b(\alpha + b)}{T(\alpha + 2b)} \right) \left(\frac{(\alpha + b)}{(\alpha + b)N + (\alpha + 2b)} \right) \left(\frac{A_t - A_{t-1}}{(P_t(R))(P_{t-1}(R))} \right) \quad (22)$$

On the other hand, the presence of plentiful water resources should increase the magnitude of log inter-period price changes.

$$\frac{\partial \log \Delta P_t(R)}{\partial R} = \begin{cases} < 0, & \text{if } (A_t - A_{t-1}) < 0 (\text{demand is falling}) \\ > 0, & \text{if } (A_t - A_{t-1}) > 0 (\text{demand is rising}) \end{cases}$$

D Power Plant Summary Statistics 10 Market Sample

Table 12 presents summary statistics for generators at the most disaggregated level of fuel source. The full 10 market sample contains data from 3,902 plants

and accounts for over 823 GW of installed nameplate capacity around the country.

Table 12: Summary of Generating Infrastructure

Fuel Type	10 Market Sample				All Plants in Data			
	Plants	Total NP (MW)	% of Plants	% of NP	Plants	Total NP (MW)	% of Plants	% of NP
Hydroelectric	1,043	80,982.0	26.7	9.8	1,440	101,616.0	24.9	9.0
Wind	268	22,261.9	6.9	2.7	563	39,126.6	9.7	3.5
Solar	92	2,804.1	2.4	0.3	109	2,929.3	1.9	0.3
Nuclear	46	77,421.2	1.2	9.4	59	96,987.8	1.0	8.6
Coal	266	163,828.4	6.8	19.9	397	245,995.8	6.9	21.7
Natural Gas	1,131	362,353.9	29.0	44.0	1,552	495,732.2	26.8	43.7
Petroleum	509	92,380.1	13.0	11.2	989	124,343.8	17.1	11.0
Other	547	21,107.6	14.0	2.6	684	26,615.3	11.8	2.3
All Fuels	3,902	823,139.2	100.0	100.0	5,793	1,133,346.8	100.0	100.0

E Line Losses

The presence of lines losses is one of the physical realities of power markets that restricts the distance between the market hubs and those plants that can profitably supply it. The flow of electricity from a generation to load node of the transmission network or grid is limited by several properties ³¹. The proliferation of higher voltage lines has facilitated transmission over longer distances. When electrical energy is transmitted over a line, some of it dissipates as heat. Therefore, more power must be generated at the point of production to serve a load located further away. To be more precise, power is equal to the product of the voltage and the current ($P = V \cdot I$). Line losses are equal to the product of current squared and the resistance of the line, $LL = I^2 \cdot R$. Resistance

³¹The capacity of transmission lines to transmit power is constrained by the conductivity and other physical characteristics of the wires, the prevailing weather and temperature conditions, and the network structure of the grid. The relative state of demand may influence which lines are congested in the sense that no additional power can be transmitted without sacrificing reliability concerns. Therefore, the path over which electrons move between given points in the grid is subject to temporal variation.

is directly proportional to the distance over which electricity is transmitted. The further away a load node is from a given generator node on the grid the more expensive it is to generate and deliver the demanded quantity of power. Increasing with this distance is the probability that some other producer will be able to supply electricity at a more competitive price³².

