Dynamic Natural Monopoly Regulation: Time Inconsistency, Moral Hazard, and Political Environments

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Abstract

This paper quantitatively assesses time inconsistency, moral hazard, and political ideology in monopoly regulation of electricity distribution. We specify and estimate a dynamic model of utility regulation featuring investment and moral hazard. We find under-investment in electricity distribution capital aiming to reduce power outages, and use the estimated model to quantify the value of regulatory commitment in inducing greater investment. Furthermore, more conservative political environments grant higher regulated returns, but have higher rates of electricity loss. Using the estimated model, we quantify how conservative regulators thus mitigate welfare losses due to time inconsistency, but worsen losses from moral hazard.

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1 Introduction

In macroeconomics, public finance, and industrial organization and regulation, policy makers suffer from the inability to credibly commit to future policies (Coase (1972), Kydland and Prescott (1977)) and from the existence of information that is privately known to the agents subject to their policies (Mirrlees (1971), Baron and Myerson (1982)). These two obstacles, "time inconsistency" and "asymmetric information," make it difficult, if not impossible, for regulation to achieve first-best policies. This paper analyzes these two forces and their interaction with the political environment in the context of regulating the U.S. electricity distribution industry, a natural monopoly sector responsible for delivering electricity to final consumers.

The time inconsistency problem in this context stems from the possibility of regulatory hold-up in rate-of-return regulation. The regulator would like to commit to a fair return on irreversible investments *ex ante*. Once the investments are sunk, the regulator is tempted to adjudicate a lower return than promised thereby expropriating sunk investments (Baron and Besanko (1987), Lewis and Sappington (1991), Blackmon and Zeckhauser (1992), Gilbert and Newbery (1994), Armstrong and Sappington (2007)). The utility realizes this dynamic, resulting in under-investment by the regulated utility which manifests itself as an aging infrastructure prone to too many power outages. The asymmetric information problem in our context is static moral hazard: the utility can take costly actions that reduce per-period procurement costs, but the regulator cannot directly measure the extent of these actions (Baron and Myerson (1982), Laffont and Tirole (1993) and Armstrong and Sappington (2007)).

These two forces interact with the political environment. Regulatory environments which place a higher weight on utility profits vis-à-vis consumer surplus grant higher rates of return. This in turn encourages more investment, alleviating inefficiencies due to time inconsistency and the fear of regulatory hold-up. That is, utility-friendly political environments suffer less from the time inconsistency problem, because such a higher weight on utility profits essentially functions as a commitment device. However, these regulatory environments engage in less intense auditing of the utility's unobserved effort choices, leading to more inefficiency in production, exacerbating the problem of moral hazard.

We specify and estimate a dynamic game theoretic model of regulator-utility interaction that captures these effects. We subsequently use the estimated model to quantify the welfare losses from time inconsistency and moral hazard. We simulate rules, such as regulatory commitment to future rate of return policies and minimum auditing requirements, which are aimed at mitigating these two problems.

In the model, the utility invests in capital and exerts effort that affects productivity to maximize its firm value. The regulator chooses a return on the utility's capital and a degree of auditing of the utility's effort choice to maximize a weighted average of utility profits and consumer surplus. The regulator cannot commit to future policies, but has a costly auditing technology. We use the solution concept of Markov Perfect Equilibrium. Markov perfection in the equilibrium notion implies a time-inconsistency problem for the regulator which in turn implies socially sub-optimal investment levels by the utility.

The core reduced-form empirical evidence supporting the formulation of the model is twofold. Using data spanning 1990 to 2012, first, we estimate that there is under-investment in electricity distribution capital in the U.S. To do so, we estimate the costs of improving reliability by capital investment. We combine those estimates with surveyed values of reliability. At current mean capital levels, the benefit of investment in reducing power outages exceeds the costs. Second, regulated rates of return are higher and energy loss is higher in more conservative regulatory environments. We measure the ideology of the regulatory environment using both within-state cross-time variation in the party affiliation of state regulatory commissioners, and cross-sectional variation in states' ideology proxied by how their U.S. Congressmen vote. Both results on regulator heterogeneity hold using either source of variation.

We estimate the model's parameters using a two-step estimation procedure following Bajari et al. (2007) and Pakes et al. (2007). Given the core empirical results and the model's comparative statics, we estimate that more conservative political environments place relatively more weight on utility profits than less conservative political environments. More weight on utility profits can be good for social welfare because it leads to stronger investment incentives, which in turn mitigates the time inconsistency problem. However, this effect must be traded-off with the tendency for lax auditing, which reduces managerial effort, productivity, and social welfare.

The estimated dynamic model allows for the evaluation of alternative institutions accounting for how the regulator and utility optimally readjust to changes in the environment. While one can use reduced form analyses to measure key relationships in the status quo, it is only with a dynamic model of strategic behavior that we can account for potential reactions to policy changes. Specifically, we simulate outcomes when (1) the regulator can commit to future rates of return, and (2) there are minimum auditing requirements for the regulator.[1] In the context of simulating commitment, the dynamic model accounts for the change in investment behavior taking into account their expectation over a long horizon.

In the first counterfactual with commitment, we find that regulators would like to substantially increase rates of return by 1.4 percentage points to provide incentives for capital investment. This result is consistent with recent efforts by some state legislatures to bypass the traditional regulatory process and legislate more investment in electricity distribution capital. The increase in the commitment rate or return raises steady state capital by 59%, and reduces power outages by 18%.

Concurrently, we find that tilting the regulatory commission towards conservatives as in Levine et al. (2005), analogous to the idea in Rogoff (1985) for central bankers, can mitigate the time inconsistency problem. We find that setting the rate of return policy to that of the most conservative regulator induces changes comparable to half of the changes under the full commitment scenario. In addition, given that conservative regulators worsen the moral hazard problem, minimum auditing requirements can complement such a policy. Minimum auditing requirements set at the level of the most liberal regulator reduce energy losses by 0.4 percentage points relative to the estimated status-quo.

[1] In Section 4 of the supplementary material, we also simulate outcomes of a setting in which the regulatory board must maintain a minimum representation of both the Democratic and Republican parties (“minority representation”).

Related Literature This paper contributes to literatures in both industrial organization and political economy. Within industrial organization and regulation, the closest papers are Timmins (2002), Wolak (1994), Gagnepain and Ivaldi (2002), and Abito (2014). Timmins (2002) estimates regulator preferences in a dynamic model of a municipal water utility. In that setting, the regulator controls the utility directly, leading to a theoretical formulation of a single-agent decision problem. By contrast, this paper studies a dynamic game where there is a strategic interaction between the regulator and the utility. Wolak (1994) pioneered the empirical study of the regulator-utility strategic interaction in static settings with asymmetric information. More recently, Gagnepain and Ivaldi (2002) and Abito (2014) have used static models of regulator-utility asymmetric information to study transportation service and environmental regulation of power generation, respectively. This paper adds an investment problem in parallel to the asymmetric information. Adding investment brings issues of commitment and dynamic decisions in regulation into focus. Lyon and Mayo (2005) study the possibility of regulatory hold-up in power generation. They conclude that observed capital disallowances for the time period they examine do not reflect regulatory hold-up. However, fear of regulatory hold-up can be present even without observing disallowances, because the utility is forward-looking. Levy and Spiller (1994) present a series of case studies on the regulation of telecommunications firms, mostly in developing countries. They conclude that "without... commitment long-term investment will not take place, [and] that achieving such commitment may require inflexible regulatory regimes." Our paper is also related to static production function estimates for electricity distribution such as Growitsch et al. (2009) and Nillesen and Pollitt (2011). On the political economy side, the most closely related papers are Besley and Coate (2003) and Leaver (2009). Besley and Coate (2003) compare electricity pricing under appointed and elected regulators. Leaver (2009) analyzes how regulators' desire to avoid public criticisms leads them to behave inefficiently in rate reviews.

More broadly, economic regulation is an important feature of banking, health insurance, water, waste management, and natural gas delivery. Regulators in these sectors are appointed by elected officials or elected themselves, whether by members of the Federal Reserve Board, state insurance commissioners, or state public utility commissioners. Therefore, different political environments can give rise to regulators who make systematically different decisions, which ultimately determine industry outcomes as we find in electric power distribution.

2 Institutional Background and Data

2.1 Institutional Background

The electricity industry supply chain consists of three levels: generation, transmission, and distribution. This paper focuses on distribution. Distribution is the final leg by which electricity is delivered locally to residences and businesses. Generation of electricity has been deregulated in many countries and U.S. states. Distribution is universally considered a natural monopoly. Most distribution is regulated in the U.S. by state "Public Utility Commissions" (PUC's) also known as "Public Service Commissions" and "State Utility Boards." The commissions' mandates are to ensure reliable and least cost delivery of electricity to end users.

The regulatory process centers on PUC's and utilities engaging in periodic "rate cases." A rate case is a quasi-judicial process through which the PUC determines the prices a utility will charge until its next rate case. The rate case can also serve as an informal venue for suggesting future behavior and discussing past behavior. In practice, regulation of electricity distribution in the U.S. is a hybrid of the theoretical extremes of rate-of-return (or cost-of-service) regulation and price cap regulation. Under rate-of-return regulation, a utility is granted rates that allow it to earn a fair rate of return on its capital and to recover its operating costs. Under price cap regulation, a utility's prices are capped indefinitely. PUC's in the U.S. have converged on a system of price cap regulation with periodic resetting to reflect changes in cost of service as detailed in Joskow (2007).

This model of regulation requires the regulator to determine the utility's revenue requirement. The utility is then allowed to charge prices to generate the revenue requirement. The revenue requirement must be high enough so that the utility can recover its prudent operating costs and earn a rate of return on its capital that is in line with other investments of similar risk (U.S. Supreme

Court (1944)). This requirement is vague enough that regulator discretion could result in variant outcomes for the same utility. Indeed, rate cases are prolonged affairs where the utility, regulator, and third parties present evidence and arguments to influence the ultimate revenue requirement. Furthermore, the regulator can disallow capital investments that do not meet a standard of "used and useful."

As a preview, our model replicates much, but not all, of the basic structure of the regulatory process in U.S. electricity distribution. Regulators will choose a rate of return and some level of auditing to determine a revenue requirement. The utility will choose its investment and productivity levels strategically. We will, for the sake of tractability and computation, abstract away from some other features of the actual regulator-utility dynamic relationship. We will not permit the regulator to disallow capital expenses directly, though we will permit the regulator to adjudicate rates of return below the utility's discount rate. We will ignore equilibrium in the financing market and capital structure. We will assume that a rate case happens every period. In reality, rate cases are less frequent. Finally, we will ignore terms of rate case settlements concerning prescriptions for specific investments, clauses that stipulate a minimum amount of time until the next rate case, an allocation of tariffs across residential, commercial, industrial, and transportation customer classes, and special considerations for low income or elderly consumers. See Lowell E. Alt (2006) for details on the rate setting process in the U.S.

2.2 Data

Characteristics of the Political Environment and Regulators: The data on the political environment consists of four components: two measures of political ideology, campaign financing rule, and the availability of ballot propositions. All these variables are measured at the state level, and measures of political ideology also vary over time. Our first measure of political ideology is the fraction of Republicans on the state PUC, which we label *Republican Influence*. Since the rate adjudication is conducted by the PUC, this measure directly captures the ideology of the regulators who make rate decisions.

Our second measure of political ideology is DW-NOMINATE score (henceforth "Nominate score"), which is a measure of U.S. Congressmen's ideological position developed by Keith T. Poole and Howard Rosenthal (see Poole and Rosenthal (2000)). We use it as a proxy for the ideology of the *state* overall, rather than U.S. Congressmen *per se*. Poole and Rosenthal (2000) analyze U.S. Congressmen's behavior in roll-call votes on bills, and estimate a random utility model in which a vote is determined by their position on ideological spectra and random taste shocks. Nominate score is the estimated ideological position of each congressman in each congress (two-year period). We aggregate U.S. Congressmen's Nominate score for each state-by-congress (two-year) observation, separately for the Senate and the House of Representatives. The value of this measure increases according to the degree of conservatism.

