The Consequences of Wildfire Liability for Firm Precaution: Evidence from Power Shutoffs in California*

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This study examines firm responses to the entire distribution of potential liability by studying power line-ignited fires in California's electric utility sector. In this setting, when a power line-ignited fire damages a structure, the owner of the power line assumes the cost. The unique setting allows me to estimate how firm precautions vary across the entire distribution of liabilities they face. Using exogenous variation in the replacement cost of structures that lie downwind of power lines, I show that firms increase their precaution by 100% in response to a $690 million increase in liability. Furthermore, I show that firms' precautionary responses weaken as the likelihood of bankruptcy from expected liability increases. In the short run, the estimates from this study imply that firms' consideration of liability has heterogeneous welfare consequences across California. *JEL* Codes: D22, Q40, L51, K13.

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Low probability, high severity events such as oil spills or product defects characterize many sectors of the U.S. economy. A popular approach to mitigate the frequency of such events is to make firms liable for potential damages in part to incentivize precaution. To understand the effectiveness of liability regulation we need to know how firms' precautions respond to changes in the amount of damages they are liable for.

In settings where a firm faces large potential liabilities from an accident, its liability cannot exceed its asset value because it may use bankruptcy to avoid further damages. This discrete drop in firms' incentives for precautions at their asset value is commonly termed the judgment-proof problem (Shavell 1986). One common solution used to solve the judgment proof problem is to cap firms' level of potential liability. However, determining the liability cap level is a difficult task for a regulator: higher caps induce firms to undertake greater precautions as they bear a larger share of liability costs, but setting too high a cap may cause the firm to declare bankruptcy, shifting liability costs onto the public. This creates ambiguity about a fundamental question in public economics: What are the efficiency tradeoffs associated with capping liability?

Motivated by this gap in the literature on liability regulation, this paper provides the first causal evidence of how firms' precautions responds to the imposition of a negligence standard in California's electric utility sector. Between 1999 and 2017, firms faced with covering liabilities due to power line fires were allowed to recoup these costs through increases in retail electricity prices. However, since November 2017, utilities have borne liability costs whenever the regulator found that their imprudence led to an ignition. Using this setting, I estimate an empirical model that shows how firms' use of one type of precaution, called a Public Safety Power Shutoff event, changed following the policy shift. The empirical model uses daily variation in the replacement cost of structures that are downwind of power lines to estimate how firms' use of power shutoffs respond to the entire distribution of potential liability. Since firms in this setting are responsible for the replacement cost of structures damaged by power line-ignited fires, variation in downwind regions across days creates exogenous changes in potential liability.

Firms use Public Safety Power Shutoff events to prevent fire ignitions along their power lines. During a power shutoff, utilities turn the power off on sections of their energy infrastructure when forecasted climate conditions suggest an ignition is likely to occur. Because electricity must be running through a power line for an ignition to happen, power shutoffs significantly reduce the likelihood of fire and potential liabilities that a firm faces. In contrast, other types of precaution available to firms such as clearing vegetation away from power lines do not provide the same assurance because an ignition could still occur.

This is an important setting to study liability regulation. Climate change is increasing the severity of power line-ignited fires in the western U.S., making it important to understand how to incentivize firms to prevent ignitions in this setting (Syphard and Keeley 2015). Furthermore, power line-ignited fires are more damaging than fires from other ignition sources because they typically occur during high wind speed events when the wind carries vegetation into the line. Since fires are also more likely to spread rapidly and grow out of control during windy conditions, power line-ignited fires tend to cause more damage than fires from other sources (Keeley and Syphard 2018). For example, one privately owned utility, Pacific Gas and Electric, faced over $30 billion dollars in liability from several fires ignited in 2017 and 2018.[1] Figure 1 plots total damages in billions of 2021 dollars by source of fire ignition and shows that, although power line-ignited fires make up less than one percent of ignitions historically, they account for most of the damage from fires in California between 2008 and 2019.

My setting also has a key advantage: it allows me to causally estimate the relationship between the level of liability a firm faces and its precaution using exogenous changes in the direction that the wind is blowing across days.[2] Prior work has typically relied on regulatory changes that cap the level of liability a firm faces to study this relationship, but in this setting I am able to measure firms' responses across the full distribution of potential liabilities that they face.

Using administrative data on precautionary measures taken by the three largest privately owned utilities in California, I find three results. First, I show that firms' precaution is positively related to the level of liability that they face. Since utilities are liable for the cost of replacing structures damaged by fires that their power lines ignite, I measure liability using this value. In most settings, causal estimation of the relationship between the level of liability that firms face and precaution is difficult because liability is likely to be endogenous. My setting allows me to remove this endogeneity by using daily variation in the replacement cost of structures that lie downwind of each firm's power

1. Los Angleles Times "Pacific Gas and Electric to file for bankruptcy as wildfire costs hit $30 billion. Its stock plunges 52%", January 14, 2019.

2. The privately owned utilities in California's electric utility industry that I study are representative of most electric utilities in the United States. In fact, in 2017 privately owned utilities supplied 72% of electricity customers in the United States (EIA Annual Electric Power Industry Report).

lines between 2018 and 2020 to generate daily variation in each utility's potential liability. I estimate that power shutoffs increase by 100 percent relative to the average likelihood of a shutoff when the total replacement cost of structures in downwind areas increases by 10 percent ($690 million).

Second, I demonstrate that firm precautions do not increase with liability when total downwind expected liability is large relative to total firm asset value, providing empirical support for the judgment proof problem. When zip codes of low or moderate ex-ante fire risk lie downwind of power lines, firm precautions increase with liability until total liability in each downwind zip code exceeds 14% of each firm's total 2022 asset value. However, when high fire risk zip codes lie downwind, precautions increase with liability until total liability exceeds 8% of firm asset value.

Third, I estimate that firms' consideration of liability when taking precautions had an ambiguous impact on short-run welfare across California. Short-run total welfare effects depend consumers' valuation of lost electricity use during a power shutoff and range between a $6 billion loss and a $700 million gain. Irrespective of consumers' valuation, the short-run welfare impact is decreasing in shutoff duration and varies widely across California zip codes.

These results have several policy relevant implications. I provide an empirical framework to estimate how firms' precautionary behaviors change across the distribution of potential liabilities, a key parameter for determining the liability cap level. Current and past policy proposals have included limits on the amount of damages homeowners can recover from electric utilities.[3] However, such policy proposals note that it is unclear what level liability should be limited at and how such limits would distribute costs between homeowners, electricity consumers, and utility shareholders.

Furthermore, I estimate how economic incentives influence the reliability of electricity supply using a novel dataset of distribution power lines. This is relevant for regulators across the U.S. who want to incentivize utilities to make investments that improve the reliability of electricity supply and upgrade aging infrastructure. Because of the projected growth of renewable energy generation in the United States, the federal government has made upgrades of energy infrastructure a cornerstone of its energy platform.[4] My work in this paper underscores that having detailed administrative data on distribution networks across the U.S. will be important for effectively upgrading energy infrastructure.

3. "Allocating Utility Wildfire Costs: Options and Issues for Consideration", California Legislative Analysts Office, 2019.

4. See https://www.energy.gov/articles/reimagining-and-rebuilding-americas-energy-grid.

This paper makes three contributions to the literature in public economics. First, it poses a channel, expected damages, through which liability regulations impact firms' decisions and quantifies how the burden of precautionary costs is distributed between firms and electricity consumers. I show that, when firms bear liability costs, they direct more precautionary effort to areas with high levels of expected liability until total damages are large relative to firm asset value. This adds to previous work documenting other determinants of firms' choice of precaution such as bankruptcy (Shavell 1986), subjective firm beliefs (Currie and MacLeod 2014), risk aversion (Shavell 1982), and market structure (Chen and Hua 2017). Furthermore, this result contributes to a growing literature that examines the determinants of wildfire suppression (Plantinga, Walsh, and Wibbenmeyer, 2022; Baylis and Boomhower, 2023).

Second, I show how precaution varies across the distribution of potential liabilities that firms face. Previous research has estimated how capping medical liability impacts doctors' prescribing behavior (Helland, Lakdawalla, Malani, and Seabury 2021), medical outcomes (Danzon, 1985; Kessler and McClellan, 1996; Currie and MacLeod, 2008; Frakes, 2013), and the labor supply of doctors (Malani and Reif, 2015; Kessler, Sage, and Becker, 2005; Klick and Stratmann, 2007; Matsa, 2007). Another related literature examines how changes in liability impact toxic waste discharges and abatement technology adoption (Akey and Appel, 2021; Alberini and Austin, 2002; Stafford, 2002). Many of these studies estimate how precaution responds to the level of liability a firm faces at one point in the liability distribution because their variation comes from caps on liability at a particular value. The empirical strategy in this paper allows me to estimate how precaution changes across the entire distribution of liability that firms face in practice.

Previous work on the judgment-proof problem by Boomhower (2019) shows that requiring firms to purchase insurance which covers damages beyond their own assets encouraged greater production by larger firms with better environmental outcomes in Texas' oil and gas sector. This paper complements Boomhower (2019) by directly estimating how firms' precautions change across the distribution of potential liability they face. Since requirements to cover damages beyond firm assets may not be feasible in settings with concentrated market power, such as the electric utility sector, the estimates in this paper provide relevant information that can be used to implement other solutions to the judgment-proof problem such as capping liability.