F Estimating the Severity of the Current California Drought

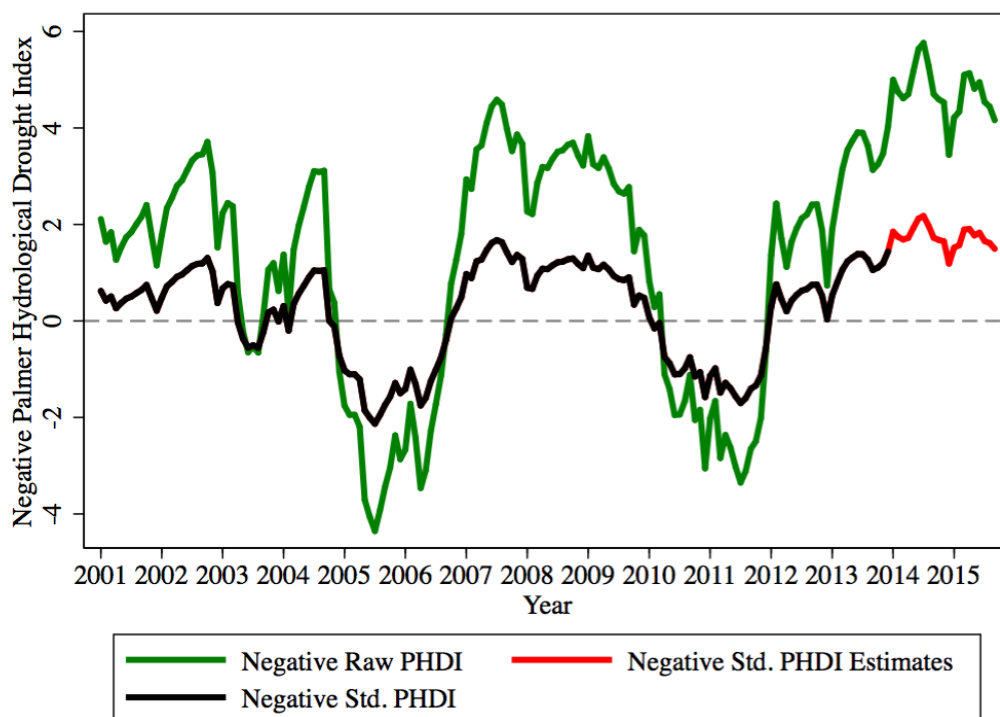
In order to estimate the cost of the current drought in California, it is necessary to determine the severity of the drought at the end of my sample and then on to the present. The out-of-sample values for my standardized PHDI variable are needed in order to seamlessly apply the drought cost estimates developed for observations in the sample period. This estimate assumes that the distribution of drought is not fundamentally changing between the end of my sample and the present. Figure 1 shows the raw negative PHDI measure as well as the in-sample and out-of-sample estimates for standardized PHDI.

G Weighting Schemes for Climate Division

The climate division drought series that are used to construct the market level drought variables can be weighted by several different variables. The main

³²Calculations that can be found in the appendix suggest that resistance losses on a line of 500 kilometers amount to about 2.5 percent of the power originally generated for a 1 GW plant operating at nameplate capacity and transmitting over a 765kV line. This percent figure does not include coronal losses that are especially dependent on temperature and precipitation

Figure 1: Historical and Project Sample Standardized Values of PHDI in California



analysis presented in section 1.5 used the hydroelectric nameplate capacity to weight each constituent series. This hydroelectric nameplate weighting scheme is preferred as it ties the relative importance of each division’s drought data to the presence and scale of hydroelectric generating facilities. The mechanism through which drought is hypothesized to impact wholesale electricity price volatility requires the presence of relatively large hydroelectric plants, possibly possessing market power.

Drought is not hypothesized to impact these markets through production changes at facilities employing thermal methods of electricity generation. It is true that thermal generating plants draw water from some of the same streams and rivers utilized directly for their hydroelectric potential. Further-

more, drought or high local temperatures can reduce the potential generating capacity of a thermal plant. However, the effects on thermal output of drought are second order relative to those confronting hydroelectric generation. While water resources are converted into the steam that turns the turbines of thermal plants, generation at these plants is relatively robust to fluctuations in the temperature of adjacent surface water. Hydroelectric generation is not as robust to fluctuations in the available water resources. To be sure, flood and drought mitigation are central to the missions of many multipurpose dams in the United States and around the globe. The ability of these dams to generate power and their agency with respect to production scheduling decisions can be greatly impacted by prevailing water availability. Large dams in the Pacific Northwest report being forced to generate electricity in periods of peak streamflow and low aggregate demand to avoid potential environmental damage that could be wrought on local aquatic life by excessive spilling³³

The analysis presented in Section 1.5 has also been conducted using alternate weighting schemes. As a robustness check, the baseline regressions have been rerun using a version of each drought metric that is constructed from the drought series of constituent climate divisions and weighted by their respective areas. The main findings of the empirical section are robust to these changes in weighting schemes.

³³A dam can either direct water through its turbines to generate electricity or spill the water directly through the dam's sluice gates. Generation may not be economically justifiable during some periods of excess water availability. Environmental constraints on spilling may lead some dam operators to schedule generation in an inefficient manner.