For campaign financing rule, we focus on whether the state places no restrictions on the amount of campaign donations from corporations to electoral candidates. We construct a dummy variable, *Unlimited Campaign*, that takes value one if the state does not restrict the amount of campaign donations. We use information provided by the National Conference of State Legislatures. As for the availability of ballot initiatives, we use the information provided by the Initiative and Referendum Institute. We construct a dummy variable, *Ballot*, that takes value one if ballot proposition is available in the state.

We use the "All Commissioners Data" developed by Janice Beecher and the Institute of Public Utilities Policy Research and Education at Michigan State University to determine the party affiliation of commissioners and whether they are appointed or elected, for each state and year.

Utilities and Rate Cases: We use four data sets on electric utilities: the Federal Energy Regulation Commission (FERC) Form 1 Annual Filing by Major Electric Utilities, the Energy Information Administration (EIA) Form 861 Annual Electric Power Industry report, the PA Consulting Electric Reliability database, and the Regulatory Research Associates (RRA) rate case database.

FERC Form 1 is filed annually by those utilities that exceed one million megawatt hours of annual sales in the previous three years. It details their balance sheet and cash flows on most aspects of their business. The key variables for our study are the net value of electricity distribution plant, operations and maintenance expenditures of distribution, and energy loss for the years 1990-2012.

Energy loss is recorded on Form 1 on page 401(a): "Electric Energy Account." Energy loss is equal to the difference between energy purchased or generated and energy delivered. The average ratio of electricity lost through distribution and transmission to total electricity generated is about 7% in the U.S., which translates to roughly $23 billion in 2010. Some amount of energy loss is unavoidable because of physics. However, the extent of losses is partially controlled by the utility. Utilities have electrical engineers who specialize in the efficient design, maintenance, and operation of power distribution systems. The configuration of the network of lines and transformers and the age and quality of transformers are controllable factors that affect energy loss.

EIA Form 861 provides data by utility and state by year on number of customers, sales, and revenues by customer class (residential, commercial, industrial, or transportation).

The PA Consulting reliability database provides reliability metrics by utility by year. We focus on the measure of System Average Interruption Duration Index (SAIDI), excluding major events which generally correspond to days when reliability is six standard deviations from the mean, though exact definitions vary over time and across utilities. SAIDI measures the average number of minutes of outage per customer-year.[2] A high value for SAIDI implies poor reliability.

The data on electricity rate cases is composed of a total of 729 cases on 144 utilities from 50 states, from 1990 to 2012. It includes four key variables for each rate case: return on equity[3], return on capital, equity ratio, and the change in revenues approved, as summarized in Panel D of Table 1.

We also use data on utility territory weather, demographics, and terrain. For weather, we use the Storm Events Database from the National Weather Service. We aggregate the variables rain,

[2]SAIDI is equal to the sum of all customer interruption durations divided by the total number of customers. We also have data on System Average Interruption Frequency Index (SAIFI) and Customer Average Interruption Duration Index (CAIDI). SAIFI does not account for duration of interruption. CAIDI is the average duration conditional on having an interruption. We focus on SAIDI as this measure includes both frequency and duration.

[3]The capital used by utilities to fund investments commonly comes from three sources: the sale of common stock (equity), preferred stock, and bonds (debt). The weighted-average cost of capital, where the equity ratio is the weight on equity, becomes the rate of return on capital that a utility is allowed to earn. Thus, return on capital is a function of return on equity and equity ratio. In the regressions in Section 4.1, we document results on return on equity because return on capital is a noisier measure of regulators' discretion due to random variation in equity ratio.

snow, extreme wind, extreme cold, and tornado for a given utility territory by year. The Storm Events Database provides regional geographic descriptions such as "Nevada, South" or "New York, Coastal." We manually assigned utilities to these regions We create interactions of these variables with measurements of tree coverage, or "canopy", from the National Land Cover Database produced by the Multi-Resolution Land Characteristics Consortium. Finally, we use population density and median household income aggregated to utility territory from the 2000 U.S. census.

3 Model

We specify an infinite-horizon dynamic game between a regulator and an electricity distribution utility. Each period is one year.[4] The players discount future payoffs with discount factor β.

The state space consists of the value of the utility's capital, k, and the regulator's weight on consumer surplus versus utility profits, α. Each period, the regulator chooses a rate of return, r, on the utility's capital base and leniency of auditing, κ ($\kappa \in [0,1]$), or equivalently, audit intensity $1-\kappa$. After the utility observes the regulator's choices, it decides how much to invest in distribution capital and how much managerial effort to engage in to reduce energy loss.

The correspondence between pass-through and auditing captures that a regulator must initiate an audit to deviate from automatic pass-through of input costs. When regulators are maximally lenient in auditing ($\kappa = 1$), i.e., minimally intense in auditing ($1-\kappa = 0$), they completely pass through changes in input costs of electricity in consumer prices. κ is an index of how high-powered the regulator sets the incentives for electricity input cost reduction.

The regulator's weight on consumer surplus evolves exogenously between periods according to a Markov process. The capital base evolves according to the investment level chosen by the utility. We now detail the players' decision problems in terms of a set of parameters to be estimated and

[4] In the data, rate cases do not take place every year for every utility. In the model, we assume a rate case occurs each period for tractability. For the years without a rate case, we assume that the outcome of the hypothetical rate case in the model is the same as the previous rate case. One partial justification is that there exist rate cases that make very minor adjustments to previous rates: in twenty seven rate cases, the absolute value of the percentage change in the revenue requirement is less than one percent. Furthermore, in 23.26% of rate cases, there is also a rate case in the previous year for the same utility in the same state. These two patterns suggest relatively low fixed costs to initiating rate cases. Endogenizing rate case timing would be an interesting extension for future work.

define the equilibrium notion.

3.1 Consumer Demand System

We assume a simple inelastic demand structure. An identical mass of consumers of size N are each willing to consume $\frac{Q}{N}$ units of electricity up to a choke price $\bar{p}+\tilde{\beta}\log\frac{k}{N}$ per unit:

$$D(p)=\begin{cases} Q & \text{if } p\leq \bar{p}+\tilde{\beta}\log\frac{k}{N} \\ 0 & \text{otherwise} \end{cases}.$$

$\tilde{\beta}$ is a parameter that captures a consumer's preference for a utility to have a higher capital base. All else equal, a higher capital base per customer results in a more reliable electric system as will be shown empirically in Section 4.3. This demand specification implies that consumers are perfectly inelastic with respect to price up to the choke price. Joskow and Tirole (2007) similarly assume inelastic consumers in a recent theoretical study of electricity reliability. Furthermore, estimated elasticities for electricity consumption are generally low, on the order of -0.05 to -0.5 (Bernstein and Griffin (2005), Ito (2014)). Including a downward sloping demand function is conceptually simple, but slows down computation by requiring the solution to a nonlinear equation to move between revenue requirement and consumer surplus.

The per unit price that consumers ultimately face is determined so that the revenue to the utility allows the utility to recoup its materials costs and the adjudicated return on its capital base:

$$p=\frac{rk+p_f Q(1+\kappa(\bar{e}-e+\varepsilon))}{Q} \tag{1}$$

where p_f is the materials cost that reflects the input cost of electricity,[5] r is the regulated rate of return on the utility's capital base k, and κ is the leniency of auditing, or equivalently, the pass-

[5]Rate cases are completed and prices (*base rates*) are determined before the effort by the utility and energy loss are realized. However, an increase in the cost of power purchase due to an unanticipated increase in energy loss can typically be added *ex-post* to the price as a *surcharge*. Thus, inclusion of both regulator's audit κ and utility's effort e in determination of p is consistent with the practice. This practice also justifies our assumption of inelastic electricity demand, because consumers are often unaware of the exact price of the electricity at the point of consumption.

through fraction chosen by the regulator, whose problem we describe in Section 3.3. $\bar{e}$ is the amount of energy loss one could expect with zero effort, e is the managerial effort level chosen by the utility, and ε is a random disturbance in the energy loss. We will elaborate on the determination of these variables as results of the utility and regulator optimization problems below. For now, it suffices to know that this price relationship is an accounting identity. pQ is the revenue requirement for the utility. The regulator and utility only control price indirectly through the choice variables that determine the revenue requirement.

It follows that per-period consumer surplus is:

$$CS = (\bar{p} + \tilde{\beta} \log \frac{k}{N})Q - rk - p_f Q(1 + \kappa(\bar{e} - e + \varepsilon)).$$

The first term is the utility, in dollars, enjoyed by consuming quantity Q of electricity. The second and the third terms are the total expenditure by consumers to the utility.

3.2 Utility's Problem

The per-period utility payoff, π, is a function of the total quantity, unit price, materials (purchased power) input cost, investment expenses, and managerial effort cost:

$$\pi(k', e; k, r, \kappa) = pQ - (k' - (1-\delta)k) - \eta(k' - (1-\delta)k)^2 - p_f Q(1 + \bar{e} - e + \varepsilon) - \gamma_e e^2 + \sigma_i u_i$$

where k' is next period's capital base, η is the coefficient on a quadratic adjustment cost in capital, δ is the capital depreciation rate, and γ_e is an effort cost parameter. u_i is an investment-level-specific i.i.d. error term which follows a standard extreme value distribution multiplied by coefficient σ_i to rationalize the dispersion in investment that is not explained by variation across the state space. u_i is known to the utility when it makes its investment choice, but the regulator only knows its distribution. η's presence improves the model fit on investment. Such a term has been used elsewhere in estimating dynamic models of investment, e.g., in Ryan (2012).

Effort reduces energy loss. In other words, effort increases the productivity of the firm by reducing the amount of materials needed to deliver a certain amount of output. The notion of the moral hazard problem here is that the utility exerts unobservable effort level e, the regulator observes the total energy loss, which is a noisy outcome partially determined by e, and the regulator's "contract" for the utility is linear in this outcome. Effort is chosen prior to the realization of ε. Furthermore, ε is iid across firms and over time. These assumptions imply that the moral hazard problem is static and resolved within each period.

We assume effort is the only determinant of the materials cost other than the random disturbance, which implies that capital does not affect materials cost. Furthermore, effort does not reduce outages, nor do we model the choice of operations and maintenance expenses to reduce outages. While this separation is more stark than in reality, it is a reasonable modeling assumption for several reasons. The capital expenditures for reducing line loss – replacing the worst performing transformers – are understood to be small relative to overall investment. In contrast, capital expenditures for improving reliability, such as putting lines underground, fortifying lines, adding circuit breakers and upgrading substations, are large. As a result, empirically we cannot estimate the beneficial impact of capital expenditures on line loss in the same way we do for reliability, and we do not include this avenue in the baseline theoretical model. In Section 5 in the supplementary material, we solve a specification that allows for capital additions to reduce line losses. The main qualitative conclusions of the counterfactuals do not change in the alternative specification. Quantitatively, allowing capital to reduce line loss both increases the time inconsistency problem which we diagnose and softens the trade-offs between having conservative versus liberal regulators.

The optimal choice of k' does not depend on κ or this period's r because neither the cost nor the benefits of the investment depend on those choices. The benefits will depend on the *future stream* of r choices, but not this period's r. Substituting the price accounting identity (equation (1) on page 12) into the utility's per-period payoff function simplifies the payoff function to

$$\pi(k,k',e,Q,p) = rk - (k' - (1-\delta)k) - \eta(k' - (1-\delta)k)^2 + (\kappa - 1)p_f Q(\bar{e} - e + \varepsilon) - \gamma_e e^2 + \sigma_i u_i.$$

The utility's investment level determines its capital state next period. The utility's dynamic problem is to choose effort and investment to maximize its expected discounted value:

$$v_u(k,\alpha) = \max_{k',e} E[\pi(k,k',e,r,\kappa)|u_i] + \beta E[v_u(k',\alpha')|k,k',e,r,\kappa,\alpha].$$

The utility's optimal effort choice has an analytical expression which we use in estimation:

$$e^*(\kappa) = \min\left\{\frac{-(\kappa-1)p_f Q}{2\gamma_e}, \bar{e}\right\}$$

When κ is equal to one, which implies minimal audit intensity ($1-\kappa=0$), the utility is reimbursed every cent of electricity input expenses. Thus, it will exert zero effort. If κ is equal to zero, then the utility bears the full cost electricity lost in distribution. Effort is a function of the regulator's audit intensity because the regulator moves first within the period.