This paper also makes important contributions to a recent literature in environmental economics and engineering. I show that liability considerations influence firms' decision to declare power shutoffs. Previous work by Abatzoglou, Smith, Swain, Ptak, and Kolden (2020) applied one utility's publicly stated climate thresholds for declaring power shutoffs to observed weather data during 2019, finding that the utility used shutoffs more than would be predicted by its own decision rules. I provide an economic explanation for this overuse of power shutoffs by documenting the role of liability in determining firms' precaution.

I also provide evidence that utilities' use of power shutoffs has heterogeneous effects across California. This adds to a recent literature that estimates the costs and benefits of public safety power shutoffs in California (Sotolongo, Bolon, and Baker, 2020; Wong-Parodi, 2020; Zanocco, Flora, Rajagopal, and Boudet, 2021; Mildenberger, Howe, Trachtman, Stokes, and Lubell, 2022).

Finally, I provide the first evidence of fire liability's impact on firms in the electric utility industry. Yoder (2008) shows that the number of fires escaping from private landowners' property during a prescribed burn declines following the implementation of strict liability regulations. I add to this evidence by causally showing that electric utilities increase precautionary actions to prevent fire ignitions along their power lines in response to greater liability for fire damages.

The rest of this paper proceeds as follows: section 1 provides background on liability regulation for power line-ignited fires in California and utilities' ignition prevention decision environment. Section 2 presents a conceptual framework with testable predictions of liability regulation's effect on utility's precautionary effort. Section 3 develops an empirical strategy to causally estimate the relationship between liability and shutoffs. Section 4 describes the data sources used in this analysis, section 5 presents the results, and section 6 concludes and suggests opportunities for future research.

1 Background

1.1 Institutional Background

This paper focuses on electricity distribution to residential and commercial consumers, the final link in the U.S. electricity supply chain which consists of generation, transmission, and distribution.[5]

5. According to the CPUC post-event reports, transmission lines account for less than 1% of lost customer hours related to power shutoffs to prevent fire ignitions. Therefore, I exclude transmission lines from the analysis in this paper.

Electric distribution utilities are generally considered natural monopolies and most are regulated by Public Utility Commissions (PUCs). The California Public Utility Commission (CPUC) mandate states that its goal is to provide "...access to safe, clean, and affordable utility services and infrastructure."

PUCs' primary regulatory tool to influence utilities' actions is called a rate case. CPUC defines rate cases as quasi-judicial "proceedings used to address the costs of operating and maintaining the utility system and the allocation of those costs among customer classes." At each rate case proceeding, the PUC determines the electricity price schedules which a utility can charge customers until its next rate case proceeding. The three largest Investor Owned Utilities (IOUs) in California each have their own separate rate cases every three years. In this way, most transmission and distribution utilities in the U.S. face price cap regulation with periodic adjustment of the cap. The PUC adjusts the price schedule so that each utility earns a fair rate of return on its capital and recovers its operating expenses. However, the PUC may disallow a capital expense from being included in the retail price if it does not meet a standard of being "used and useful."

Importantly, in California utilities could request to recover uninsured costs associated with fires ignited by their distribution infrastructure during rate cases between 1999 and 2017. Thus, while utilities paid for residential damages and suppression costs associated with fires ignited by their equipment, they expected to recover these costs through an increase in the electricity price cap. After a 2017 ruling in a rate case proceeding that rejected San Diego Gas and Electric's application to recover fire-related costs through electricity rates, utilities faced a greater likelihood that they would be financially accountable for such costs, increasing their expected liability. The next section discusses the history of fire liability for utilities in California.

1.2 Liability Regulation in California

Liability regulations impact the incentives for individuals and firms to take risk and exert precaution. In the case of fire ignited by utility-operated infrastructure, utilities may adjust their level of precaution according to the proportion of fire-related damages they would be held accountable for if an ignition occurs. Similarly, individual homeowners may increase effort to reduce the probability of wildfire-related damage to their property when a firms' share of liability from a power line ignited wildfire is low. Regulators choose the degree of liability that a firm faces by choosing from two types of regulations: strict liability and a negligence rule. Under strict liability, the firm is fully liable for the resulting damages of a fire ignited by their equipment. In contrast, the negligence rule sets a minimum threshold of precaution that firms must meet in order to avoid financial responsibility for damages. In the canonical model, the firm will take the highest level of precaution under strict liability and reduce its level of ignition prevention to just meet the threshold when subject to the negligence rule (Kaplow and Shavell 1999).

In California, the state has held IOUs to a strict liability standard for fire damages since a 1999 state supreme court decision, *Barham v. Southern California Edison Company (1999).* A key factor in the Court's decision was the fact that, just as a government can raise revenue through taxes, IOUs can raise revenue through retail electricity rates in California.[6] The Court reasoned that since the state government is strictly liable for damages it causes under the Takings clause of the California constitution, IOUs could be held strictly liable for damages related to power line-ignited fires. As a result, IOUs faced strict liability for fire damages in excess of their insurance coverage, but could recover these costs through increases in the retail price of electricity. IOUs continued to challenge the Court's ruling in *Barham* as recently as 2012, arguing that they could not have the same liability status as a government because their ability to raise rates is subject to the approval of the CPUC.[7] The Court continued to maintain, however, that because there was no evidence CPUC would not allow IOUs to recover costs through electricity rate increases, strict liability would continue to apply.

Although IOUs faced strict liability, the precedent established by *Barham* ensured that their liability net of revenue increases from raised electricity rates would be low. The precedent that IOUs could recover liability costs through increased electricity rates was not tested until several damaging fires ignited by power lines operated by San Diego Gas and Electric in 2007. The 2007 fires were the first time since the *Barham* decision that the liability costs associated with power line-ignited fires exceeded an IOU's liability insurance coverage (Hafez 2020). As a result, San Diego Gas and Electric's application to recover uninsured liability costs through electricity rate increases was a novel test of the strict liability standard. Ultimately, CPUC rejected San Diego

6. The Court's decision argues that IOUs' ability to raise electricity rates is akin to a government's ability to levy taxes. IOUs are currently challenging this logic in court by pointing out that their ability to raise electricity rates is subject to approval by the CPUC.

7. Pacific Bell Telephone Co. v. Southern California Edison Co., 208 Cal. App. 4th 1400, 1403 (2012).

Gas and Electric's application to recover liability costs through electricity rates in December 2017, citing San Diego Gas and Electric's lack of precaution in preventing the 2007 fires as the deciding factor.[8] Because IOUs could no longer expect to automatically recover costs through electricity rate increases following the 2017 CPUC decision, their liability for fire damages increased dramatically. CPUC's decision states that "If the preponderance of the evidence shows that the utility acted prudently, the Commission will allow the utility to recover costs from the ratepayers." While CPUC declined to define a precise negligence threshold in its decision, the decision dramatically increased each IOU's expected share of responsibility for liability.

The "prudent manager" standard remained in effect until SB 901 added section 451.1 to the Public Utilities Commission Code which took effect for all fires ignited after January 1, 2019. Section 451.1 replaced the "prudent manager" standard with twelve non-exclusive criteria that CPUC uses to determine whether an IOU can recover costs associated with fire liabilities through electricity rates. The criteria take into account the IOU's design, maintenance, and operation of assets in addition to the severity and unpredictability of the weather event which caused the ignition. While, section 451.1 clarified the standard used to judge each utility's negligence it still significantly increased the share of costs associated with fire damages utilities expected to bear relative to the pre-2017 regulatory environment. If the reader is interested in learning more about the history of liability law and IOUs in California, Hafez (2020) provides a complete and succinct description. The next section describes utilities' allocation of ignition prevention effort and demonstrates how increasing the share of damages born by IOUs changes this allocation.

1.3 The ignition prevention decision environment

IOUs face a complex decision making environment as they determine how and where to invest in strategies that lower the risk of fire ignited by their electrical infrastructure.[9] Utilities' ignition-prevention decisions have significant economic consequences; despite accounting for 1-5% of total fire ignitions in Southern California, utility-operated equipment accounts for 20-30% of total area burned by wildfires (Syphard and Keeley 2015). Ignitions by power lines typically occur between

8. Application of San Diego Gas & Electric Company (U 902 E) for Authorization to Recover Costs Related to the 2007 Southern California Wildfires Recorded in the wildfire Expense Memorandum Account, filed Sept. 25, 2015. Decided Dec. 26, 2017.

9. This section draws from Wildfire Mitigation Plans submitted by Southern California Edison, Pacific Gas and Electric, and San Diego Gas and Electric to CPUC in 2019, 2020, and 2021.

July and December and their two leading causes are wind-blown vegetation and equipment failure. Much of the transmission and distribution infrastructure operated by IOUs in California is outdated (in 2017 Pacific Gas and Electric estimated that the average age of its transmission towers was 68 years old). As climate change has increased vegetative aridity and the severity of weather events in IOU service territories, the risk of fire ignition has also risen. In determining which areas to prioritize for ignition mitigation activities, utilities weigh the benefits of providing electricity to their residential, industrial, and commercial customers with the cost of each activity and the ignition risk associated with each section of their distribution and transmission infrastructure.

To determine the ignition risk of a section of power line, utilities consider historical and forecasted weather conditions, infrastructure age, vegetative growth, presence of outdated equipment with known ignition risk, and the value of electricity demanded by customers on that section. After determining the baseline risk of a power line segment, a team at each utility then chooses an ignition mitigation activity which reduces the risk at least cost. Utilities perform a range of ignition prevention activities including vegetation management, installation of weather stations along power lines, burying power lines underground, upgrading equipment, inspecting power lines, and turning off the power to targeted sections of the grid when weather conditions elevate the probability of ignition. Use of ignition prevention activities differs across utilities and over time as conditions change and utilities learn more about the effectiveness of each action. For example, Pacific Gas and Electric primarily deployed shutoff events and infrastructure upgrades in 2019 to reduce the probability of ignition, while Southern California Edison focused on installing covered conductors that reduce the probability of ignition on high risk assets. Recently, each IOU has increased efforts to bury sections of high-risk assets underground.