H Market Hub Physical Locations

Table 13 details the physical locations chosen to represent each of the market hubs. Some of these selections were obvious, while others required considerable research using google maps and a variety of web sources from the EIA and local plant operators. Given the methodology for assigning climate divisions to markets, the findings are unlikely to change in the presence of minor permutations to the market hub location. That is, a shift of a Market hub by several kilometers will generally not change the set of climate divisions with centroids within 500 km of the hub. If the assigned set of climate divisions does not change, the results will not either.

Table 13: Imputed Wholesale Market Locations

Price Hub	Latitude	Longitude	Actual placement
NEPOOL Mass Hub New England	42.186541	-72.637886	ISO New England, 1 Sullivan Road, Holyoke, MA 01040
PJM West Pennsylvania	40.454228	-80.569914	Wylie Ridge Substation Weirton, WV 26062
ERCOT Houston	30.090292	-95.605827	Northwester Houston (followed right of ways)
Indiana	39.751975	-86.181154	Midwest ISO
Entergy Louisiana	29.946938	-90.147940	Entergy 1617 River Road Westwego, LA 70094
Mid Columbia	45.595261	-121.113963	BPA Celilo Substation and Converter Station
SP 15 - Southern California	34.085146	-118.143296	Southern California Edison Co., 501 S Marengo Ave, Alhambra, CA 91801-1955
NP 15 - Northern California	37.712375	-121.565242	Altamont Pass Wind Farm Substation, Tracy, CA 95391
Palo Verde	33.385142	-112.859801	Palo Verde Nuclear Generating Station
ERCOT SOUTH Texas	30.572001	-97.440203	800 Airport Rd, Taylor, TX 76574

I Heat Content and Net Generation: All Fuels

An alternative specification is also examined for modeling the response of energy inputs to drought. The marginal plant in most regions burns natural gas to generate electricity. Therefore, the national average natural gas price paid by electrical power producers, NGP_t , is a good indicator of the cost of alternative production.³⁴ The full set of heat content and share of net generation regressions using the alternative specification are presented in Table 14 and Table 15 for completeness. Table 16 presents the full set of regression results for all dependent variables using the original specification.

Table 14: Heat Content by Fuel Group and the Impact of Drought

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Hydro	Coal	Natural Gas	Petroleum	Nuclear	Solar	Wind	Other	Total
PHDI	-94.52*** (18.666)	23.26 (18.262)	60.59** (19.800)	-23.44* (9.534)	-10.60 (8.564)	0.536 (0.355)	15.42 (11.200)	-2.784 (1.569)	-31.54 (29.931)
CDD	-47.03 (24.527)	381.2*** (63.177)	714.4*** (131.872)	63.27** (19.475)	49.56* (21.409)	2.719 (2.252)	11.67* (5.922)	0.573 (1.394)	1176.3*** (178.575)
NGP	23.21** (8.359)	117.9*** (15.616)	-56.75*** (11.736)	19.32*** (5.424)	8.329 (8.875)	-0.0863 (0.065)	-4.813*** (1.169)	1.202 (0.691)	108.3*** (22.700)
Baseline	797.4	5725.6	1581.4	338.0	2281.6	0.128	22.93	303.0	11050.1
Observations	47,596								

The dependent variable in each regression is the energy inputs for a given fuel group.

Cluster robust standard errors are presented in parentheses with significance denoted: *, $p < 0.10$; **, $p < 0.05$; $p < 0.01$, ***.

PHDI, CDD and NGP are standardized to have a mean of zero and a standard deviation of one.

The units for all coefficient estimates are billions of Btus. The sample period is 2002 through 2013.

³⁴As the natural gas price data is available for years after 2001, the sample is set to January of 2002 through December of 2013. The use of state-level natural gas prices was also investigated. In some cases only one firm sells or purchases natural gas for power generation in a given state. Out of concern for privacy, price observations are missing in such cases. The more disaggregated state data is therefore incomplete for the national analysis performed here.