3.3 Regulator's Problem

The regulator's payoff is the geometric mean[6] of expected discounted consumer welfare, or consumer value (CV) as in Mermelstein et al. (2012) for dynamic merger analysis, and the utility value function, v_u, minus the cost of auditing and the cost of deviating from the market rate of return:

$$u_R(r,\kappa;\alpha,k) = E[CV(r,\kappa,k,e)|r,\kappa]^{\alpha} E[v_u(r,\kappa,k,e)|r,\kappa]^{1-\alpha} - \gamma_\kappa(1-\kappa)^2 - \gamma_r(r-r^m)^2$$

where α is the weight the regulator puts on consumer welfare against utility value, r is the regulated rate of return, $1-\kappa$ is the audit intensity, γ_κ is an auditing cost parameter to be estimated, r^m is a benchmark market return for utilities, and γ_r is an adjustment cost parameter to be estimated. CV is the value function for consumer surplus:

$$E[CV(r,\kappa,k,e)|r,\kappa] = \sum_{\tau=t}^{\infty} \beta^{\tau-t} E[(\bar{p}+\tilde{\beta}\log\frac{k_\tau}{N})Q - r_\tau k_\tau - p_f Q(1+\kappa_\tau(\bar{e}_\tau - e_\tau + \varepsilon_\tau))|r_t,\kappa_t]].$$

[6]An important principle in rate regulation is to render a non-negative economic profit to utilities, which is a type of "individual rationality condition". The usage of geometric mean in this specification ensures a non-negative value of the firm in the solution in a tractable manner. This specification is also analogous to the Nash bargaining model in which players maximize the geometric mean of their utilities.

By default the utility is reimbursed for its total electricity input cost. The regulator incurs a cost for deviating from the default of full pass-through of electricity input costs: $\gamma_\kappa(1-\kappa)^2$. This cost of deviating from full pass-through matches the institutional reality of automatic adjustment mechanisms for recovery of electricity input costs. Automatic adjustment clauses adjust electricity prices, without a rate case, to reflect changes in the cost of input electricity. Such adjustments are subject to prudence reviews. The modeled cost of deviating from full pass-through is the cost of engaging in a prudence review. In a prudence review, the regulator must investigate, solicit testimony, and fend off legal challenges by the utility for disallowing the utility's electricity costs. The further the regulator moves away from full pass-through, the more cost it incurs. This desire for full pass-through creates a trade-off with providing incentives for effort.

Line loss is a noisy outcome resulting from the utility's effort choice. The regulator uses a linear contract in the observable outcome, as in Holmstrom and Milgrom (1987), to incentivize effort by the utility. The modeling of the regulator using automatic pass-through with periodic audits matches institutional reality. 99% of eligible utilities have automatic pass-through of purchased power according to SNL (2015). Furthermore, Graves et al. (2007) state that most automatic adjustment clauses are accompanied by periodic audits that can induce more detailed prudence reviews.

The term $\gamma_r(r-r^m)^2$ is an adjustment cost for deviating from a benchmark rate of return such as the average return for utilities across the country. A regulator who places all weight on utility profits would not be able in reality to adjudicate the implied rate of return to the utility. Consumer groups and lawmakers would object to the supra-normal profits enjoyed by investors in the utility relative to similar investments. A regulator who places more weight on utility profits can increase rates by small amounts, for example by accepting arguments that the utility in question is riskier than others, but only up to a certain degree.

The two terms, $\gamma_\kappa(1-\kappa)^2$ and $\gamma_r(r-r^m)^2$, in the regulator's per-period payoff are both disutility incurred by the regulator for deviating from a default action. Regulators with different weights on utility profits and consumer surplus will deviate from these defaults to differing degrees.

We assume that the weight on consumer surplus is a function of partisan composition of the commission and political ideology of the state. Specifically,

$$\alpha = a_0 + a_1 rep + a_2 d$$

where *rep* is the fraction of Republican commissioners in the state, d is the Nominate score of the utility's state, and the vector $\mathbf{a} \equiv (a_0, a_1, a_2)$ is a set of parameters to be estimated.

3.4 Equilibrium

We use the solution concept of Markov Perfect Equilibrium.

Definition. *A Markov Perfect Equilibrium consists of*

- *Policy functions for the utility:* $k'(k,\alpha,r,\kappa,u_i)$ *and* $e(k,\alpha,r,\kappa,u_i)$
- *Policy functions for the regulator:* $r(k,\alpha)$ *and* $\kappa(k,\alpha)$
- *Value function for the utility:* $v_u(k,\alpha)$
- *Value function for consumer surplus ("consumer value"):* $CV(k,\alpha)$

such that

1. *The utility's policies are optimal given its value function and the regulator's policy functions.*
2. *The regulator's policy functions are optimal given consumer value, the utility's value function, and the utility's policy functions.*
3. *The utility's value function and consumer value function are equal to the expected discounted sums of per-period payoffs implied by the policy functions of the regulator and utility.*

3.5 Discussion of the Game

There are two, somewhat separate, interactions between the regulator and the utility. The first involves the investment choice by the utility and the rate of return choice by the regulator. The second involves the effort choice by the utility and the audit intensity choice by the regulator. In this section, we discuss these two interactions, model predictions, and related conceptual issues.

In the first interaction, the regulator and utility are jointly determining the amount of investment in the distribution system. The regulator's instrument in this dimension is the regulated rate of return. In the second interaction, the utility can engage in unobservable effort, which affects the cost of service by decreasing the amount of electricity input needed to deliver a certain amount of output. The regulator's instrument in this dimension is the cost pass-through, or auditing policy.

3.5.1 Investment, Commitment, and Averch-Johnson Effect

If the utility expects a stream of high rates of return, it will invest more. The regulator cannot commit to a path of returns, however. Therefore, the incentives for investment arise indirectly through the utility's *expectation* of the regulated rates that the regulator adjudicates from period to period. This dynamic stands in contrast to the Averch-Johnson effect (Averch and Johnson (1962)) whereby rate-of-return regulation leads to over-investment in capital or a distortion in the capital-labor ratio towards capital. The idea of Averch-Johnson is straightforward. If a utility can borrow at rate s, and earns a regulated rate of return at $r > s$, then the utility will increase capital. The key distinction in our model is that r is *endogenously chosen* by the regulator *as a function of the capital base* to maximize the regulator's objective function. r may exceed s at some states of the world, but if the utility invests too much, then r will be endogenously chosen below s. This feature of the model might seem at odds with the regulatory requirement that a utility be allowed to earn a fair return on its capital. However, capital expenditures must be incurred prudently, and the resulting capital should generally be "used and useful." In our formulation, the discretion to decrease the rate of return substitutes for the possibility of capital disallowances when regulators have discretion over what is deemed "used and useful."

3.5.2 Cost Pass-Through, Automatic Adjustment, and Auditing

The utility bears the costs of unobservable effort to reduce energy loss by procuring electricity cost-effectively from nearby sources and prioritizing the tracking down of problems in the distribution network that are leading to loss. If the regulator fully passes through costs associated with energy loss without question, then the utility's management has no incentive to exert unobservable effort.[7] On the other hand, if the regulator deviates from full pass-through, he bears a cost because of automatic adjustment clauses. There is effectively a moral hazard problem in the game between the regulator and the utility. The regulator chooses how high-powered to set the incentives for the utility to exert unobservable effort through the fraction of electricity input costs it allows the utility to recoup. The regulator trades off setting high-powered incentives to reduce loss against the cost of deviating from its desire for full pass-through. This trade-off is analogous to the classic incentives versus insurance trade-off in moral hazard, where the desire for full pass-through, due to the existence of automatic adjustment clauses, stands in for the insurance incentive.

3.5.3 Predictions of the Model

The regulator's actions in both interactions are determined by α. Intuitively, the utility likes high returns and weak auditing. Therefore, the lower α, the higher the rate of return the regulator will adjudicate, and the less auditing it will engage in. To summarize these relationships, we numerically solved the model at a variety of parameter values to generate predictions of the model. Starting from the estimated parameters which we describe in later sections, we doubled, halved, tripled, and divided by three the parameters γ_e, γ_κ, γ_r, and η. We considered four alterations to the distribution of α. In two of them, we changed the support of α. In the other two, we made the transition matrix of α more persistent in one case and less persistent in the other. Finally, we made all pairwise combinations of these changes for a total of 182 different sets of parameters.[8] We find that for all combinations, the model makes consistent predictions on the sign of key relationships. Section 3.1 of the supplementary material provides details on the implementation and results. To summarize, the model generates the following predictions:

[7] For example, Hempling and Boonin (2008) states that "[cost pass-through mechanisms]... can produce disincentives for utility operational efficiency, since the clause allows the utility to recover cost increases, whether those cost increases arise from... (c) line losses." This document goes on to assert that an effective pass-through mechanism should contain meaningful possibilities for auditing the utility's operational efficiency to mitigate such concerns.

[8] There are twenty total individual parameter changes: four changes for each of the four parameters γ_e, γ_κ, γ_r, and η, two changes to the support of α distribution, and two changes to the persistence of α transition matrix. This gives $\binom{20}{2}$=190 pairwise combinations. Some of the pairs exactly offset each other, resulting in a total of 182 distinct sets of parameters.

Model Predictions

1. Utility's effort is increasing in α, while rate of return is decreasing in α.

2. Investment is decreasing in α.

3. Rate of return and investment are positively correlated when α is serially positively correlated. (As we parameterize α as a function of local political variables, it is natural that α is serially positively correlated.)

4. Reliability and α are negatively correlated when α is serially positively correlated.

In Section 4, we present a set of regression results that corroborate these predictions. We directly target some of these relationships, but not all, in the model estimation. Thus, those we do not target provide a test for validating the model. In Section 6, we compare the quantitative predictions of our model for these relationships at the estimated parameters to their analogs in the data. Now we discuss two conceptual issues behind our model.

3.5.4 Related Issue 1 – Necessary Conditions for a Time Inconsistency Problem

The model generates a time inconsistency problem for the regulator. In this subsection, we discuss the empirical basis for analyzing this industry in a model with time inconsistent regulator policies. The most direct evidence is that we estimate under-investment in the industry, i.e., the fact that in our data the benefit from a reliability improvement exceeds its cost. We derive this conclusion in Section 5.1. We complement this direct evidence with evidence on necessary conditions for the existence of a time inconsistency problem. The two necessary conditions are regulator discretion and forward-looking behavior by the utility. If the regulator has no discretion on the rate of return, then the rate of return will be dictated by external cost of capital conditions, and the utility would not fear negative regulatory conditions. At the same time, absent forward-looking behavior by the utility, there can be no time inconsistency problem. We provide evidence in Section 4.1 that regulators have discretion in setting the rate of return by showing that approved returns on equity correlate with regulatory ideology. As for the forward-looking behavior by the utility, its *existence* is self-evident from the fact that the utility invests at all. Here we present two pieces of evidence on its *significance*: (1) evidence on other sectors of the power industry from the literature, and (2) investment behavior by utilities in Illinois following a change in that state's regulatory environment.

Evidence from the Literature Several studies provide evidence that firms in the energy industry choose investment strategically in consideration of their uncertainty regarding future regulation. For example, Fabrizio (2012) studies the influence of regulatory uncertainty on investment in renewable energy generation in U.S. states for the period 1990-2010. She classifies the degree of uncertainty in the regulatory environment based on whether a state had previously repealed or suspended deregulation of the electricity industry. She finds that in regulatory environments that had previously repealed or suspended deregulation, policies on renewable portfolio standards tend to be less successful in inducing investment in renewable energy generating plants.