Precautionary actions available to utilities differ widely in their ability to prevent ignitions, their cost, and which individuals bear that cost. Power shutoffs, when targeted well, guarantee that an ignition cannot occur because electricity is not running through the line when an incident occurs. However, power shutoffs are also socially costly, sometimes leaving affected communities without power for extended periods of time. In contrast, the effectiveness of other types of precaution such as vegetation management may be more difficult to measure and impose costs on either the utilities or (if the cost of precautionary measures is incorporated into retail electricity rates) all electricity consumers in California.

Historically, utilities in California have not relied on power shutoffs to reduce the likelihood of ignition because they disrupt the service of electricity to customers. CPUC defines Public Safety Power Shutoff events as actions taken by utilities to temporarily turn off power to specific areas in order to reduce the risk of fires caused by electric infrastructure. Of the three largest IOUs in California, only San Diego Gas and Electric utilized shutoffs to prevent ignitions prior to 2017.[10] Because shutoff events require the utility to interrupt service to customers it is seen as a measure of last resort to mitigate fire ignitions. As a result, each IOU has invested in devices which further segment high-risk areas of their transmission and distribution networks, allowing more targeted blackouts that affect fewer customers.

CPUC approves the use of power shutoff events by IOUs, first granting approval to San Diego Gas and Electric in 2012, Pacific Gas and Electric in 2018, and Southern California Edison in 2018. Figure 2 plots the share of total customer hours impacted by shutoff events between 2013 and 2023 by year separately for each of the three largest California utilities. The most affected customer hours occurred during 2019 in Pacific Gas and Electric's and Southern California Edison's service territories. A similar pattern exists for the number of commercial customer hours and medically vulnerable customer hours affected by power shutoffs. Between 2021-2023 all three utilities used power shutoffs less frequently than in previous years, potentially reflecting the transition to longer-term precautionary actions such as burying power lines underground. This study focuses on firms' short-run use of precaution between 2018 and 2020, leaving studies of long-run precautionary behavior for future work.

Utilities consider climatic conditions, the condition of electrical infrastructure, and the value of lost electricity load in potentially impacted areas to determine when and where to declare power shutoffs. Pacific Gas and Electric reports the criteria it uses to declare shutoff events on page 982 of its 2021 Wildfire Mitigation Plan. The minimum criteria for deciding a shutoff in a high fire threat area are sustained wind speeds greater than 20 miles per hour, dead fuel moisture below 9%, relative humidity below 30%, and a fire potential index greater than 0.2.[11] Despite these criteria, utilities have discretion in declaring power shutoffs: Abatzoglou, Smith, Swain, Ptak, and Kolden

10. San Diego Gas and Electric sought and received approval from CPUC to initiate power shutoffs in its service territory starting in 2013.

11. The fire potential index measures the likelihood of an ignition causing a catastrophic wildfire using wind speeds, temperature, humidity, dead and live fuel moisture, and vegetative cover types.

(2020) provide evidence that shutoff events are used more frequently by Pacific Gas and Electric than would be implied by their minimum climate criteria.[12]

According to the canonical economic model of liability regulation, the increase in the share of liability born by utilities following CPUC's 2017 decision should increase the level of ignition prevention effort (Kaplow and Shavell 1999). Furthermore, increasing the liability born by utilities should also increase their use of more costly prevention activities such as shutoff events. Finally, the increase in liability should cause utilities to direct ignition prevention efforts to regions of their service area with a high property values. Since destroyed property values make up a significant portion of liability damages born by utilities when their equipment ignites a fire, they have an incentive to direct ignition prevention activities to these regions.

The next section develops a conceptual framework of liability in the context of the electric utility industry and presents several testable hypotheses.

2 Conceptual Framework

The conceptual framework demonstrates two points: (1) Increasing the level of potential liabilities could lead firms to use more or fewer power shutoffs. (2) Utilities use more shutoffs when ignitions are likely.

The framework in this paper is adapted from Lim and Yurukoglu (2018) who show that a regulator's inability to commit to a predictable path of capital returns leads utilities to systematically underinvest in capital. Here, I consider a simplified version of the model with no strategic interaction between the regulator and the utility. In this model, the utility takes the regulator's choice of capital return as given rather than as an output from a negotiation process.

For simplicity, I model a single utility's decision to make defensive capital investments and supply electricity to one distribution circuit. If the utility supplies electricity, it receives future net revenue and faces expected liability damages from a potential ignition along its power lines. However, if the utility declares a power shutoff it receives no revenue and faces no expected damages. The utility self protects against expected damages by making defensive capital investments that

12. Abatzoglou, Smith, Swain, Ptak, and Kolden (2020) note that this could be due to differences in climate modelling between their study and Pacific Gas and Electric's internal methods.

reduce the probability of ignition.[13] In making its decisions, the firm compares the marginal reduction in damages from self protection to total expected damages. Whenever expected damages exceed the marginal benefit of self protection, the firm shuts off the power.

I make several important assumptions in this model. First, because the model only considers one distribution circuit, the firm will never make additional defensive capital investments if it shuts off the power. In practice, defensive investments may complement power shutoffs because utilities could self protect against damages on days when the ignition risk is low. Second, in a departure from reality, I do not allow for strategic interaction between the firm and the regulator. The results from Lim and Yurukoglu (2018) suggest that allowing for such interaction would cause firms to increase shutoff use more and invest in defensive capital less. Third, I do not model the firm's non-defensive capital investment decisions. Finally, the model assumes that consumers value their homes at the structure replacement cost. This simplifying assumption does not affect the framework's predictions, but it would increase the benefit of shutoffs for households in the calculation of how liability regulation affects social welfare in section 6.

2.1 Firm's Problem

The regulator sets a per unit output price p that allows the utility to recoup a reasonable return on defensive capital (γk) and per-unit liability costs (ν).

$$p = \gamma k + \nu \tag{1}$$

Where k represents the stock of firm defensive investment which it uses to self insure against damages from a potential fire ignition and γ is the exogenous rate of return on defensive investment that is set by the regulator. The firm inelastically supplies Q units of electricity to consumers who purchase a quantity Q of electricity up to a "choke" price ($\bar{p}$) above which they are no longer willing to pay.

13. I define self protection in the same way as Ehrlich and Becker (1972), where defensive investments reduce the probability of ignition rather than total damages.

$$D(p) = \begin{cases} Q & \text{if } p \leq \bar{p} \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

The utility earns revenue by supplying electricity to retail consumers and reduces expected liability costs by renting defensive capital that reduces damages from a potential ignition from households at the prevailing interest rate (r). The utility can also prevent ignitions by supplying no electricity to consumers (declaring a power shutoff).

$$\max\{\pi_1, \pi_0\}$$

Where

$$\pi_1(k) = \max_{k'}\{-r(k' - (1-\delta)k) + \beta(\phi p Q)\}$$

$$\pi_0(k) = \max_{k'}\{-r(k' - (1-\delta)k) + \beta(pQ - \theta(k')\bar{d})\}$$

Where the utility earns π_1 in profits if it shuts off the power and π_0 in profits if it supplies power, δ is the capital depreciation rate, and $\bar{d}$ is the dollar amount of liability damages if an ignition occurs. In the empirical analysis later in this paper, $\bar{d}$ is the total replacement cost of structures threatened by a power line ignition. The utility can self protect against liability costs by investing in defensive capital (k') which reduces the probability of ignition ($\theta(k')$) or by declaring a power shutoff which reduces the probability of ignition to zero. When the utility shuts off the power it recoups a fraction $\phi \in [0, 1]$ of its revenues by exerting market power in wholesale electricity markets. β is the per-period discount factor. Substituting the price of electricity from equation 1, allows us to rewrite the utility's profit functions.

$$\pi_1 = \max_{k'}\{-r(k' - (1-\delta)k) + \phi\beta(\gamma k + \nu)\}$$

$$\pi_0 = \max_{k'}\{-r(k' - (1-\delta)k) + \beta(\gamma k + \nu - \theta(k')\bar{d})\}$$

If the firm supplies electricity (π_0) it pays defensive capital rental costs today and receives future net revenues (pQ) while facing expected liability costs from a potential ignition ($\theta(k')\bar{d}$). Whenever the firm chooses to shutoff the power (π_1), it pays capital rental costs today and receives only a fraction of its revenue in the future, but since an ignition cannot occur it also faces no expected damages.

When the utility shuts off the power it creates lost producer and consumer surplus. Intuitively, the utility incurs a private cost from shutoffs through lost producer surplus and benefits from shutoffs because it faces no expected liability cost. So the utility's privately optimal choice of shutoffs depends on the relative magnitude of producer surplus and expected liability costs. Importantly, the utility does not internalize the loss in consumer surplus when it turns off the power, causing the utility's privately optimal choice of shutoffs to exceed the socially optimal level.