Table 15: Share of Net Generation by Fuel Group and Drought

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Hydro	Coal	Natural Gas	Nuclear	Petroleum	Wind	Solar	Other
PHDI	-0.00809*** (0.002)	0.00336 (0.002)	0.00688* (0.003)	0.000350 (0.001)	-0.000703 (0.001)	-0.00192 (0.001)	0.0000540 (0.000)	0.0000576 (0.000)
CDD	-0.00862 (0.005)	-0.00424 (0.004)	0.0212*** (0.004)	-0.0126*** (0.003)	0.00339* (0.001)	0.00216 (0.001)	-0.0000142 (0.000)	-0.00131* (0.001)
NGP	0.00115 (0.001)	0.00679*** (0.002)	-0.00881*** (0.002)	-0.000535 (0.001)	0.00181** (0.001)	-0.000692** (0.000)	0.00000287 (0.000)	0.000277 (0.000)
Average Share	0.0947	0.521	0.137	0.188	0.0320	0.00323	-0.000148	0.0237
Observations	6,912							

The dependent variable in each regression is the share of net generation from the given fuel group. Cluster robust standard errors are presented in parentheses with significance denoted: *, $p < 0.10$; **, $p < 0.05$; $p < 0.01$, ***. PHDI, CDD and NGP are standardized to have a mean of zero and a standard deviation of one. The units for all coefficient are percent share of net generation. The sample period is 2002 through 2013.

Table 16: Drought and Heat Content by Fuel Group

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Hydro	Coal	Natural Gas	Nuclear	Petroleum	Wind	Solar	Other	Total
$PHDI_{s,t}$	-746.2** (235.651)	146.3 (120.420)	297.9 (216.888)	-47.12 (55.344)	-158.2 (129.482)	70.75 (152.907)	3.597 (4.092)	-34.12** (12.172)	-467.1* (225.028)
$CDD_{s,t}$	-388.4 (331.986)	2946.8*** (666.581)	5288.1** (1945.115)	509.5*** (144.339)	444.0 (340.405)	77.87 (59.108)	5.260 (4.331)	16.23 (14.087)	8899.4** (2589.260)
Baseline	5,180.9	36,786.9	11,963.4	15,770.7	1,672.2	175.7	3.405	2,053.4	73,606.6
Observations	6,912								

The dependent variable in each regression is the energy inputs for a given fuel group. Cluster robust standard errors are presented in parentheses with significance denoted: *, $p < 0.10$; **, $p < 0.05$; $p < 0.01$, ***. PHDI and CDD are standardized to have a mean of zero and a standard deviation of one. The units for all coefficient estimates are billions of Btus. The sample period is 2002 through 2013.

J Aggregation to the Climate Division and State Level

One empirical complication of conducting analysis at the climate division level is the presence of zeros and negative values in the dependent variables. Climate divisions, as sub-state level, environmentally-informed regions, may contain no plants producing power with a given fuel group during a given month. As a result, such division-month observations record zero energy inputs to electrical production and no net generation for the corresponding months. Net generation can obtain negative values for a plant if the plant uses more electricity

than it produces.³⁵ Even when plants are aggregated within fuel group to the climate division level, negative net generation values are obtained for a small portion of the original sample. Aggregating to the state level, mitigates the severity of the zeros problem and offers a level of analysis that is better suited to controlling for state-level institutional differences in power markets.³⁶ Climate divisions offer the most geographically disaggregated level of analysis, which is preferable for evaluating the impacts of environmental factors. However, as electricity market participants are often subject to state level regulations in addition to federal laws, analysis at the state level lends additional robustness to the findings of chapter 1. Equation (1.3) presents the specification used to evaluate state level net generation by fuel group and how it responds to drought, demand for cooling services, and natural gas prices.

K The Appearance of Drought

When the photo in Figure 2 was taken on July 31, 2015, the 1.99 million acre feet of water stored in Lake Shasta accounted for 44 percent of the total capacity and 62 percent of the historical average for that date.³⁷ Recreational facilities such as the one pictured are an example of a competing use of the water that flows through the dam. While neither power generation or recreational

³⁵This may happen when a plant is down for maintenance or uprating, the most negative minimum value among the fuel groups evaluated was found for nuclear. Nuclear plants generally produce large quantities of base load power, but require considerable amounts of power to operate cooling and other systems while the plant is down for refueling.

³⁶When the data is aggregated to the state level only the nuclear fuel group contains negative observations for the heat content used for electrical generation. Net generation still obtains negative values for all fuel groups except solar, wind and total.