Ishii and Yan (2011) also study the influence of regulatory uncertainty, but focus on the investment by independent power producers in U.S. states for the period of 1996-2000. They first find that investment level was significantly lower three years prior to new state legislation that restructured the electricity industry, and investment level rose as the uncertainty about the legislation resolved itself. They also quote the following statement by an energy firm's CEO, which demonstrates the importance of stability in regulatory policies on energy firms' investment decisions:

> "Significant uncertainties that are unclear or unmanageable lead us to make decisions not to invest in projects affected by such uncertainties. One uncertainty that fits this description is the risk of adverse governmental laws or actions. In general, we choose to invest in markets where the regulator has made the commitment to develop rules that are transparent, stable, and fair. The rules do not have to be exactly what we want, so long as we can operate within their framework. Consequently, we look for markets where the rules of competition are clear, encouraged and relatively stable." (Geoffrey Roberts, President & CEO, Entergy Wholesale Operations, U.S. Senate Hearing on S.764, June 19, 2001)

Although the nature of the uncertainties studied in these papers is different from the time inconsistency problem we study, they are closely related in that both undermine policy stability and result in low investment. These studies validate our assumption that energy firms behave in a forward-looking manner in their investment decisions.

Investment Behavior by Distribution Utilities in Illinois Following a Change in Legislation Another piece of evidence on utilities' forward-looking behavior can be found in Illinois, an environment where a regulatory regime towards distribution has recently changed. The legislature in Illinois enacted legislation in 2011 to force the regulator to pay a designated return on new investments in the electricity distribution infrastructure. Amongst other measures, the *Energy Infrastructure Modernization Act* (EIMA) in Illinois authorized $2.6 billion in capital investment for Commonwealth Edison (ComEd), the electricity distributor serving greater Chicago. The EIMA authorized $565 millions in capital investment for Ameren Illinois, the second largest electric distributor in Illinois. One of the main explicit goals is reducing SAIDI by 20 percent. ComEd praised the act as "bringing greater stability to the regulatory process to incent investment in grid modernization." (McMahan (2012)).

We examine the rate of investment before and after this legislation by the two utilities in Illinois affected by the EIMA: Ameren Illinois and ComEd. For Ameren Illinois, mean investment, net of retirements, in the three years after the change in regulation was 3.6% compared to 2.0% in the three years prior. For ComEd, mean investment, net of retirements, in the three years after was 5.6% compared to 4.4% in the three years prior. We also look at additions to the distribution plant over net distribution plant as a measure of investment that is gross of retirements. On these measures, Ameren Illinois was 9.2% after versus 7.4% before. ComEd was 8.9% after versus 7.7% before. For both utilities, investment rates increased after the change in regulatory environment.

Table 2 compares these changes in investment to all investor owned utilities that border either utility.[9] We regress our measures of investment on utility fixed effects, year fixed effects, and a

[9]These are Ameren Missouri, Duke Energy Indiana, Interstate Power and Light, Kentucky Utilities, MidAmerican Energy, Northern Indiana Public Service Co., Southern Indiana Gas and Electric Co., Wisconsin Energy, and Wisconsin Power and Light.

dummy variable for the EIMA being in effect. The dummy variable EIMA equals one for Ameren Illinois and ComEd in years 2012 to 2014. While the number of observations is insufficient to have statistically precise estimates, we nonetheless find marginally significant effects of EIMA when looking at the second investment measure.

3.5.5 Related Issue 2 - Contractibility of the Rate of Return and the Utility's Effort Level

Another conceptual issue in our regulatory setting is the possibility that the regulator and the utility may want to enter into a contract on the rate of return for the future, or into a more complex contract regarding the utility's effort to reduce energy loss. We will later demonstrate in a counterfactual simulation that social welfare may be improved by the regulator's contract on the rate of return it plans to adjudicate in the future. Furthermore, one could imagine more complex contractual schemes to strengthen incentives to reduce line losses than the simple linear-in-loss setup we have modeled.

We justify the modeling approach on these two fronts by appealing to the theoretical literature on incomplete contracting. It has long been recognized in the incomplete contract literature that traditional optimal contracting solutions tend to be distant from practice. Tirole (1999) provides an overview of the debate between complete contract theorists and incomplete contract theorists and mentions three rationales for the prevalence of incomplete contracting: (1) unforeseen contingencies, (2) cost of writing a contract, and (3) cost of enforcing a contract. In Section 3.2 of the supplementary material, we discuss how each of these three reasons applies to the regulator's decision on the rate of return and to the contractibility of the utility's effort. There we also discuss institutional reality, which gives further support for our modeling approach.

4 Preliminary Analyses

In this section, we document a series of reduced-form relationships between key variables. First, we investigate the relationship between regulated rates of return and political ideology. Second, we investigate the relationship between investment and regulated rates of return. Third, we investigate the relationship between electricity reliability and investment. Fourth, we investigate the relationship between energy loss and political ideology. These relationships form the basis of estimation and calibration of parameters. In the first and fourth regressions, our aim is to estimate the causal effect of political ideology on the rate of return and energy loss, respectively. In the rest of the regressions, regressors are endogenous variables chosen by either the regulator or the utility. Thus, our aim is to understand the overall relationships between key variables in our model rather than to obtain causal effects.

4.1 Political Ideology and Return on Equity

We first investigate the relationship between political ideology and the return on equity approved in rate cases. The analysis in this subsection connects to the first model prediction in Section 3.5.3, that rate of return is decreasing in α. The relationship predicts how α should vary as a function of political ideology. As discussed in Section 2.2, we use two measures of political ideology: *Republican Influence* (the fraction of Republicans on the PUC) and the Nominate score. In all the specifications with *Republican Influence* as a regressor, we include utility-state fixed effects. Thus, we exploit only temporal variation, which helps us to isolate the causal effect of regulator ideology from the influence of unobserved heterogeneity across utilities and states. A related advantage of *Republican Influence* as an ideology measure is that the fraction of Republicans on the PUC varies frequently in most of the states, due to high turnover of commissioners. Figure 1 illustrates how the fraction of Republican commissioners trails the party of the Governor in Michigan.[10]

FIGURE 1 HERE

We complement the analysis with an additional set of specifications, where we use *Nominate score* as a regressor in place of *Republican Influence*. In sum, we estimate regressions of return on equity on state and regulator ideology and other features of political environments using the

[10]The election of governors, who subsequently appoint regulators, is determined by other factors such as taxation or education rather than electricity pricing. Even in states with elected regulators, the election of low-profile public officials such as regulators is determined primarily by partisan tides (see Squire and Smith (1988) or Lim and Snyder (2015)). Thus, reverse causality is not a serious concern.

following specifications[11]:

$$Return\ on\ Equity_{it} = \beta_1 Republican\ Influence_{it} + \alpha_i + \gamma_t + \varepsilon_{it} \quad (2)$$

$$\begin{aligned} Return\ on\ Equity_{it} &= \beta_1 Nominate_{it} + \beta_2 UnlimitedCampaign_i + \beta_3 Ballot_i \\ &\quad + \beta_4 ElectedRegulators_i + \beta_5 x_{it} + \gamma_t + \varepsilon_{it} \quad (3) \end{aligned}$$

where *UnlimitedCampaign*, *Ballot*, and *ElectedRegulators* are dummy variables, x_{it} is a vector of demographic and financial covariates for utility-state i in year t, α_i are utility-state fixed effects, and γ_t are year fixed effects.

Panel A in Table 3 presents results from specifications with *Republican Influence* as a regressor. Columns (1), (2), (6), and (7) use the whole set of utility-state-year observations. In other columns, we impose restrictions on the data period. The result shows an interesting cross-time pattern in the relationship between *Republican Influence* and return on equity. In Columns (1), (2), (6), and (7), we find weaker relationships than in the later years. *Republican Influence* is still statistically significant if we control for the identity of the parent company. Parent companies change within utility-state over time due to mergers and acquisitions. As different parent companies face different financing conditions and costs of capital, these changes affect the rates of return granted by the PUC. Therefore, including parent company fixed effects reduces some of the noise of the residual, allowing us to estimate a more precise ideology effect.

As we restrict data to later periods, the coefficient of *Republican Influence* not only becomes statistically stronger, but its magnitude also becomes larger. For example, Column (10) implies that replacing an all-Democrat commission with an all-Republican commission increases return on equity by 1.3 percentage points for recent years (year>2005), which is approximately one standard deviation. Even after including year fixed effects, the magnitude is 0.7 percentage points (Column (5)).[12]

[11] In Section 1.1 of the supplementary material, we assess the sensitivity of these regressions with respect to conditioning on wholesale market structure (deregulation).

[12] In this context, not filtering out year fixed effects is more likely to capture the effect of political ideology accurately. There can be nationwide political fluctuation that affects the partisan composition of PUC's. For example, if the

This finding that the influence of regulators' party affiliation increases over time provides good evidence that our regressions capture the true influence of regulatory ideology rather than the influence of unobservable factors. As well documented in McCarty, Poole, and Rosenthal (2008), the ideological distance between Republican and Democratic politicians in the U.S. has been rising during our data period. That is, politicians' party affiliation has become a stronger signal of their ideology in recent years. Thus, if our regressions capture the true influence of regulator ideology, then the relationship between regulators' party affiliation and their decisions must be stronger in recent years. This implication of ideological polarization is exactly consistent with our finding.

Focusing on recent years also has the advantage of eliminating measurement error due to the changing nature of partisanship in Southern states that lasted into the mid 1990's. In Table S.7 of the supplementary material, we present these regressions splitting the sample by time period and by Southern states, and find a large negative, albeit imprecise, estimate of *Republican Influence* only in the pre-1998 South.

Panel B uses Nominate score for the U.S. House (Columns (1)-(5)) and Senate (Columns (6)-(10)) for political ideology. In Columns (1), (2), (6) and (7) of Panel B, we use all state-utility-year observations, without conditioning on whether they were years in which a rate case occurred (henceforth "rate case year"). In Columns (3)-(5) and (8)-(10), we use only rate case years. The statistical significance of the relationship between return on equity and political ideology is robust to variation in the set of control variables. Columns (2) and (7) condition on utility-state fixed effects as opposed to the other columns which include cross-state variation in political ideology. These also include parent company fixed effects as we discussed regarding Panel A.

The magnitude of the coefficient is again fairly large. For example, if we compare Massachusetts, one of the most liberal states, with Oklahoma, one of the most conservative states, the difference in return on equity due to ideology is about 0.61 percentage points, which is approximately 47% of the standard deviation in return on equity.

U.S. president becomes very unpopular, all candidates from his party may have a serious disadvantage in elections. Thus, the partisan composition of any elected PUC would be affected nationwide. Party dominance for governorship can be affected likewise, which affects composition of the appointed PUC's. Including year fixed effects in the regression filters out this nationwide change in the partisan composition of regulators, which narrows sources of identification.

We find that the influence of not having restrictions on campaign donations from corporations or the availability of ballot propositions is not statistically significant. Considering that the skeptical view toward industry regulation by the government in the public choice tradition has been primarily focused on the possibility of "capture", the absence of evidence of a relationship between return on equity and political institutions that can directly affect the extent of capture is intriguing. Our estimate also implies that states with elected regulators are associated with higher level of profit adjudicated for utilities, which contrasts with implications from several existing studies that use outcome variables other than return on equity.[13]

4.2 Return on Equity and Investment

To understand how political environments affect social welfare through rate regulation, we need to consider their relationship with investment, which subsequently affects the reliability of electric power distribution. Thus, we now turn to the relationship between return on equity and investment. The analysis in this subsection corroborates our third model prediction in Section 3.5.3, that rate of return and investment are positively correlated when α is serially positively correlated.

We use two different measures of investment: the average yearly rate of addition to the value of distribution plant, gross of retiring plants (the first measure) and net of retiring plants (the second measure). We take the average rate of addition to the distribution plant per year between rate case years as a proportion of the distribution plant in the preceding rate case year. We run regressions

[13] Formby, Mishra, and Thistle (1995) argue that election of regulators is associated with lower bond ratings of electric utilities. Besley and Coate (2003) also argue that election of regulators helps to reflect voter preferences better than appointment, thus the residential electricity price is lower when regulators are elected. They document that electing regulators is associated with electing a Democratic governor (Table 1 on page 1193). However, they do not include having a Democratic governor as an explanatory variable in the regression of electricity price. Thus, the combination of the relationship between electing regulators and state-level political ideology and our result that liberal political ideology yields low return on equity may explain the contrast between their results and ours. Overall, our study differs from existing studies in many dimensions including data period, key variables, and econometric specifications. A thorough analysis of the complex relationship between various key variables used in existing studies and structural changes in the industry over time would be necessary to uncover the precise source of the differences in results.

of the following form:

$$Investment_{it} = \beta_1 Return\ on\ Equity_{it} + \alpha_i + \varepsilon_{it}$$

where $Investment_{it}$ is the average yearly investment by utility-state i after rate case year t until the next rate case, $Return\ on\ Equity_{it}$ is the return on equity, and α_i represents utility-state fixed effects.