Assuming without loss of generality that the utility starts with no defensive capital ($k = 0$), solving the firm's problem when it does not declare a blackout is trivial. When the firm shuts off the power, its profit is constant regardless of defensive capital investment made by the firm.

$$\pi_1^* = \beta\phi\nu \quad \forall \quad k_1^{'*}$$

In the state of the world where it does not declare a blackout (π_0) the firm invests in defensive capital such that the marginal benefit of investment (reduction in expected damages and increased revenue) equals the marginal cost of investment (the rental rate paid to households).

$$-\beta\theta'(k')\bar{d} + \beta\gamma = r \tag{3}$$

Where $-\beta\theta'(k')\bar{d}$ is the reduction in expected liability costs from increasing defensive investment, $\beta\gamma$ is the increase in revenue the firm receives by increasing its defensive capital stock, and r is the rental rate of capital. The utility then chooses whether or not to declare a shutoff by comparing its optimized profit when it declares a shutoff (π_1^*) to when it supplies electricity (π_0^*). Whenever the firm can earn greater expected profits by supplying electricity, it does not shut off the power.

This paper empirically studies how changes in expected liability costs impact utilities' use of power shutoffs. I use exogenous variation in wind direction and speed across days to estimate how utilities' use of shutoffs changes when they face higher total expected liability costs. In the model, firms face higher liability costs when the total replacement cost of structures threatened by a potential ignition ($\bar{d}$) is large. Increasing $\bar{d}$ in the model shifts π_0 down, but leaves π_1 unchanged. Depending on how large the drop in π_0 is, the firm may use more shutoffs or keep supplying electricity. I show that firms increase their use of shutoffs when areas with higher total structure replacement cost are threatened by a potential ignition. In addition, utilities should utilize blackouts more when they face high realizations of the probability of ignition ($\theta(k')$). As a result, we expect there to be more blackouts on days when the weather is conducive to fire ignitions along power lines (prediction (2)). I provide evidence of prediction (2) in Appendix A.

3 Empirical Framework

According to the theory developed in section 2, utilities' use of shutoffs should respond (either positively or negatively) to the liability cost they bear. One way to test this hypothesis would be to estimate a linear model that relates the probability of a shutoff at circuit i on day t (y_{it}) to the total replacement cost of structures near circuit i ($Value_i$).

$$y_{it} = \nu Value_i + \varepsilon_{it} \tag{4}$$

Under the conditional independence assumption, ν identifies the effect of liability on firms' use of shutoffs. However, the conditional independence assumption is unlikely to hold in this example because unobserved determinants of shutoffs such as the moisture content of vegetation, regional weather conditions, and the presence of critical energy infrastructure are likely correlated with structure replacement costs. To overcome this challenge and isolate the effect of structure replacement cost on shutoffs, I use daily changes in wind direction to create exogenous variation in structure replacement costs that would be threatened by an ignition, if it occurred. Since power line-ignited fires are more likely to occur during periods of extreme wind speeds (Syphard and Keeley 2015), wind direction is likely to be a relevant determinant of whether a region is threatened by a wildfire on any given day, t. Furthermore, since average daily variation in wind direction is uncorrelated with both power shutoffs and structure replacement costs the conditional independence assumption likely holds.

To determine which regions lie downwind of power lines in California during each day between 2018 and 2020, I combine real-time data on maximum wind speeds from weather stations operated by utilities along their electricity infrastructure with an estimate of how long a lit ember could remain airborne if picked up by the wind from Albini, Alexander, and Cruz (2012).[14] Appendix A describes this procedure.

I use circuit level changes in wind direction across days to assign which zip codes lie downwind of a utility's power lines. There are several justifications for using zip codes as the unit of analysis in this study. First, it uses borders which are determined by the California government, rather than boundaries that I have chosen myself. Second, using zip codes allows me to control for other characteristics that are important determinants of utilities' shutoff use such as population and total energy use which are not available at finer geographic scales using publicly available data. Finally, the data on structure replacement costs is available for the universe of parcels in California at the zip code level, but may be missing at more granular levels of aggregation. In Appendix B, I re-estimate the relationship between structure replacement cost and shutoff use using only variation in wind direction within twenty kilometers of power lines, finding similar results to the aggregate zip code analysis.

Figure 3 demonstrates how I determine downwind structure replacement cost in the empirical analysis using an example of 13 zip codes from San Diego County in California. The tan zip code in the center of both panels contains three distribution circuits and the black circles represent the centroid of each circuit. In my empirical framework, I define each tan zip code in my sample as an "origin" zip code. All of the white and yellow zip codes lie downwind of the origin zip code at some point during 2018 and 2020. I define these zip codes as "destination" zip codes because they are the set of possible destinations where an ember could land if picked up at a circuit in the origin zip

14. Albini, Alexander, and Cruz (2012) estimate that the maximum spotting distance for a wind driven fire is 10 kilometers. Assuming that wind speeds are at the third quartile observed across my sample between 2018 and 2020 (9.5 meters per second), the 10 kilometer estimate implies that an ember could remain airborne for up to 18 minutes. Estimates are robust to other assumptions of how long a lit ember could remain airborne (such as 5 minutes).

code. Each black line points in the direction that the wind is blowing, and its end point indicates how far away from each circuit a lit ember could travel given observed wind speed and direction. When the black line intersects with a zip code, I define the zip code as downwind of the origin zip code. Therefore, in panel (a) of Figure 3 the three yellow destination zip codes to the north of the origin are downwind, while the following day (shown in panel (b)) the three destination zip codes to the west are downwind. I estimate the relationship between the total replacement cost in the downwind zip codes and shutoff use at circuits in the origin zip code. As a result, this strategy uses daily variation in liability that is driven by exogenous changes in wind speed and direction. Equation 5 formally presents this research design.

Since there may be underlying static characteristics about each zip code, such as geography, that correlate with shutoff declaration and threatened property values, I construct a paired data set of origin and destination zip codes and control for a pair fixed effect following Kuhn, Kooreman, Soetevent, and Kapteyn (2011). For each day t and origin zip code o the data file contains a set $(N(o))$ of neighboring destination zip codes indexed by d which are ever downwind of zip code o between 2018 and 2020. By including pair fixed effects, ν_{od}, this strategy accounts for time invariant characteristics of pairs that may be correlated with structure replacement cost and power shutoffs, such as underlying vegetation moisture. Furthermore, I include a calendar day fixed effect which accounts for day-specific unobserved heterogeneity which impacts all zip code pairs, such as seasonality or statewide climatic factors.

$$(5)\quad y_{jodt} = \beta_1 Value_d \times DW_{jodt} + \beta_2 Value_d + \beta_3 DW_{jodt} + \beta_3 X_{jot} + \beta_4 X_{jdt} + \nu_{od} + \delta_t + \gamma_{jt} + \varepsilon_{odt}$$

Where y_{jodt} is a binary variable indicating whether a shutoff is in effect in zip code o which is ever upwind of zip code d on day t and has power lines operated by utility j. $Value_d$ is the de-meaned log total (or average) structure replacement cost in zip code d and DW_{odt} is equal to one if zip code d is downwind of zip code o on day t. The model includes time-varying covariates (X_{jot}, X_{jdt}) which are specific to zip codes o and d respectively and include average daily wind speed, temperature, specific humidity, and maximum wind speed. In order to allow the effect of the climatic controls to non-linearly impact the outcome, I bin each control variable into septiles.

The coefficient of interest, β_1 may not capture the causal effect of liability on power shutoff declaration if daily variation in wind direction is correlated with a community's underlying fire severity. I account for this possibility by controlling for a categorical measure of underlying wildfire risk (called the wildfire hazard potential) and the share of zip code population living in a region of heightened fire risk (share of population living in the Wildland Urban Interface in 2010) interacted with the downwind indicator. I provide more information on these controls and their sources in section 4. Finally, I include utility by year fixed effects (γ_{jt}) which account for annual changes in utilities' plans to prevent ignitions.

Since I de-mean the structure replacement cost in equation 5, β_3 is the change in shutoff likelihood when a zip code with average structure replacement cost is downwind. The coefficient of interest β_1 measures the average percentage point change in the likelihood of a power shutoff with respect to a one percent increase in downwind structure replacement cost. Furthermore note that while the coefficient β_2 captures the effect of non-threatened property values, it cannot be estimated because the replacement cost is collinear with the pair fixed effects. Under the conditional independence assumption, β_1 and β_3 identify the causal effect of downwind structure replacement cost on the probability of a shutoff.

4 Data

4.1 Outcomes

Power Shutoff Events I obtain the date, duration, location, and number of impacted customers from power shutoff post-event reports for the period 2013-2020 from the California Public Utilities Commission.[15] Since Pacific Gas and Electric, Southern California Edison, and San Diego Gas and Electric serve nearly 80% of electricity consumers in California and account for the largest share of power shutoffs historically, I restrict the sample to events initiated by one of these utilities. Furthermore, I exclude publicly owned utilities from this analysis because they have not been granted the authority to conduct power shutoff events by the regulator. As shown in Table 1, there were 46 concurrent power shutoffs on the most active day of power shutoffs in my sample.

15. Utilities are required to submit under Ordering Paragraph 1 of California Public Utilities Commission (CPUC) Decision (D.) 19-05-042.

However, shutoff events are very infrequent at the daily level, occurring on average 3.1% percent of total pair-days in the sample. The last row of table 1 shows that there are 546 zip codes in California that ever experience a shutoff between 2018 and 2020.

Energy Infrastructure Information on the geographic location of distribution and transmission lines operated by Pacific Gas and Electric, Southern California Edison, and San Diego Gas and Electric is collected from publicly available Geographic Information System (GIS) files submitted to the California Office of Infrastructure Safety in 2020. The GIS data shows the location of each transmission and distribution line within a circuit and exclude critical energy infrastructure. Since the California Public Utility Commission reports shutoff events at the circuit level, I aggregate the line level data to the circuit level before string matching events to circuits by circuit name. On average across the three utilities, I match 97 percent of events to circuits using string matching.