³⁷This reservoir level data comes from the California Department of Water Resources and is made available through the California Data Exchange Center.

boating are consumptive uses of water, the former cannot happen through hydroelectric facilities without releasing the water downstream, prohibiting its local use. The second set of uses is impacted if too little water is kept behind the dam. Safely rafting in the relatively shallow parts of the reservoir is also prohibited by the proximity of the water level to the rocky and sediment-laden lakebed. Numerous campgrounds sprinkled around the edge of the lake are much less attractive destinations when the water level is so low.

Figure 2: Shasta Lake, CA in July 2015



Photo Source: Author

L Lobbying Data Appendix

The data used in chapter 2 is primarily drawn from the xml files of disclosure filings provided to the public through the Senate Office of Public Records'

website. Google Refine (now Open Refine) was used to format the xml files in an intelligible manner and clean the data prior to statistical analysis. While the disclosure forms all render comparable data structures, the presentation of values within cells is prone to heterogeneity in the reports. The same firm will often capitalize its name in several different fashions and misspellings of responses can potentially confound examination. One possible explanation for this inconsistency is that multiple lobbyists may be tasked with filling out the disclosure filings related to a given client- registrant pair's efforts.

I use the fingerprinting method of key collision found in Google Refine to group responses to categorical variables where appropriate. This algorithm trims leading and trailing white spaces within a value, renders the response in lower case while removing all punctuation and finally groups response values by key common substrings (keys). Fingerprinting is the default method of key collision because it minimizes the possibility for false positives, as the variation it eliminates is unlikely to differentiate truly distinct values.

While this method consolidates variously represented (yet indistinct) responses, it fails to catch all occurrences of this problem in the data. Therefore, a second pass is made on the data using a variation of the fingerprinting method just described. The size of keys, measured in character length, can be altered. Smaller keys improve the ability of the algorithm to catch similar values, but this comes at the cost of an increase in the probability of false positives. To counter this potential problem, all changes are manually reviewed for accuracy. In order to ensure that different years of data are cleaned in the same manner, I

develop a code in JSON to replicate my cleaning algorithm consistently across samples.³⁸ The possibility for minor measurement error remains, but further efforts at name verification produce no immediate improvements over the employed method. That is, manual examination of a sample of the data reveals no failures of the cleaning algorithm to properly group categorical responses.

The Center for Responsive Politics categorizes lobbying clients by their rough sector and industry. The CRP utilizes about 400 distinct categories. These groupings were developed specifically to define different interest groups rather than industrial categories. The analysis presented within chapter 2 has used the CRP's categorization scheme, but future work will test the robustness of my findings through employing alternate industry indicators.

The three key count variables detailing the number of government agencies contacted, the number of lobbyists hired and the number of issues lobbied, require additional cleaning to eliminate all measurement error. A small yet positive fraction of filings contains the name of a given lobbyist twice. The method that follows has been tested for efficacy, but is not yet implemented. The names of all lobbyists are included on the filing report. I construct a string that concatenates all these names with the pipe character forming a separator. These names often contain commas and other punctuation that can complicate the cleaning process. The algorithm employed to turn these messy strings into reliable data follows.

³⁸JSON, which stands for JavaScript Object Notation, is a language independent lightweight data- interchange text format that is derived from a subset of the JavaScript Programming Language. Both humans and computers read JSON with ease. The JSON code used in this project contains over 300 commands and is around 6,500 lines long.

First, all commas are eliminated from the concatenated string. Next the string is converted to an array, splitting the string at the pipe characters. Third, the resulting array is evaluated with duplicate elements being dropped. Once the array contains only unique elements, it is transformed back into a concatenated string. The difference in the number of characters in the resulting string is compared with and without the separator characters. The resulting number is increased by one to get the number of distinct responses for a given categorical variable.

As a robustness check and in order to evaluate changes in the extensive margin of lobbying, I balance the panel of all firms that ever file a lobbying disclosure form over the 2009 to 2012 period. Zero values are imputed for organization-period pairs that are not observed in the data. The fact that an organization that can be compelled to lobby decides not to in a given period is valuable information. We should like to know when to expect a firm or other organization to lobby actively. Fixed-value variables such as industry and client state can be imputed for missing observations from the reports filed in other time periods. All filing specific data is entered as zero in the periods for which no disclosures are filed.

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