The result in Table 4 shows that there is a non-trivial and statistically significant relationship between return on equity adjudicated in a rate case and subsequent investment by utilities. For example, Column (2) shows that a one percentage point increase in return on equity is associated with a 0.36 percentage point increase in the value of distribution plant, which is approximately a fifth of a standard deviation of net average yearly investment.[14] The economic model in Section 3 of a utility's dynamic investment problem generates a positive correlation between investment and rates of return when regulator types are serially correlated.

4.3 Investment and Reliability

A utility's reliability is partially determined by the amount of distribution capital and labor maintaining the distribution system. Our focus is on capital investment. Outages at the distribution level result from weather and natural disaster related damage, animal damage, tree and plant growth, equipment failure due to aging or overload, and vehicle and dig-in accidents (Brown (2009)). Capital investments that a utility can make to increase its distribution reliability include putting power lines underground, line relocation to avoid tree cover, installing circuit breaks such as re-closers, replacing wooden poles with concrete and steel poles, installing automated fault location devices, increasing the number of trucks available for vegetation management and outage response, and replacing aging equipment.

[14]Moreover, we can regard this relationship as a *lower bound* of the influence of rate of return on investment. Precisely, investment behavior is influenced by utility's *expectation of future rate of return* rather than one from the preceding rate case. Thus, the rate in the preceding rate case can be regarded as a proxy measure of the future rate of return with a measurement error, i.e., a case of a right-hand-side variable with a measurement error.

In Table 5, we examine how changes in capital levels affect realizations of reliability. Later, we use the estimate from this analysis to calibrate $\tilde{\beta}$ in the demand function specified in Section 3.1, which captures consumers' valuation of capital. Here, we estimate regressions of the following form:

$$\log(SAIDI_{it}) = \beta_1 k_{it} + \beta_2 l_{it} + \beta_3 x_{it} + \alpha_i + \gamma_t + \varepsilon_{it}$$

where $SAIDI_{it}$ measures outages for utility-state i in year t, k_{it} is a measure of utility-state i's distribution capital stock in year t, l_{it} is utility-state i's expenditures on operations and maintenance in year t, and x_{it} is a vector of storm and terrain related explanatory variables. In this regression, there is mis-measurement on both the left and the right hand side, and a likely correlation between ε shocks and expenditures on capital and operations and maintenance. Mis-measurement on the left hand side is because measurement systems for outages are imperfect. Mis-measurement on the right hand side arises by aggregating different types of capital into a single number based on an estimated dollar value. The error term, ε, is likely to create a bias in our estimate of the effect of adding capital to reduce outages. We employ utility-state fixed effects, so that the variation identifying the coefficient on capital is within utility-state over time. Absent utility-state fixed effects, utilities in territories prone to outages would invest in more capital to prevent outages. This would induce a correlation between high capital levels and poor reliability. Even including utility-state fixed effects, a prolonged period of stormy weather would damage capital equipment and increase outage measures. The utility would compensate by replacing the capital equipment. Thus we would see poor reliability and high expenditure on capital in the data. This correlation would cause an upward bias in our coefficient estimates on β_1 and β_2, which reduces the estimated sensitivity of SAIDI to investment. Despite this potential bias, the result in Column (4), which is our preferred specification, shows a strong negative relationship between capital investment and SAIDI.

The unreported coefficient on operations and maintenance is positive, likely due to a more severe case of the same selection problem. In periods of severe weather, the utility has to spend money on operations to repair the damage and restore power, which would include overtime pay to line workers. To estimate the effect of operations and maintenance expenses, we would like to isolate secular changes in budgeting by the utility rather than short term responses to weather events. We tried a variety of approaches to address concerns of operations and maintenance expenditure being endogenous. For example, we instrumented for operations and maintenance expenditure with mean wages by state and year for "Electrical Power-Line Installers and Repairers" occupation code 49-9051 from the Bureau of Labor Statistics Occupational Employment Statistics database. We also attempted to use spending on operations and maintenance by nearby utilities as well as spending on operations and maintenance for transmission by the same utility to capture correlated wages. However, these instruments either did not solve the selection problem (and reproduced a positive coefficient on operations and maintenance expenditures), or produced negative but imprecise estimates.

4.4 Political Ideology and Utility Management (Energy Loss)

The preceding three subsections indicate one important channel through which political environments influence social welfare: improvement of reliability under conservative regulators because higher returns lead to higher investment. Going in the opposite direction, conservatives' favoritism toward the utility relative to consumers implies a possibility that conservative regulators may aggravate potential moral hazard problems. To take a balanced view on this issue, we investigate the influence of regulator ideology on the inefficiency of utility management, measured by energy loss. The investigation in this subsection connects to our model prediction in Section 3.5.3, that utility's effort is increasing in α. The relationship corroborates the implication from Section 4.1: both rate of return and energy loss vary in a way that is consistent with liberal regulators putting more weight on consumer surplus relative to utility profits.

The average amount of energy loss is about 7% of total production. The amount of energy loss is determined by system characteristics and actions taken by the utility's managers to optimize system performance.

Table 6 presents regressions of the following form:

$$\log(energy\ loss_{it}) = \beta_1 Republican\ Influence_{it} + \beta_2 x_{it} + \alpha_i + \gamma_t + \varepsilon_{it}$$

where x_{it} is a set of variables that affect energy loss by utility-state i in year t, such as distribution capital, operation and management expenses, and the magnitude of sales. We find that conservative regulators are associated with more energy loss. Moving from all Republican commissioners to zero Republican commissioners reduces energy loss by 13%, which would imply 1 percentage point less total energy generated for the same amount of energy ultimately consumed.

We conclude that a conservative political environment potentially encourages better reliability through higher return on equity and more investment, but it also leads to less static productivity as measured by energy loss. To conduct a comprehensive analysis of the relationship between political environment and welfare from utility regulation, we now turn to the estimation of the model we specified in Section 3.

5 Model Estimation

We estimate eight parameters: the effort cost parameter γ_e, the audit cost parameter γ_κ, the quadratic adjustment cost coefficient η, the market rate adjustment cost parameter γ_r, the coefficient of the error term in the utility's investment decision σ_i, and the mapping from political ideology of the state and party affiliation of regulators to the regulator's weight on consumer surplus versus utility profits, $\mathbf{a} \equiv (a_0, a_1, a_2)$. We denote $\theta \equiv (\gamma_e, \eta, \gamma_\kappa, \gamma_r, \sigma_i, \mathbf{a})$. We calibrate the other quantities in the model to represent a typical utility. We fix the yearly discount factor of the players, β, at 0.96. We fix the capital depreciation rate at 0.041.[15] We set p_f, the wholesale price of electricity, to \$70 per megawatt-hour. We set r_m to 10% per year. We set N to 500,000 customers, and Q to 15 million megawatt-hours. We set $\bar{e}$ so that zero effort results in the utility losing one third of its electricity input cost in distribution.

[15] This is the average level in our data computed from FERC Form 1 Depreciation Expense and the Internal Revenue Service Modified Accelerated Cost Recovery System (MACRS) depreciation rate for electricity distribution capital.

We use a sub-sample of the data for estimation. We excluded utilities with less than 50,000 customers or whose net distribution capital per customer exceeds \$3,000. These outlier utilities are mostly in the Mountain West and Alaska. The population density and terrain of these utilities are sufficiently different from the bulk of U.S. electricity distribution utilities that we do not want to combine them in the analysis. We also excluded utility-years where the energy loss exceeds 15% or the absolute value of the investment rate exceeds 10%. The energy loss criterion eliminates around sixty observations.[16] The investment restriction is to deal with acquisitions and deregulation events. Our final sample is 2331 utility-state-year observations, just above two-thirds of the full sample of utility-state-years with the bulk of the difference being from dropping small utilities.

5.1 Demand Parameters: Value of Reliability

We calibrate the demand parameters so that the willingness-to-pay of the representative consumer for a year of electricity service at the average capital level in the data is \$24,000.[17] We set the willingness-to-pay for improving reliability, as measured by SAIDI, by one minute to \$2.488 per customer per year. The choice of the value of reliability has first order implications for the counterfactual analysis that we perform. We estimated this number using the results of Sullivan et al. (2009) who use survey data to estimate the cost of power interruptions. These valuations are behind the "Interruption Cost Calculator" created by the U.S. Department of Energy. These values are endorsed by the Electric Power Research Institute (EPRI) for assessing the benefits of smart grid projects. Estimated values for improvements in reliability are heterogenous by customer class, ranging from \$0.5-\$3 to avoid a 30 minute outage for residential consumers to \$324-\$435 for small commercial and industrial consumers to \$4,330-\$9,220 for medium to large commercial and industrial consumers.[18] To get to \$2.488 per minute of SAIDI per customer per year, we use the

[16]The implied energy loss values are unreliable in these cases because they are either derived from utility territories that operate in multiple states but report one aggregate level of energy loss, or imply zero or negative losses. These dropped observations are not associated with more liberal commissions.

[17]The \$24,000 number is somewhat arbitrary as we are not modeling whether the consumer is residential, commercial, or industrial. Adjusting this value will have a direct effect on the estimated level of a_0, but is unlikely to affect other results in this paper.

[18]While some of these customers may have back-up generation, that is rarely enough to support full operation of the plant during an outage. For example, a hospital might back-up enough power to keep treating its current patients,

mid-point of the estimates by customer class,and set 0.38 percent of consumers to medium to large commercial and industrial, 12.5 percent to small commercial and industrial, and the remaining 87.12 percent to residential where these percentages correspond to the fraction of industrial, commercial, and residential consumers respectively from the EIA data.

From these values, a crude calculation for the level of under-investment is derived as follows. The present value of $2.488 per minute per customer per year is $62.224 per minute per customer at a discount factor of 0.96. The reliability on capital regression implies that the one-time, per-customer change in the capital base required to improve SAIDI by one minute is $26.234 for the mean utility. The benefit exceeds the cost such that moderate decreases in the benefit would still be consistent with under-investment. Our model improves the credibility of this crude calculation by including depreciation, future investment, and investment costs not captured by the book value of the assets.[19]

5.2 Regulator and Utility Parameters

We estimate the parameters in θ using a two-step procedure for dynamic games following Bajari et al. (2007) (BBL) and Pakes et al. (2007). This method avoids a computationally costly re-solving of the equilibrium. The estimation objective function evaluates candidate sets of parameters by simulating value functions implied by those parameters and the observed policies in the data, and comparing the observed policies to those that are optimal given the simulated value functions and candidate parameters. Our problem has two features which are non-standard. First, the effort and regulatory auditing policies are unobserved, as in Misra and Nair (2011) and Lewis and Bajari (2014) who study moral hazard in different settings. Second, one of the state variables, the regulator's weight on consumer surplus, is not observed directly. The solution in both cases is to derive the unobserved quantity as a function of model parameters and data.

but divert new emergency room patients to another hospital, or cancel non-urgent outpatient procedures.

[19]This calculation is conservative in the following dimensions: first, we are using SAIDI excluding major events. Including major events would imply a larger reliability benefit from the same investment, as long as investments also reduce outages from major events. Second, we exclude any non-reliability benefits from capital investment, such as beautification from putting power lines underground.

The data are, for every utility-state (i) and year (t): a capital base k_{it}, an investment level inv_{it},[20] realized energy loss l_{it} in MWh, a return on capital r_{it}, a fraction of Republican commissioners rep_{it}, and a state Nominate score d_{it} (U.S. House). The following list describes the steps for calculating the estimation objective function for a given set of model parameters θ. We then detail each step:

Estimation Steps

1. Consider candidate model parameters $\theta = (\gamma_e, \eta, \gamma_\kappa, \gamma_r, \sigma_i, \mathbf{a})$.
2. Transform political data into weights on consumer surplus using $\mathbf{a}$. Discretize and estimate a nine state Markov process for weight on consumer surplus.
3. Transform energy loss into unbiased estimates of effort and audit intensity using γ_e and first order condition for optimal effort.
4. Estimate policy functions for investment, effort, rate of return, and audit intensity.
5. Forward simulate value functions implied by θ and estimated policy functions.
6. Solve for optimal policies given by implied value functions and θ.
7. Compute moments implied by both optimal policies and the Markov process for the weight on consumer surplus.
8. Calculate the objective function.