4.2 Treatment and Control Variables

Climate Data I obtained wind speed and direction at ten minute intervals from the 3,041 weather stations operated by Pacific Gas and Electric, Southern California Edison, and San Diego Gas and Electric along their energy infrastructure. In addition, I collected information on temperature, relative humidity, and precipitation from the 892 weather stations operated by the National Weather Service and Remote Automatic Weather Stations in California.[16] For each station, I compute daily average and maximum temperature, humidity, precipitation, and wind speed. Then, for each circuit I compute the inverse distance weighted average for each climate variable across all stations within 20 kilometers of the circuit, generating daily average and maximum temperature, relative humidity, precipitation, and wind speed for each distribution circuit operated by Pacific Gas and Electric, Southern California Edison, and San Diego Gas and Electric in California. Since station-level wind data is limited for destination zip codes where Pacific Gas and Electric, Southern California Edison, and San Diego Gas and Electric have limited or no operations, I obtain wind speeds for destination zip codes from NOAA's High Resolution Rapid Refresh (HRRR). HRRR is an atmospheric model with a 3km grid cell resolution which provides hourly information on wind speed.

Replacement Cost of Structures Since electric utilities are liable for the cost of replacing structures damaged by power line-ignited fires, I use parcel-level structure replacement costs to measure

16. The weather station data was accessed through the Mesonet API.

potential damages rather than the market value of each property. I obtain parcel level replacement costs of each property in California in the year that it is assessed from the Zillow Transaction and Assessment Database (ZTRAX) which contains parcel-level assessed values and transaction information for most counties in the U.S.[17] Zillow computes the replacement cost by taking the difference between the market value of the property and the market value of the land in the year of assessment. I adjust replacement costs to 2021 dollars using the consumer price index.[18] As reported in Table 1, the average replacement cost is substantial at around $6.9 billion and there is significant variation across zip codes with a standard deviation of $6.6 billion.

Vegetative Cover I use the discrete Wildfire Hazard Potential index to capture underlying vegetative conditions in the areas surrounding distribution circuits in California.[19] Values of the WHP index indicate wildfire risk and range from 1 (very low) to 5 (very high). The WHP index is intended to guide strategic long-term management of vegetation and is based on vegetation and fuels data from LANDFIRE 2014, a collection of databases which describe vegetation and fire characteristics across the U.S..[20] As a result, the WHP reflects vegetative conditions at the end of 2014.

Wildland Urban Interface Since utilities' decision to declare a shutoff event could be impacted by whether a circuit is located in an area that is high fire risk, I obtain the boundaries of the Wildland Urban Interface (WUI) from the California Department of Forestry and Fire Protection's Fire and Resource Assessment Program. The WUI is defined as an area with dense housing adjacent to vegetation that can burn in a wildfire.[21] Because the property value analysis is estimated at the zip code level, I compute the share of total 2010 zip code population living within the WUI.

Energy Use The level of electricity demanded by consumers downwind of a distribution circuit is likely correlated with both property values and utilities' decision to declare a power shutoff. To account for this, I compute annual zip code electricity demanded by residential, commercial, and

17. Data provided by Zillow through the Zillow Transaction and Assessment Dataset (ZTRAX). More information on accessing the data can be found at http://www.zillow.com/ztrax. The results and opinions are those of the author(s) and do not reflect the position of Zillow Group.

18. Federal Reserve Economic Data, series CPALTT01USA659N.

19. Dillon, Gregory K; Gilbertson-Day, Julie W. 2020. Wildfire Hazard Potential for the United States (270-m), version 2020. 3rd Edition. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2015-0047-3

20. The LANDFIRE program is jointly supported by the U.S. Department of Agriculture, the Forest Service, and the U.S. Department of the Interior.

21. Specific housing density and vegetation thresholds for WUI classification can be found at https://frap.fire.ca.gov/media/10300/wui$_19_a$*da.pdf*.

industrial consumers using data from each utility and the California Energy Consumption Database. Whenever a utility suppresses or aggregates demand across multiple zip codes, I compute annual zip code demand by subtracting total demand in all zip codes within a county from the total county-level demand and allocating the remainder to each zip code with suppressed data according to its share of 2010 county-level population. Average annual electricity demand is approximately 89 GWh in each zip code in my sample. I estimate that 25 zip codes in California have less than 0.5 GWh of annual energy demand, all of which are small and sparsely populated.

Potential Liabilities In order to identify structures that would be threatened by a potential ignition, I use daily variation in wind direction at the centroid of the area where each distribution circuit operated by Pacific Gas and Electric, Southern California Edison, or San Diego Gas and Electric in California overlaps with a zip code. Using data on the daily average wind direction and maximum wind speed described above, I assign destination zip codes to each origin zip code for each day of the sample. I describe this process in detail in Appendix A.

Sample Restriction I construct the final sample by dropping all days that do not fall under the minimum criteria for a shutoff event as defined by Pacific Gas and Electric on p.982 of their 2021 wildfire mitigation plan.[22] I make this sample restriction based on the reported wind speeds and humidity in origin zip codes rather than destination zip codes because this reflects climate conditions around the power lines themselves. I further drop months where no shutoff events occur between 2018 and 2020 since these months do not help identify the coefficient of interest from model 5. In Appendix A, I demonstrate that the estimated results are not substantially affected by this sample restriction. The final sample consists of a daily panel of 10,687 unique origin-destination zip code pairs. Due to the sample restriction mentioned above, humidity is always less than 30% and wind speeds are always greater than 20 miles per hour. Downwind climate conditions refer to the average across all zip codes downwind of a distribution circuit.

22. The minimum criteria are wind speeds greater than 20 mph and relative humidity less than 30%. Pacific Gas and Electric has many other criteria for declaring a shutoff, but these are the minimum criteria that I can observe using the publicly available climate data.

5 Results

In settings where firms' assets are significantly less than their liability costs from an accident, it may be optimal for firms to declare bankruptcy (Shavell 1986). A common solution to this problem posed by regulators is to cap firm liability, providing incentives for precaution without leading to bankruptcy. However, because prior estimates of firms' precautionary response to liability are from one point in the distribution of potential liabilities, regulators have limited information about which level to place the cap on damages. The estimates in this section leverage firms' full distribution of potential liabilities from power line-ignited fires, flexibly estimating the precautionary response to liability.

Table 2 reports the main results from regression model 5. The coefficient of interest is reported in row 1 and is interpreted as the percentage point change in power shutoff declaration probability that results from a 10 percent increase in the replacement cost of downwind structures relative to days when the properties are not downwind. Since I de-mean the replacement cost of structures, the estimate in row 2 reflects the change in shutoff likelihood when a zip code with average total replacement cost lies downwind. Column 1 reports the unconditional estimate of a ten percent increase in downwind structure replacement costs on utilities' use of power shutoffs, column 2 controls for daily climate characteristics at each origin and destination zip code, column 3 adds origin-destination zip code pair fixed effects, and the preferred specification in column 4 adds calendar day and utility-by-year fixed effects. The estimate in Column 4 suggests that, on average, utilities are 0.03 percentage points (100%) more likely to use a power shutoff when a region with 10% higher total zip code replacement cost lies downwind and is statistically significant at the 95% confidence level. Assuming that baseline total replacement cost is at the average level I observe in the sample ($6.9 billion) implies that shutoff use increases by 100% when potential liabilities increase by $690 million.

Since total structure replacement cost and population are positively correlated, the positively estimated relationship between total liability and shutoff use in Table 2 could reflect utilities' increased willingness to undertake precaution when densely populated regions lie downwind. To assess whether utilities' shutoff use responds to the typical liability in downwind zip codes rather than total liability, I re-estimate equation 5 using the average structure replacement cost in downwind zip codes rather than the total. Column 2 of Table 3 presents the estimates from this analysis,, suggesting that utilities use shutoffs 0.17 percentage points more when the mean downwind zip code structure replacement cost is about 1 standard deviation higher.[23] The point estimate is marginally insignificant at the 95% level and qualitatively similar to utilities' estimated response to total liability.

Although prior work suggests that the relationship between liability and precaution should be nonlinear, the estimates in table 3 assume a linear relationship. I relax this linearity assumption by binning total zip code replacement cost by decile and re-estimating equation 5. Figure 4 reports the resulting estimates of downwind total replacement cost on power shutoff use. The estimates in figure 4 suggests that shutoff use increases in total structure replacement cost until liability exceeds $10 billion (the eighth decile of total replacement cost), after which it begins to decrease.

Shavell (1986) posits that as the ratio of liability to assets increases, the firm will eventually begin to take fewer precautions to prevent an accident. I can directly test this prediction by redefining the treatment variable of interest in equation 5 as the ratio of potential liabilities to each firm's total asset value for each destination zip code in the sample.[24] As above, I bin the asset share by decile to allow for non-linearity in the relationship between liability and firms' precautions.

Figure 5 reports the point estimates and their associated 95% confidence intervals separately for destination zip codes with low (panel A) and high (panel B) underlying fire risk. If liability regulation is effective in this setting, then firms should use greater precaution where expected liability and fire risk are the highest. Conversely, if firms are judgment proof, then precautions should increase at low levels of expected liability and decrease at higher levels of expected liability. Figure 5, Panel A shows that when expected fire risk is low, precaution is positively related to the ratio of liability to asset value. The point estimates are significant at the 95% confidence level until the ninth decile of firms' liability-asset share, suggesting that shutoff use may be lower when low-fire risk, high liability regions lie downwind.