We discretize the state space into a grid of twenty points for the capital level and nine points for the weight on consumer surplus level. We first transform the data on the fraction of Republican commissioners and the Nominate score of a state into an implied weight on consumer surplus by $\alpha_{it} = a_0 + a_1 rep_{it} + a_2 d_{it}$. This resolves the issue of one dimension of the state space being unobserved. We use the implied α_{it} series to approximate a first-order Markov process for the weight on consumer surplus over the discretized grid.

Next, we invert energy loss l_{it} into an unbiased estimate of effort according to the model. First, l_{it} is equal to electricity procured minus electricity delivered:

$$l_{it} = Q_{it}(1 + \bar{e} - e_{it} + \varepsilon_{it}) - Q_{it}.$$

[20] For the investment variable, we use a three-period moving average to account for time to build.

We assume that ε_{it} has mean zero. It follows that

$$\hat{e}_{it} = \bar{e} - \frac{l_{it}}{Q_{it}}.$$

We assume the utility serves Q units of energy every period, where Q is the mean of Q_{it} across all utilities and years to the nearest five million.

We then recover an estimate of the audit intensity. The first order condition of the utility with respect to effort choice implies $\kappa = 1 - \frac{2\gamma_e e}{Q p_f}$. This relationship generates the audit policy κ_{it} from the estimated effort levels and the candidate effort cost parameter γ_e. Since this function is linear in effort, the unbiased estimate of effort generates an unbiased estimate of audit intensity. This resolves the two non-standard issues in the two-step estimation procedure.

We next regress the policy variables $inv_{it}, \hat{e}_{it}, r_{it}$, and $\hat{\kappa}_{it}$ on the state variables k_{it} and α_{it}.[21] We use linear regressions on k and α. Introducing higher order terms produced imprecise estimates of the higher order factors. Starting from each point on the state space grid and using the candidate parameters and estimated policies, we forward-simulate 300 paths of length 200 of α and k.

For each path, we compute the stream of per-period payoffs for both utility and consumers. The mean present values at each point in the state space constitute the estimated value functions.

Given the candidate model parameters and the simulated value functions, we solve for the optimal policies for each player in each state given the opponent's observed policies. The criterion function compares these optimal policies to the initial estimated policy functions. Intuitively, the procedure is choosing the model's parameters such that the observed policies are equilibrium policies. We construct an extremum criterion function composed of the difference between observed policies and predicted policies averaged over different points in the state space. We add nine moments into the criterion function: the mean and the variance of three variables (the rate of return, investment level, and energy loss), mean leniency of auditing,[22] and two regression coefficients

[21] The estimation error due to $\hat{e}_{it}$ being different from e_{it} does not change the asymptotic properties of this step. The residual from this policy function estimation does affect the value function estimates in theory, but in practice the number of stochastic shocks we could accommodate computationally is limited.

[22] As leniency of auditing, κ, corresponds to pass-through of lost energy, we estimated a regression of revenue on energy loss. The implied pass-through rate was above 1, though statistically we could not rule out values between

from the effort and rate of return on fraction of Republican commissioners and Nominate scores. Explicitly, the criterion function has the following components:

$$G(\theta) = \begin{bmatrix} \frac{1}{N_{k,\alpha}} \sum_{k,\alpha} inv(k,\alpha) - \hat{inv}(k,\alpha;\theta) \\ \frac{1}{N_{k,\alpha}} \sum_{k,\alpha} e(k,\alpha) - \hat{e}(k,\alpha;\theta) \\ \frac{1}{N_{k,\alpha}} \sum_{k,\alpha} r(k,\alpha) - \hat{r}(k,\alpha;\theta) \\ \frac{1}{N_{k,\alpha}} \sum_{k,\alpha} \kappa(k,\alpha;\theta) - \hat{\kappa}(k,\alpha;\theta) \\ \frac{1}{NT} \sum_{i=1}^{N} \sum_{t=1}^{T} r_{it} - \hat{\bar{r}}(\theta) \\ \frac{1}{NT} \sum_{i=1}^{N} \sum_{t=1}^{T} (r_{it} - \bar{r})^2 - \hat{\sigma}_r^2(\theta) \\ \frac{1}{NT} \sum_{i=1}^{N} \sum_{t=1}^{T} inv_{it} - \hat{\bar{inv}}(\theta) \\ \frac{1}{NT} \sum_{i=1}^{N} \sum_{t=1}^{T} (inv_{it} - \bar{inv})^2 - \hat{\sigma}_{inv}^2(\theta) \\ \frac{1}{NT} \sum_{i=1}^{N} \sum_{t=1}^{T} e_{it} - \hat{\bar{e}}(\theta) \\ \frac{1}{NT} \sum_{i=1}^{N} \sum_{t=1}^{T} (e_{it} - \bar{e})^2 - \hat{\sigma}_e^2(\theta) \\ \frac{1}{NT} \sum_{i=1}^{N} \sum_{t=1}^{T} \kappa_{it}(\theta) - \hat{\bar{\kappa}}(\theta) \\ \hat{\beta}_{e,data} - \hat{\beta}_e(\theta) \\ \hat{\beta}_{r,data} - \hat{\beta}_r(\theta) \end{bmatrix}$$

where $\hat{x}$ for policy x denotes the optimal choice implied by the model at the candidate parameters θ. We minimize the weighted sum of squares of $G(\theta)$:

$$\hat{\theta} = \underset{\theta}{\operatorname{argmin}} \, G(\theta)' W G(\theta)$$

where W is a weighting matrix. The first four components of $G(\theta)$ are the differences between observed policies and implied optimal policies averaged across points in the state space. The next seven components are the mean and the variance of outcomes. The final two components compare regression coefficients from the data to regression coefficients implied by the model. We match coefficients from two regressions: the coefficient on the Nominate score in a regression of the regulated rate of return on Nominate score and fraction of Republican commissioners, and the coefficient on the fraction of Republican commissioners in a regression of effort on Nominate score

0.91 and 1. We set the mean κ to 0.975 for the purpose of estimation to reflect that challenges to automatic pass-through are rare. Altering this value between 0.9 up to just below 1 does not change the ultimate counterfactual results qualitatively. However, such a change may affect the estimated audit cost and effort cost parameters.

and fraction of Republican commissioners.[23] We set the weighting matrix W to adjust for differences in scaling across moments. We compute confidence intervals by block-bootstrap, clustering by utility-state.

6 Estimation Results

In this section, we interpret the economic magnitude of parameter estimates and discuss the empirical identification of the parameters. Table 7 shows the estimation results.

Magnitudes and Model Fit: The effort cost parameter, γ_e, implies that decreasing energy loss by 1 percentage point from the mean of 7% of total production, at the mean effort level, would entail a disutility worth about $284,000 to utility management. This is comparable to the cost of hiring one to two power system engineers. The adjustment cost for capital, η, is small relative to the actual cost of capital, that is, the linear term in investment. For a 10% investment from the mean capital level, the adjustment cost is equal to 14.87% of the cost of the capital itself. This parameter is likely picking up heterogeneity across utilities not specified in the dynamic model, such as population growth rates and idiosyncratic features of the terrain. The regulator's cost parameters, γ_r and γ_κ, imply that adjusting the rate of return by one standard deviation in the data (1.3 percentage points) from the mean bears the same cost as decreasing cost pass-through rate by 0.1 percentage points from the mean (97.5% to 97.4%).

The mapping from political variables to weight on consumer surplus describes regulator heterogeneity. a_0 sets the level of weight on consumer surplus. It is very close to one. This reflects that current electricity prices are a very small fraction of willingness-to-pay for electricity. The value is sensitive to the calibration of willingness-to-pay for electricity, described on page 32. a_1 is larger in magnitude than a_2. Both are negative, implying that more conservative areas, whether measured by Nominate scores or fraction of Republican commissioners, place relatively less weight on consumer surplus than liberal areas, leading to higher rates of return and more energy loss.

[23] These regressions do not include utility-state fixed effects as some of the specifications in Section 4. Allowing for utility-state fixed effects would require having different Bellman equations for each utility, whereas our computationally simpler procedure models a representative utility.

In Figure 2, we plot the policy surfaces at the estimated parameters for investment and rate of return as functions of capital per capita and the weight on consumer surplus.

FIGURE 2 HERE

Both the rate of return and investment are decreasing in the two dimensions. Investment decreases in the weight on consumer surplus because of persistence in the stochastic process of the weight.

FIGURE 3 HERE

In Figure 3, we plot all of the policy functions at the estimated parameters, averaged across levels of capital, in the dimension of weight on consumer surplus. Auditing is increasing in the weight on consumer surplus, which implies that effort is also increasing in this dimension.

Table 8 reports model fit on targeted moments used explicitly in estimation, and un-targeted moments not used in the estimation objective function. The estimated model does well matching the first moments of the key choice variables.

While the model predicts the variance of investment well, it does not offer a good fit for the variance of energy loss nor the variance of rate of return. There are clear reasons for this. Investment is subject to a random shock whose variance we estimate. The estimated variance allows the model to fit this second moment. We did not include shocks for energy loss nor rate of return. As discussed in the previous section, incorporating more stochastic processes into the estimation raises the computational burden. The model also matches the regression coefficients of rate of return and energy loss on political ideology variables, two of which are targeted explicitly as moments. We also check two more untargeted moments: the coefficient on rate of return in the regression of investment on rate of return, the coefficient of Nominate score in a regression of effort on Nominate score, and the coefficient on *Republican Influence* in a regression of log(SAIDI) on *Republican Influence*. On these, the model does reasonably well in that we can not reject that the coefficients from the model equal the coefficients in the data. Reliability is nonetheless somewhat less sensitive to political environments in the model than in the data. This is because the α process in the model is estimated from pooling all states in the sample together, whereas α may be more persistent in more extreme states. More persistence in α would lead to a larger effect of political ideology on reliability as utilities in more utility-friendly jurisdictions would accumulate capital at a higher rate, because rates of return would be more likely to remain higher for longer. Similarly, utilities in less utility-friendly jurisdictions would invest less with such persistence, and therefore have lower reliability.

Empirical Identification: Even though the model is non-linear, parameter estimates are sometimes intuitively linked to specific features of the data. The sources of empirical identification for our model parameters can be well-understood by analyzing how parameter estimates change if certain moments of the data were to change. Here we describe the most important results on the relationships between model parameters and moments in the data. In Section 3.3 of the supplementary material, we provide details of such an analysis using the notions of sensitivity and sufficiency as in Gentzkow and Shapiro (2013), and present a table (Table S.9) that documents the results described below.

The effort cost parameter, γ_e, is sensitive to the mean of effort estimated from the data. The relationship is negative, i.e., higher effort in the data leads to lower estimates of effort cost. The quadratic investment cost parameter, η, is most sensitive to mean investment in the data. The coefficient of the error term in investment, σ_i, is sensitive to the standard deviation of investment. The market return adjustment cost, γ_r, is most sensitive to the mean rate of return in the data.

Parameters a_1 and a_2 are sensitive to the regressions of effort and rate of return on political variables as well as the standard deviations of effort and rate of return. These relationships provide an intuitive link between the regression results in Section 4 and the estimates of our non-linear dynamic model. We estimate that conservative regulators place more weight on utility profits than liberal regulators. This is because, in the model, regulators who place more weight on utility profits grant higher returns and engage in less auditing, which leads to less effort and more energy loss, and in the data we observe higher rates of return and more energy loss with conservative regulators.