Since expected liability is higher for downwind zip codes with more extreme fire risk, judgment proof firms should be less responsive to potential liabilities when high risk regions are downwind.

23. In Appendix A, I estimate robustness specifications that explicitly control for population. While I find that downwind population is a relevant determinant of shutoff use, it does not alter the estimates in table 3.

24. Specifically, I calculate the ratio of total zip code replacement costs to PG&E, SCE, and SDG&E's 2022 total asset values.

Figure 5, Panel B presents the same relationship between the liability-asset share and power shutoff use for destination zip codes with high underlying fire risk. Almost all point estimates are insignificant at the 95% confidence level and do not increase with the liability-asset share.

Overall, the results from this regression suggest that firms' precautions increase with their potential liability until expected liabilities are a large share of each utility's total asset value. This finding is consistent with predictions of the judgment proof problem and highlights the importance of market structure in determining the effectiveness of liability regulations. Since the firms in this setting are natural monopolies, the judgment proof firms will continue to operate even after declaring bankruptcy. This lies in stark contrast to Boomhower (2019) which finds evidence of market concentration as smaller, judgment proof firms exit the market following a regulation which internalized future expected liabilities from environmental accidents. In this setting market power is already concentrated and firms are still judgment proof, limiting the effectiveness of liability regulation to direct firm precaution to the regions with high expected damages.

5.1 Robustness

Factors such as vegetation conditions near power lines, extent of interaction between housing and wilderness, and energy consumption patterns could drive utilities' use of shutoffs. If these factors are also correlated with structure replacement costs, then the estimated relationship between shutoffs and potential liability could be biased. In table 4, I estimate several modifications of regression model 5 to test the robustness of the preferred estimate in table 2. Column 1 replicates the preferred estimate from table 2. Column 2 adds a control for the share of total population in destination zip code d living in the WUI interacted with the downwind indicator, DW_{odt}. This covariate captures daily changes in the number of structures near vegetation that is likely to burn in the event of a fire. In column 2, I also control for the average WHP index in each destination zip code interacted with the downwind indicator. This covariate measures the propensity of vegetation in the downwind zip code to spread fire. Column 3 adds separate controls for monthly electricity usage in the origin and destination zip codes respectively. These additional covariates capture patterns in electricity usage that are relevant to firms' shutoff decision.

The empirical model in equation 5 uses daily changes in downwind structure costs to estimate the relationship between shutoffs and liability. However, evidence suggests that utilities monitor forecast wind conditions in addition to current conditions. As a result, utilities may base their shutoff decisions on their expectation of which regions will be downwind in the upcoming days. To account for this behavior, I define a destination zip code as downwind if it lies downwind of the origin zip code at any time in the next five days. For example, the downwind indicator, DW_{odt}, is set equal to one if a destination zip code is downwind anytime over the next five days (between day t and day $t+5$). I report the results from this specification in column 4 of table 4. The main estimate of interest is positive, statistically significant, and of a similar magnitude in all specifications.

Since the empirical framework in equation 5 is specified at the zip code level, it may include properties that are located far away from high-ignition risk circuits. If utilities only consider structures that are very close to high-risk power lines (and therefore very likely to be destroyed if an ignition occurs), then the zip code analysis could be misspecified. In appendix A, I address this by estimating equation 5 at the circuit level. I do this by using daily variation in the replacement cost of structures that lie downwind of power lines and are located within 20 kilometers of a circuit. Using this local variation, I estimate similar effects to the preferred estimate in table 2.

6 Discussion and Conclusion

This paper provides the first causal evidence of how firms' precautions responds to liability across the full distribution of potential liabilities that they face. I document a nonlinear relationship between potential liability and firm precautions in California's electric utility sector, showing that firms increase precautions until liabilities are extreme. While this is a novel result that helps inform existing models of firm precautions, it can also be used to determine how the application of strict liability to investor-owned electric utilities in California affected social welfare. The welfare effects of strict liability are unclear in this setting because the type of precaution firms utilize in the short run, power shutoffs, provide both positive and negative welfare consequences to Californians. Power shutoffs generate positive welfare effects because they reduce the likelihood of fire ignition by power lines. However shutoffs also leave consumers without power, sometimes for extended periods of time. In the short run, the net change in social welfare depends on the relative magnitude of averted damages from power shutoffs and the value of consumers' lost electricity use during shutoffs. The long-run welfare consequences of liability in this setting additionally depend on the relationship between power shutoffs and other types of precautions like burying power lines underground, the relative effectiveness of shutoffs versus other types of precautions, and the long-run effect of liability on other types of precautions such as electrical grid hardening. Since this paper is focused on firms' short-run precautionary response to liability, I leave the long-run welfare consequences of liability regulations for future work.

6.1 Short Run Welfare

Thus far, I have provided empirical evidence suggesting that precautions and liability are positively related when expected liabilities make up a small fraction of total firm asset value and unrelated when the ratio of expected liabilities to firm asset value is large. The welfare implications of this relationship are ambiguous for two key reasons. First, power shutoffs impose costs on households that lose power while also preventing structure destruction from power line ignited fires, ambiguously affecting household welfare. Second, shutoffs may increase or decrease firm welfare depending on whether firms' response to downwind liabilities increases or decreases their expected liability payments.

Using the conceptual framework from section 2, I derive the short-run welfare change resulting from an increase in liabilities from a potential ignition in Appendix D. Since this study focuses on liability, I compute the difference in welfare change when firms use power shutoffs to respond to downwind potential liability ($\Delta WF(\bar{d})$) and the welfare change when firms do not respond to potential liability ($\Delta WF^R(\bar{d})$).

$$\begin{aligned}\Delta WF(\bar{d}) - \Delta WF^R(\bar{d}) = &-\bar{p}Q\Big[P(L \mid \bar{d}') - P(L \mid \bar{d})\Big] + \\ &\theta\Big[\bar{d}'P(L \mid \bar{d}') - \bar{d}P(L \mid \bar{d}) - (\bar{d}' - \bar{d})P(L \mid \bar{d})\Big]\end{aligned} \tag{6}$$

Where $\bar{p}$ is the consumers' maximum willingness to pay per kilowatt hour, Q is the amount of electricity consumed by households, $\bar{d} < \bar{d}'$ are damages that firms are liable to pay, $P(L \mid \bar{d})$ is the probability of a power shutoff, and θ is the probability of ignition from power lines.

Three parameters characterize the relative short-run welfare change from a change in damages when shutoffs do versus do not depend on potential liabilities in equation 6: (1) the change in probability of shutoff event following an increase in the share of liability born by firms ($P(L = 1 \mid \bar{d}') - P(L = 1 \mid \bar{d})$), (2) the relative change in expected damages when firms do and do not respond to potential liabilities ($\bar{d}'P(L \mid \bar{d}') - \bar{d}P(L \mid \bar{d}) - (\bar{d}' - \bar{d})P(L \mid \bar{d})$), and (3) consumers' maximum willingness to pay for electricity ($\bar{p}$).

There are several important caveats to the welfare change represented in equation 6. In the model, consumers value their home at its replacement cost and receive a payment from the utility equal to the home replacement cost if the structure burns down. As a result, households in this model are indifferent whether or not their home burns down. In practice, consumers may have a value of their home which exceeds the replacement cost, causing consumer surplus to potentially increase when firms use more shutoffs. Thus, the welfare change in equation 6 is likely larger (in absolute terms) than a more detailed model that incorporates intrinsic home values.

I also assume that the adjustment of defensive capital cannot occur in the short term (making term three in Appendix D, equation 5 equal to zero). Since the sample includes three post-policy years and the utilities have extensive networks of power lines, the extent of defensive capital investment is limited in this setting. However, future analyses of defensive capital's impact on the likelihood of ignition would be informative.

To compute the welfare change in equation 6 for each zip code, I use the estimated relationship between liability and power shutoff use from this paper, estimates of the probability of power line fire ignitions in each zip code, data on total zip code energy demand, the distribution of structure replacement costs downwind of each zip code, an estimate of consumers' valuation of lost electricity demand during a power outage, and power shutoff duration in hours. Appendix E explains this process in detail. I add the welfare effects across zip codes to calculate the total welfare effect of firms' consideration of potential liability in their decision to declare a power shutoff.

The welfare effects vary greatly across zip codes and depend heavily on how long a shutoff lasts and consumers' valuation of lost electricity use. Since there is a wide range of empirical estimates of the value of lost load, I bound the short run welfare effect using the smallest and largest estimates from the existing literature. The largest estimate of the value of lost load from Gorman (2022) is \$65 per kWh, while the smallest estimate for my sample period is the average retail price of electricity in California in 2018 (\$0.20 per kWh). In addition, I separately calculate the welfare effect using the average and maximum power shutoff outage duration for each utility between 2018 and 2020.

Using the higher value of lost load estimate implies that total welfare declines when firms' shutoff use responds to potential liabilities, with $317 million in lost welfare from a shutoff of average duration and $6 billion in lost welfare from a shutoff of maximum duration. Welfare effects vary greatly across zip codes, indicating that there may be meaningful differences in the welfare cost born by different communities across California.

The lower value of lost load estimate ($0.2 per kWh) indicates that total welfare increases when firms consider potential liability in their shutoff decisions, with $867 million in total welfare gain from a shutoff of average duration and $848 million in total welfare gain from a shutoff of maximum duration. Again, the welfare effects vary greatly across zip codes. These welfare estimates highlight the importance of the value of lost load (and studies that estimate it) in determining the welfare consequences of economic policies which impact reliability in the energy sector and the meaningful welfare impacts of reducing the duration of power shutoffs.

6.2 Conclusion

In this paper I use exogenous daily variation in wind direction to estimate the causal relationship between liability and short-run firm precaution across the full distribution of liabilities that firms face in California's electric utility sector. Theoretical models of firm behavior suggest that the firm precaution responds ambiguously regulator's application of liability and that firm precaution should respond non-linearly to the level of liability that it faces. Prior empirical work estimates the relationship between liability and firm precaution at one point in the distribution of liabilities that it faces, ignoring important non-linearities in firm precaution. This paper advances the previous empirical literature by developing an empirical framework that can estimate the causal relationship between liability and firm precaution across the full distribution of liabilities it faces, capturing important non-linearities.

To evaluate the effectiveness of liability regulations, I study California's electric utility sector, a setting where firms face extreme liability from fires ignited by the power lines that they operate. I construct a daily panel of upwind-downwind zip code pairs across California between 2018 and 2020 and use exogenous daily variation in wind direction to estimate how firms use of power shutoffs to prevent fire ignitions changes as the value of structures downwind of their power lines varies.

Since the empirical framework leverages daily variation in wind direction and I control for other important drivers of firms' power shutoff use such as wind speed, I am able to causally estimate the relationship between liability and firm precaution.

This paper finds that firms increase precautions in response to the level of liability that they face. However, firms' precautionary response to liability is highly non-linear: firms are very responsive to the level of liability that they face at lower levels of liability, but are less responsive at the highest deciles of liability that they face. This result provides evidence that the risk of bankruptcy when potential liabilities exceed firm value likely dampens firms' precautions.

There are several key implications for policymakers from this paper: First, liability encourages firms to direct greater precaution to areas with the highest expected damages until damages make up a large share of firm asset value. If policymakers' objective is to direct precautions to the regions with greatest expected damages, then liability regulation alone is ineffective. Second, policymakers can influence which ignition prevention efforts the utility undertakes by clearly defining which strategies will allow the utility to avoid a negligence ruling. In the California context, the 2017 rule change and subsequent rule amendments did not clearly specify what utility actions (or lack thereof) would lead them to be negligible for fire damages. This lack of clarity may have led utilities to use shutoff events as a signal that they are not acting negligently, leading to an overuse of blackouts at the expense of longer term mitigation investments. Third, since the welfare effects of liability vary significantly across zip codes, policymakers should be wary of potential distributional consequences of liability regulations.

There are several areas where future research can extend this analysis to further inform our knowledge of liability regulations and how they impact firm precaution in the power line-ignited fire setting. First, future research should explore whether the circuits with the highest welfare loss from an increase in liability are located in areas with a large share of disadvantaged community members. For example, if expected damages are low and the value of lost load is high in disadvantaged communities, then this implies that increasing the share of liability on firms is regressive in this setting. Second, future studies should take a longer term view of the impact of liability regulation on utilities' ignition prevention behavior. Although liability regulation has an ambiguous welfare impact in the short term, it could be beneficial in the long term if it encourages precautionary activities that both reduce the likelihood of ignition and the probability that a power shutoff occurs.

Finally, more work is needed to identify which ignition prevention strategies most effectively reduce the likelihood of a fire caused by power lines.[25] In particular, cost benefit analyses may need to be revised to account for the fact that capital investments both reduce the probability of ignitions *and* blackouts in the future.

25. Warner, Callaway, and Fowlie (2024) provides helpful information on long-term precautionary behavior by collecting data on other measures of ignition prevention, such as burying power lines.

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7 Tables

Table 1: Zip Code Pair Panel Summary Statistics

	Mean (SD)	Min	Max	N
N Shutoffs	0.111	0	46	433,201
	(0.94)			
Shutoff (0/1)	0.031	0	1	433,201
	(0.17)			
Replacement Cost (Billions)	6.850	0	37	433,201
	(6.57)			
Median Replace Cost (Thousands)	52.739	0	223	433,201
	(27.73)			
Percent of Asset Value (%)	764.908	0	4,840	433,201
	(783.22)			
Temperature (F)	38.977	31	90	433,201
	(5.02)			
Humidity (%)	9.348	0	30	433,201
	(7.20)			
Wind Speed (mph)	24.108	20	88	433,201
	(4.20)			
Downwind Temp. (F)	58.644	10	106	420,499
	(11.41)			
Downwind Humid. (%)	55.235	2	100	420,499
	(24.66)			
Downwind Wind Speed (mph)	15.479	2	82	420,499
	(6.85)			
Downwind WHP Index	3.026	0	5	433,201
	(1.01)			
Downwind WUI Pop (%)	0.389	0	37	433,201
	(2.02)			
Annual Energy Use (GWh)	89.946	0	649	431,518
	(104.86)			
Downwind Annual Energy Use (GWh)	89.151	0	649	429,503
	(103.52)			
N Zip Codes	546.000			

Notes: Wind and weather data is taken from weather stations operated by utilities in California and interpolated to each distribution circuit centroid using inverse distance weighting. Total replacement costs are taken from the Zillow ZTRAX dataset and converted to 2021 dollars. Median replacement costs are computed for each zip code from the parcel-level Zillow data. Disadvantaged community (DAC) status comes from the CalEnviroScreen 3.0 update and is computed as the share of total 2010 zip code population living in a census tract categorized as a DAC. The number of zip codes denotes the total number of zip codes that ever experience a shutoff during 2018-2020.

Table 2:
Effect of Total Zip Code Replacement Cost on the Probability of a Shutoff

	Shutoff Indicator (1)	Shutoff Indicator (2)	Shutoff Indicator (3)	Shutoff Indicator (4)
Value x DW	0.00565	0.00578	0.03033	0.02924
	(0.00345)	(0.00375)	(0.01113)	(0.00914)
DW	-0.03761	-0.04325	0.10939	0.08343
	(0.01243)	(0.01365)	(0.03500)	(0.02491)
Controls		x	x	x
Pair FE			x	x
Utility x Year FE				x
Day FE				x
Mean of Dep. Var	0.031	0.031	0.031	0.031
Observations	433,205	420,503	420,331	420,329

Notes: Wind and weather data is taken from weather stations operated by utilities in California and interpolated to each distribution circuit centroid using inverse distance weighting. Total replacement costs are taken from the Zillow ZTRAX dataset and converted to 2021 dollars. The underlying data consists of pairs of upwind, ever-downwind zip codes for every day during select days between 2018-2020. The outcome is a binary variable equal to 1 if a shutoff event is active in origin zip code o. Value measures the total cost of replacing structures in each destination zip code d and DW is a binary variable equal to 1 when zip code d is downwind of zip code o on day t. Controls include daily average temperature, relative humidity, precipitation, and maximum wind speed binned by septiles for each origin zip code o and destination zip code d. Standard errors are clustered at the high fire threat district by calendar week level.

Table 3:
Effect of Total and Mean Zip Code Replacement Cost on the Probability of a Shutoff

	Total Value (1)	Mean Value (2)
Value x DW	0.02924	0.03224
	(0.00914)	(0.01773)
DW	0.08343	0.07256
	(0.02491)	(0.02269)
Controls	x	x
Pair FE	x	x
Day FE	x	x
Mean of Dep. Var	0.031	0.031
1 SD Effect	0.386	0.174
Bootstrap 95% CI	[0.010,0.048]	[-0.0001,0.07]
Observations	420,331	420,331

Notes: Wind and weather data is taken from weather stations operated by utilities in California and interpolated to each distribution circuit centroid using inverse distance weighting. Total replacement costs are taken from the Zillow ZTRAX dataset and converted to 2021 dollars. The underlying data consists of pairs of upwind, ever-downwind zip codes for every day during select days between 2018-2020. The outcome is a binary variable equal to 1 if a shutoff event is active in origin zip code o. Value measures the total (Column 1) or mean (Column 2) cost of replacing structures in each destination zip code d and DW is a binary variable equal to 1 when zip code d is downwind of zip code o on day t. Controls include daily average temperature, relative humidity, precipitation, and maximum wind speed binned by septiles for each origin zip code o and destination zip code d. Standard errors are clustered at the high fire threat district by calendar week level.