7 Counterfactual Experiments

We perform two sets of counterfactual experiments: (1) alternative rate of return policies by the regulator, including endowing the regulator with a commitment device and (2) alternative auditing policies for the regulator.[24] In the first set, we explore a full commitment benchmark and setting the rate of return policy equal to the most conservative regulator's policy. In the second, we explore maximal auditing by the regulator and setting the audit policy equal to the most liberal regulator's policy. Thus, each set explores a theoretical benchmark and partisan extreme. The key intuition is that conservative environments reduce the problem of time inconsistency, while liberal environments reduce the problem of moral hazard. We compare the outcomes in each counterfactual scenario to the outcomes from the baseline model solution at the estimated model parameters.[25] [26]

7.1 Rate of Return Policies including Commitment

As a theoretical benchmark, we solve for the regulator's optimal policy when it can credibly commit to future rates of return. This idea is analogous to Taylor's rule on monetary policy (Taylor (1993)), which stipulates the amount of change in the nominal interest rate in response to changes in inflation and output. Theoretically, commitment should lead to higher rates of return and higher investment by overcoming the fear of regulatory hold-up. Our results in Table 9 confirm and quan-

[24]In Section 4 of the supplementary material, we analyze a third set of counterfactuals regarding alternative regulatory commission design. There, we explore enforcing minority representation, which limits the degree to which a commission can swing to one partisan extreme or the other, and a perfectly centrist commission.

[25]Certain summary statistics in the baseline in the tables on counterfactuals are slightly different from those in Table 8. This is because the baseline reflects policy functions from computing the *full solution* of the model at the estimated parameter values while Table 8 reflects the optimal policy functions from the two-step estimation procedure using the opponent's estimated policy function. Those two policy functions differ from each other due to several features of our two-step estimation procedure. First, they differ due to sampling error. Second, we use a linear regression in the estimation of policy functions. Without data constraints, we would want to estimate higher-order polynomials to improve accuracy. Third, we make an adjustment to the α process that we describe below in footnote 26.

[26]In this section, including in the baseline scenario, we make two adjustments to the estimated α process: (1) we set the transition probabilities so that there is 0.5 probability of staying in the same α state and 0.25 probability of moving to an adjacent state (0.5 for the boundary states), (2) we translate the support of the state space so that the implied steady state mean α is the same as in the estimated α process. The purpose of (1) is primarily for clarity of definition. With the unadjusted process of α, the definition of the minority representation and centrist commission counterfactuals would be less transparent. The purpose of (2) is to prevent (1) from changing the overall steady state utility-friendliness of the regulatory commission. We checked that the baseline and commitment counterfactuals with the unadjusted α process produced quantitatively similar results. Therefore, using the adjusted process does not influence the results substantively while making the exposition of the counterfactuals more clear.

tify the importance of this intuition.

We model commitment by changing the timing of actions in the dynamic game. In the commitment counterfactual, the regulator first chooses a rate of return policy that specifies r in each state (k, α). This policy is then held fixed. The utility solves a single agent problem conditional on this policy. To make this problem computationally tractable, we constrained the regulator's problem so that their commitment policy must be a scalar multiple of their equilibrium policy from the estimated MPE.[27] Furthermore, we hold the audit policy fixed at the estimated equilibrium audit policy. These two restrictions reduce the commitment problem to a single dimensional optimization problem. We evaluate the commitment policy by averaging over different regulator preferences according to the ergodic distribution implied by the Markov process for α.

In a world where the regulator could credibly commit to future rates of return ("Full Commitment"), the adjudicated rate of return is 14 percent higher than in the baseline. In every state, investment rises substantially.[28] The steady state mean capital level rises by 59%. Mean investment is lower than under the baseline because the system spends more time at higher capital levels, and investment is decreasing in capital. Consumers would pay higher prices and receive service with around 25.4 fewer outage minutes per year, or an 18% improvement in reliability. Utility value increases dramatically while consumer value slightly decreases. That consumer value decreases is natural when thinking about commitment. Under commitment, the regulator finds itself in states of the world where it would like to decrease the rate of return to increase consumer surplus, as it would in a Markov Perfect Equilibrium. That consumer welfare decreases slightly may also be driven by our restriction to regulator policies, which are a scalar multiple of the Markov Perfect Equilibrium policy.

The main driver of this result (commitment increasing capital) is that the cost of improvements

[27] The nesting of the utility's dynamic problem within each evaluation of the regulators policy is what renders the unconstrained optimization infeasible. The scalar constraint has the appeal of preserving the concavity of the regulators policy (which helps make the utility's problem well-behaved) while reducing the dimension of the search to a single dimension, which we can robustly optimize by a grid search.

[28] In Table 9, Investment w.r.t. Baseline is the un-weighted mean ratio of investment across states. The steady state means of investment (row 6) for baseline and commitment are closer to each other because the steady state capital is higher under commitment, and investment is decreasing in capital.

in reliability from capital additions is small compared to the their estimated benefit at current capital levels. When the regulator can commit to future policies, it can induce the utility to invest up to the point where the marginal benefit of investment in reliability improvements equals the marginal cost of investment in capital. While there are not heterogenous types of capital in our model, under-investment can be understood as a combination of too much aging infrastructure and too little investment in new technologies such as automated switching systems.

Higher investment does not occur in the Markov Perfect Equilibrium because of the fear of regulatory hold-up. Absent commitment by the regulator, the utility won't make large investments because once the investments are sunk, the regulator's incentives lead to adjudicating a low rate of return, rendering the investments unattractive. Such anticipation by the utility implies that regulatory hold-up can be a real impediment to welfare without one ever observing actual instances of large investments followed by decreases in regulated rates.

Actions that the government can actually take in reality for commitment include passing legislation for large investment programs. For example, the Illinois legislature enacted the *Energy Infrastructure Modernization Act* in 2011, which we described above on page 22. In Missouri, the *Infrastructure Strengthening and Regulatory Streamlining Act* was also proposed to improve stability in rate regulation and incent investment. This legislation would have required Ameren Missouri to increase its capital base by 14.5% targeted at capital investments that improve distribution reliability. These legislative initiatives bypass the traditional regulatory process conducted by rate cases with a more rigid legislative regulatory process. Finally, in Washington D.C., the district government passed the *Electric Company Infrastructure Improvement Financing Act of 2014*, also known as DC Power Line Undergrounding (DC PLUG). This legislation requires 1 billion dollars of investment in undergrounding and other hardening and directly funds half of the investment through public money. This is another example of bypassing the traditional regulatory process to increase investment in the distribution system to improve reliability.[29]

The implied magnitudes in this counterfactual are sensitive to the value of reliability. However,

[29]Precisely speaking, legislation is not an unbreakable commitment as it can be reversed by future legislatures. However, the probability of reversing legislation is significantly lower than the probability of a PUC reversing an administrative action, especially given the legislators' low turnover and concerns for their reputation.

the qualitative outcome that regulated rates of return and investment are too low is not. In Section 1.2 of the supplementary material, we tabulate how changes in the estimated value of reliability and changes in the estimated cost of improving reliability by capital investment would approximately affect the estimated degree of under-investment. We would estimate that the average electricity distribution system has the appropriate capital level if either the aggregate value of reliability improvements from observed levels were 42% of the estimated value, or if the costs of improvement were 2.37 times the magnitude we estimate.

In "Conservative Rate" in Table 9, we constrain regulators to choose rates of return equal to or greater than those chosen by the most conservative regulator. This constraint binds in all states, so equilibrium rates of return are equal to those of the most conservative regulator. Interestingly, this policy does slightly better than the constrained full commitment policy on consumer welfare, though the results are similar. Recall our full commitment policy is constrained to be a scalar multiple of the MPE rate of return policy. Because different regulators have different political ideologies, the MPE rate of return policy assigns different rates of return for the same capital level depending on the commission make-up. The "Conservative Rate" policy eliminates these distortions. The results indicate that tilting towards a conservative regulator in areas with poor reliability is a possible substitute for commitment policies.

7.2 Auditing Policies

We now switch focus to the problem of moral hazard, which manifests itself as energy loss. In Table 10, we consider a uniform implementation of the maximum audit intensity estimated from our data ("Most Liberal Audit").[30] We also consider the theoretical benchmark of maximal audit policy ("Maximal Audit"), which maximally incentivizes the utility to reduce energy loss.

Under the audit policy set at the most liberal regulator's level, energy loss decreases by about five percent (half a percentage point of the total energy distributed). This implies that society could consume the same amount of electricity with half a percentage point less generation, saving on the

[30] To implement this, the most stringent auditing practices could be studied and replicated. For example, the government can set up a rule by which the regulatory commission is required to audit utility behavior every six months.

order of 1 billion dollars per year. “Maximal Audit” leads to zero energy loss. The utility is worse off as it suffers a disutility from the associated increase in effort. However, the improvement in consumer value dominates the loss in utility profits. As a result, total welfare increases.

8 Conclusion

This paper quantifies two fundamental forces in natural monopoly regulation, time inconsistency and moral hazard, and explores their interaction with regulators' political ideology, focusing on electricity distribution in the U.S. We estimate that there is under-investment in electricity distribution capital. We document that more conservative political environments lead to higher regulated rates of return and less static productivity as measured by energy loss. We explain these facts with a dynamic regulator-utility game. The regulator sets the utility's rate of return and audits the utility's effort each period. The utility chooses investment and managerial effort each period. Conservative regulators, who place relatively more weight on utility profits, grant higher rates of return which lead to more investment. This behavior is advantageous for society in light of under-investment due to the time inconsistency problem. However, these regulators also engage in less auditing, which leads to less managerial effort by the utility, which exacerbates the moral hazard problem.

Using estimates of the model, we simulate welfare gains in the benchmark environments where the above two issues are mitigated. The welfare loss from time inconsistency exceeds that from moral hazard, though both are important. The results suggest tilting towards conservative regulators in areas with poor reliability, and tilting towards liberal regulators in areas with good reliability.

Future research could go in two directions. One direction would be to improve the model by incorporating more heterogeneity in both demand and supply, for example by distinguishing between industrial and residential consumers and allowing for heterogeneity in the reliability benefits of capital across geographic conditions. The second direction would be to examine time inconsistency and moral hazard in other domains of regulation. Natural gas distribution, banking, and health insurance are all large sectors subject to regulation by political agents.

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9 Tables

Table 1: Summary Statistics (Data Period: 1990-2012)

Variable	Mean	S.D.	Min	Max	# Obs
Panel A: Characteristics of Political Environment					
Nominate Score - House	0.1	0.29	-0.51	0.93	1127
Nominate Score - Senate	0.01	0.35	-0.61	0.76	1127
Unlimited Campaign	0.12	0.33	0	1	49[a]
Ballot	0.47	0.5	0	1	49
Panel B: Characteristics of Public Utility Commission					
Fraction of Republicans	0.44	0.32	0	1	1145
Elected Regulators	0.22	0.42	0	1	49
Number of Commissioners	3.9	1.15	3	7	50
Panel C: Information on Utilities and the Industry					
Median Income of Service Area ($)	47495	12780	16882	94358	4183
Population Density of Service Area	791	2537	0	32445	4321
Total Number of Consumers	496805	759825	0	5278737	3785
Number of					
Residential Consumers	435651	670476	0	4626747	3785
Commercial Consumers	57753	87450	0	650844	3785
Industrial Consumers	2105	3839	0	45338	3785
Total Revenues ($1000)	1182338	1843352	0	12965948	3785
Revenues ($1000) from					
Residential Consumers	502338	802443	0	7025054	3785
Commercial Consumers	427656	780319	0	6596698	3785
Industrial Consumers	232891	341584	0	2888092	3785
Net Value of Distribution Plant ($1000)	1246205	1494342	-606764	12517607	3682
Average Yearly Rate of Addition to Distribution Plant between Rate Cases	0.0626	0.0171	0.016	0.1494	511
Average Yearly Rate of Net Addition to Distribution Plant between Rate Cases	0.0532	0.021	-0.0909	0.1599	511
O&M Expenses ($1000)	68600	78181	0	582669	3703
Energy Loss (Mwh)	1236999	1403590	-7486581	1.03e+07	3796
Reliability Measures					
SAIDI (minutes)	137.25	125.01	4.96	3908.85	1844
SAIFI (times)	1.48	5.69	0.08	165	1844
CAIDI (minutes)	111.21	68.09	0.72	1545	1844
Bond Rating[b]	6.9	2.3	1	18	3047
Panel D: Rate Case Outcomes					
Return on Equity (%)	11.27	1.29	8.75	16.5	729
Return on Capital (%)	9.12	1.3	5.04	14.94	729
Equity Ratio (%)	45.98	6.35	16.55	61.75	729
Rate Change Amount ($1000)	47067	114142	-430046	1201311	677

Note 1: In Panel A, the unit of observation is state-year for Nominate scores, and state for the rest. In Panel B, the unit of observation is state for whether regulators are elected, number of commissioners, and state-year for the fraction of Republicans. In Panel C, the unit of observation is utility-year, except for average yearly rate of (net and gross) addition to distribution plant between rate cases for which the unit of observation is rate case. In Panel D, the unit of observation is (multi-year) rate case.
Note 2: All the values in dollar terms are in 2010 dollars.

Table 2: Increases in Investment after the *Energy Infrastructure Modernization Act (EIMA)*

	Dependent Variable			
	Net Investment		Gross Investment	
Variable	(1)	(2)	(3)	(4)
EIMA	0.0168	0.0104	0.0185*	0.0199*
	(0.0125)	(0.00708)	(0.00859)	(0.00510)
Observations	66	4	66	4
R-squared	0.451	0.520	0.391	0.884
Year FE	Yes	Yes	Yes	Yes
Utility FE	Yes	Yes	Yes	Yes
Std. Error	Clustered by Utility	Collapse	Clustered by Utility	Collapse

Notes: Standard errors in parentheses: *** $p<0.01$, ** $p<0.05$, * $p<0.1$. The sample consists of Ameren Illinois, ComEd, and all utilities which share a boundary with either Ameren Illinois or ComEd. The dummy variable EIMA equals one for Ameren Illinois and ComEd in years 2012 to 2014, and zero otherwise. In columns (1) and (3), we cluster standard errors by utility. In columns (2) and (4) we follow Bertrand et al. (2004) and collapse the data. Specifically, we first regress the investment measure on state fixed effects and year fixed effects. We regress the mean residuals for Ameren Illinois and ComEd, before and after the EIMA, on an indicator variable equal to one after the policy change.

Table 3: Regression of Return on Equity on Political Ideology

Dependent Variable: Return on Equity

Panel A: Republican Influence as a Measure of Ideology										
Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Republican Influence	0.0500	0.268**	0.227*	0.471***	0.719***	-0.0484	0.382*	0.824***	1.212***	1.307***
	(0.141)	(0.103)	(0.126)	(0.141)	(0.201)	(0.321)	(0.217)	(0.231)	(0.224)	(0.270)
Observations	3,342	3,342	2,481	1,771	1,047	3,342	3,342	2,481	1,771	1,047
R-squared	0.703	0.752	0.727	0.738	0.771	0.460	0.623	0.590	0.629	0.724
Time Period	All	All	Year>1995	Year>2000	Year>2005	All	All	Year>1995	Year>2000	Year>2005
Utility-State FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Parent FE	No	Yes	No	No	No	No	Yes	No	No	No
Year FE	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No

Panel B: Nominate Score as a Measure of Ideology										
	House of Representatives					Senate				
Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Nominate Score	0.924**	0.637*	0.659**	0.755**	0.706**	0.777**	0.400*	0.548**	0.555**	0.497**
	(0.370)	(0.352)	(0.313)	(0.345)	(0.325)	(0.291)	(0.201)	(0.250)	(0.242)	(0.246)
Campaign Unlimited				0.292	0.304				0.272	0.283
				(0.257)	(0.243)				(0.231)	(0.219)
Ballot				-0.249	-0.244				-0.251	-0.245
				(0.204)	(0.205)				(0.192)	(0.194)
Elected Regulators					0.357*					0.310*
					(0.190)					(0.180)
Observations	3,329	3,329	721	528	528	3,329	3,329	721	528	528
R-squared	0.276	0.752	0.398	0.391	0.399	0.283	0.751	0.403	0.393	0.399
Sample	All	All	Rate Case	Rate Case	Rate Case	All	All	Rate Case	Rate Case	Rate Case
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Utility-State FE	No	Yes	No	No	No	No	Yes	No	No	No
Parent FE	No	Yes	No	No	No	No	Yes	No	No	No
Demog. Controls	No	No	No	Yes	Yes	No	No	No	Yes	Yes
Financial Controls	No	No	No	Yes	Yes	No	No	No	Yes	Yes

Note: Unit of observation is rate case in Panel B, Columns (3)-(5) and (8)-(10). It is utility-state-year in others. Standard errors, clustered by state, are i parentheses. *** p<0.01; ** p<0.05; * p<0.1

Table 4: Regression of Investment on Return on Equity

	Dependent Variable	
	Average Yearly Rate of Addition to Distribution Plant	Average Yearly Rate of Net Addition to Distribution Plant
Variable	(1)	(2)
Return on Equity	0.0031***	0.0036***
	(0.0010)	(0.0011)
Observations	510	510
R-squared	0.440	0.384
Utility-State FE	Yes	Yes

Note: Unit of observation is rate case. Robust standard errors, clustered by utility-state, in parentheses. *** p<0.01; ** p<0.05; * p<0.1

Table 5: Regression of Reliability Measure on Investment

	Dependent Variable			
	SAIDI		log(SAIDI)	
Variable	(1)	(2)	(3)	(4)
Net Distribution Plant	-9.92*	-11.67*		
($ million)	(5.28)	(5.94)		
log(Net Distribution Plant)			-0.272	-0.524***
($ million)			(0.170)	(0.173)
Observations	1,687	1,195	1,684	1,192
R-squared	0.399	0.663	0.744	0.769
Utility-State FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Controls	O&M expense	O&M expense Weather	O&M expenses	O&M expenses Weather

Note 1: Robust standard errors, clustered by state, in parentheses. *** $p<0.01$; ** $p<0.05$; * $p<0.1$
Note 2: A higher value of SAIDI means lower reliability.

Table 6: Regression of Log Energy Loss on Political Ideology

Dependent Variable: log(energy loss)

Variable	(1)	(2)	(3)	(4)	(5)	(6)
Republican Influence	0.169***	0.118**	0.133**	0.133**	0.130**	0.130**
	(0.054)	(0.055)	(0.058)	(0.059)	(0.059)	(0.059)
log(Net Distribution Plant)			0.483***	0.460**	0.418**	0.418**
			(0.168)	(0.173)	(0.166)	(0.166)
log(Operations and Maintenance)				0.074	0.059	0.059
				(0.078)	(0.078)	(0.078)
log(Sales)					0.221	0.221
					(0.143)	(0.143)
Observations	3,286	3,286	3,276	3,276	3,263	3,263
R-squared	0.906	0.908	0.908	0.908	0.909	0.909
Utility-State FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	No	Yes	Yes	Yes	Yes	Yes
Weather and Demographics	No	No	No	No	No	No
Sample Restrictions	Yes	Yes	Yes	Yes	Yes	No

Note 1: Unit of observation is utility-state-year. Robust standard errors, clustered by state, in parentheses. *** p<0.01; ** p<0.05; * p<0.1. In columns (1)-(5), we use the following sample restriction: $0.5 < \text{efficiency} < 1$ where $\text{efficiency} = \frac{\text{total sales}}{\text{total sales+loss}}$. We use this restriction to minimize the influence of outliers in the energy loss variable.

Table 7: Parameter Estimates

Parameter	Related Model Component	Estimate	95%-CI Lower-bound	95%-CI Upper-bound
$\gamma_e(10^7)$	effort cost	5.8504	5.2900	6.6613
$\gamma_\kappa(10^{10})$	audit cost	17.4760	13.4229	21.0956
$\gamma_r(10^{10})$	market return adjustment cost	2.8868	2.0778	9.1118
$\eta(10^4)$	quadratic investment cost	11.2177	5.9422	22.3227
$\sigma_i(10^7)$	investment-level-specific error	2.4146	1.0069	8.6828
a_0	weight on consumer surplus	0.9998	0.9971	1.0052
a_1	weight on consumer surplus	-0.0046	-0.0211	-0.0005
a_2	weight on consumer surplus	-0.0019	-0.0020	0.0012
N		2331		
Criterion		0.0006335		

Table 8: Model Fit

Moment	Data	Model
Targeted Moments		
Mean Investment	0.0500	0.0509
Mean Energy Loss	0.0675	0.0674
Mean Rate of Return	0.0963	0.0938
Standard Deviation of Investment	0.0278	0.0341
Standard Deviation of Energy Loss	0.0223	0.0023
Standard Deviation of Rate of Return	0.0133	0.0046
Regression Coefficient Effort on Republican Influence	-0.0062	-0.0065
Regression Coefficient Rate of Return on House Nominate	0.0034	0.0033
Un-targeted Moments		
Regression Coefficient Investment on Rate of Return	0.0008	0.0016
Regression Coefficient log(SAIDI) on Republican Influence	-0.1204	-0.0507
Regression Coefficient Effort on House Nominate	-0.0030	-0.0016

Notes: The data values for the targeted moments come from the estimation sample. The data value for Investment on Rate of Return is analogous to Table 4 Column (2), but with return on capital instead of return on equity and inclusion of year effects. We add a mean zero normally distributed random draw with standard deviation 0.0087=0.0133-0.0046 (from the row 'Standard Deviation of Rate of Return') to the return on capital to make the regression more comparable to the data. The data value for log(SAIDI) on *Republican Influence* is the analog of Table S.8, Column (2) with the estimation sample.

Table 9: Results of Rate of Return Counterfactual Experiments

	Baseline	Conservative Rate		Full Commitment	
			Δ %		Δ %
Mean Return on Capital	0.100	0.103	3.24%	0.108	8.36%
Return Policy w.r.t. Baseline	1.000	1.062	6.20%	1.140	**14.00**%
SD Return on Capital	0.003	0.001	-55.57%	0.004	15.79%
Mean Audit	0.974	0.974	-0.01%	0.974	-0.01%
SD Audit	0.000	0.000	-3.20%	0.000	-14.01%
Mean Investment Rate	0.052	0.056	7.62%	0.051	-2.93%
SD Investment Rate	0.028	0.024	-16.16%	0.019	-34.59%
Investment Policy w.r.t. Baseline	1	1.308	30.80%	1.459	**45.90**%
Mean Energy Loss	0.069	0.068	-0.92%	0.068	-1.09%
SD Energy Loss	0.002	0.002	-3.20%	0.002	-14.01%
Utility Value Per Capita	1616.012	2131.540	31.90%	2981.877	84.52%
Consumer Value Per Capita	539558.700	539619.620	0.01%	539291.004	-0.05%
Total Welfare	541174.712	541751.160	0.11%	542272.882	0.20%
Steady State Capital Per Capita	1179.306	1462.226	23.99%	1880.266	**59.44**%
SAIDI (average outages)	144.687	134.416	-7.10%	119.240	**-17.59**%

Note: Different rates of change (Δ%) in summary statistics can be associated with seemingly identical numbers due to round-up errors.

Table 10: Results of Auditing Policy Counterfactual Experiments

	Baseline	Most Liberal		Maximal Audit	
			Δ %		Δ %
Mean Return on Capital	0.100	0.100	-0.09%	0.100	-0.03%
SD Return on Capital	0.003	0.003	1.83%	0.003	2.66%
Mean Audit	0.974	0.974	-0.04%	0.967	-0.79%
SD Audit	0.000	0.000	-96.92%	0.000	-100.00%
Mean Investment Rate	0.052	0.052	-0.16%	0.052	-0.10%
SD Investment Rate	0.028	0.029	0.40%	0.029	0.40%
Mean Energy Loss	0.069	0.065	-5.22%	0.000	-100.00%
SD Energy Loss	0.002	0.000	-96.92%	0.000	-100.00%
Utility Value Per Capita	1616.012	1609.517	-0.40%	1602.792	-0.82%
Consumer Value Per Capita	539558.700	539734.130	0.03%	543068.318	0.65%
Total Welfare	541174.712	541343.647	0.03%	544671.110	0.65%

Note: Different rates of change (Δ%) in summary statistics can be associated with seemingly identical numbers due to round-up errors.