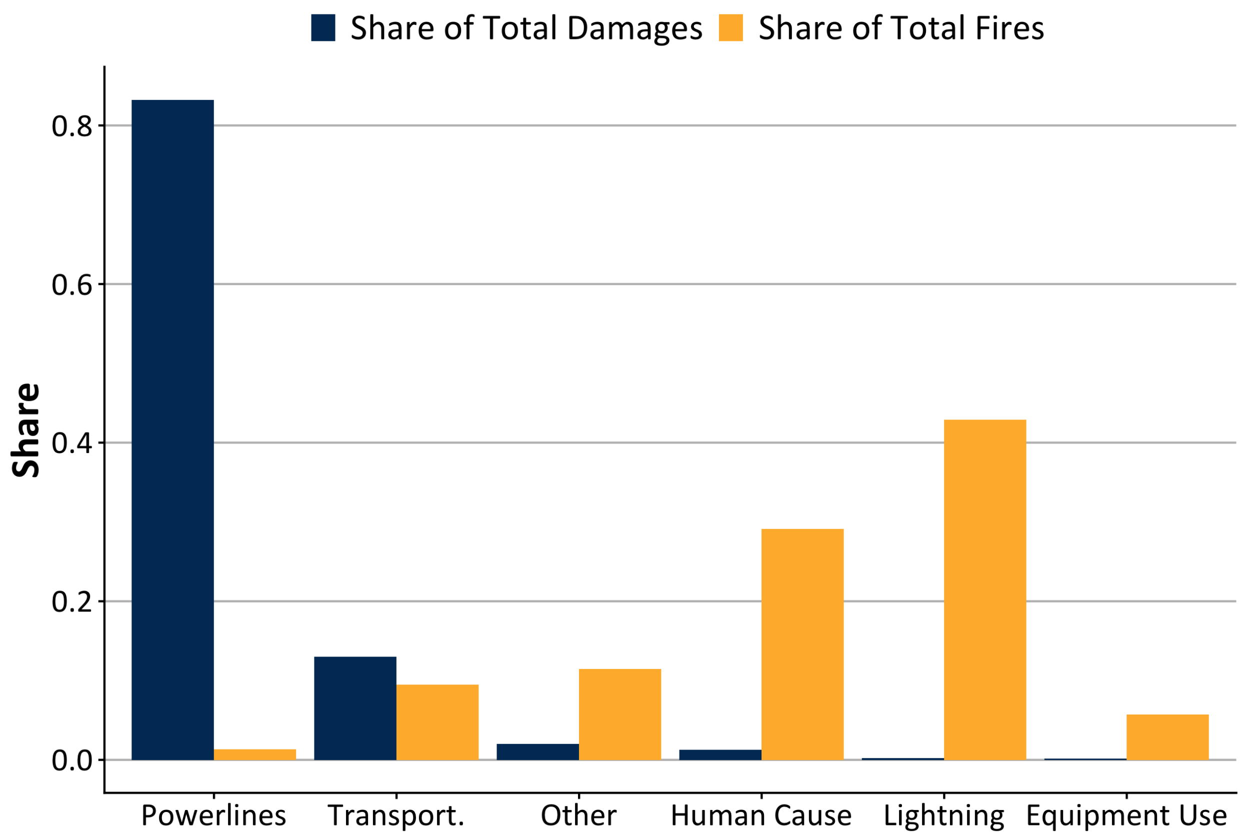
Table 4:
Robustness Analysis Estimates

	Main Model (1)	WUI Controls (2)	Usage Controls (3)	5 Day Treatment (4)
Value x DW	0.02920	0.02130	0.02258	0.02286
	(0.00914)	(0.00897)	(0.00763)	(0.00803)
DW	0.06954	0.20841	0.04543	0.04999
	(0.02144)	(0.06104)	(0.01589)	(0.01844)
Controls	x	x	x	x
Pair FE	x	x	x	x
Day FE	x	x	x	x
Mean of Dep. Var	0.031	0.031	0.031	0.031
1 SD Effect	0.385	0.281	0.298	0.302
Observations	420,329	420,329	415,148	420,329

Notes: Column 1 replicates the main estimate from column 4 of table 2. Column 2 adds controls for the share of total population in zip code d living in the Wildland Urban Interface. Column 3 adds controls for monthly zip code electricity usage in zip codes o and d separately. Column 4 assigns a destination zip code (d) as downwind if it is downwind anytime in the next 5 days (from t to $t+5$). Wind and weather data is taken from weather stations operated by utilities in California and interpolated to each distribution circuit centroid using inverse distance weighting. Total replacement costs are taken from the Zillow ZTRAX dataset and converted to 2021 dollars. The underlying data consists of pairs of upwind, ever-downwind zip codes for every day during September-December 2019-2020. The outcome is a binary variable equal to 1 if a shutoff is active in origin zip code o. Value measures the total structure replacement cost in each destination zip code d and DW is a binary variable equal to 1 when zip code d is downwind of zip code o on day t. Standard errors are clustered at the high fire threat district by calendar week level.

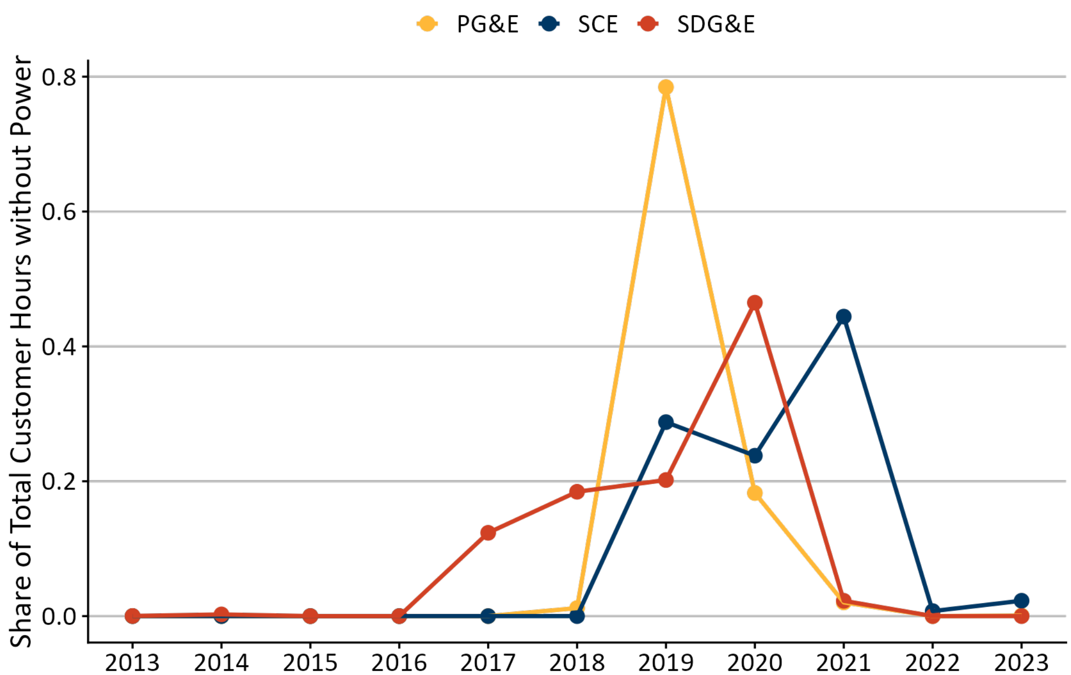
8 FIGURES

Figure 1:
Share of Wildfire Ignitions (1910-2016) and Damages (2008-2019) by Source



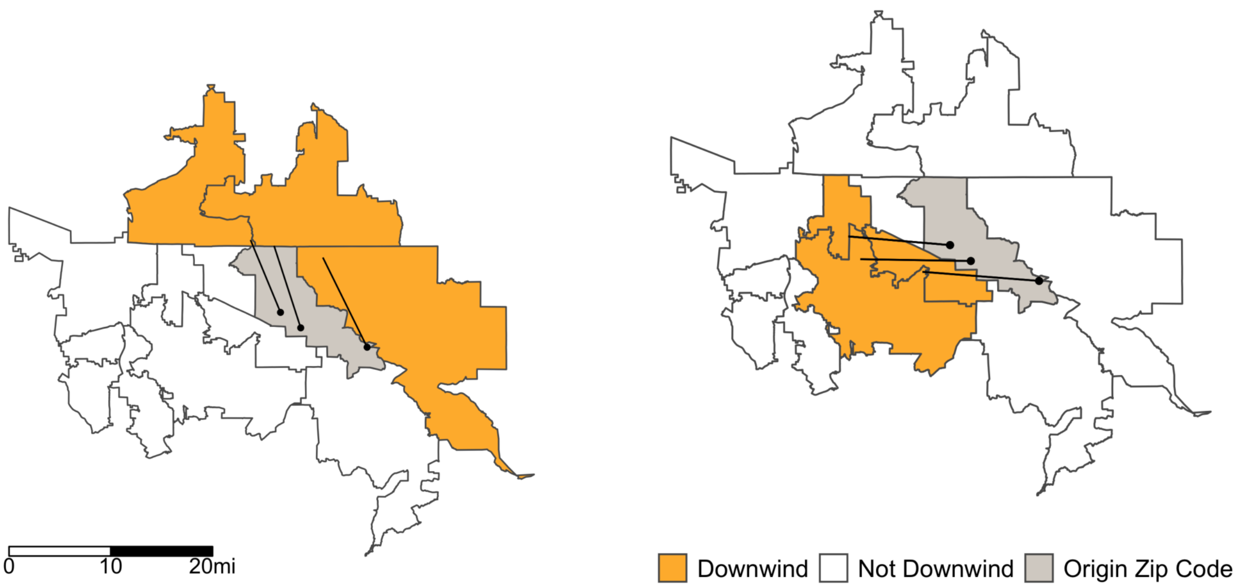
Notes: Share of total wildfire ignitions in California by cause of ignition between 1910 and 2016 are shown in yellow. The "Other" category includes fires caused by arson, debris, smoking, camping, playing with fire, railroads, lumber, equipment, and vehicles. Data are from Keeley and Syphard (2018). Share of total wildfire damages by ignition cause between 2008 and 2019 in California are shown in blue. Damages are defined as the replacement cost of homes destroyed by wildfire. The "Other" category includes fires caused by arson, debris, smoking, camping, playing with fire, railroads, lumber, equipment, and undefined cause. Data were collected by the author from CalFire historical wildfire activity data, also referred to as "redbooks."

Figure 2:
Share of Total Customer Hours Impacted by Shutoff Events



Notes: Total customer hours computed by the author from public safety power shutoff post event reports. The share is computed by dividing impacted customer hours in each year by each utility's cumulative customer hours impacted by shutoff events between 2013 and 2023. Customer hours include commercial and residential customers served by California's three largest privately-owned utilities, Pacific Gas and Electric, Southern California Edison, and San Diego Gas and Electric. Reports are available from the California Public Utility Commission.

Figure 3:
Example of Regions that are Downwind of Power Lines Across Days

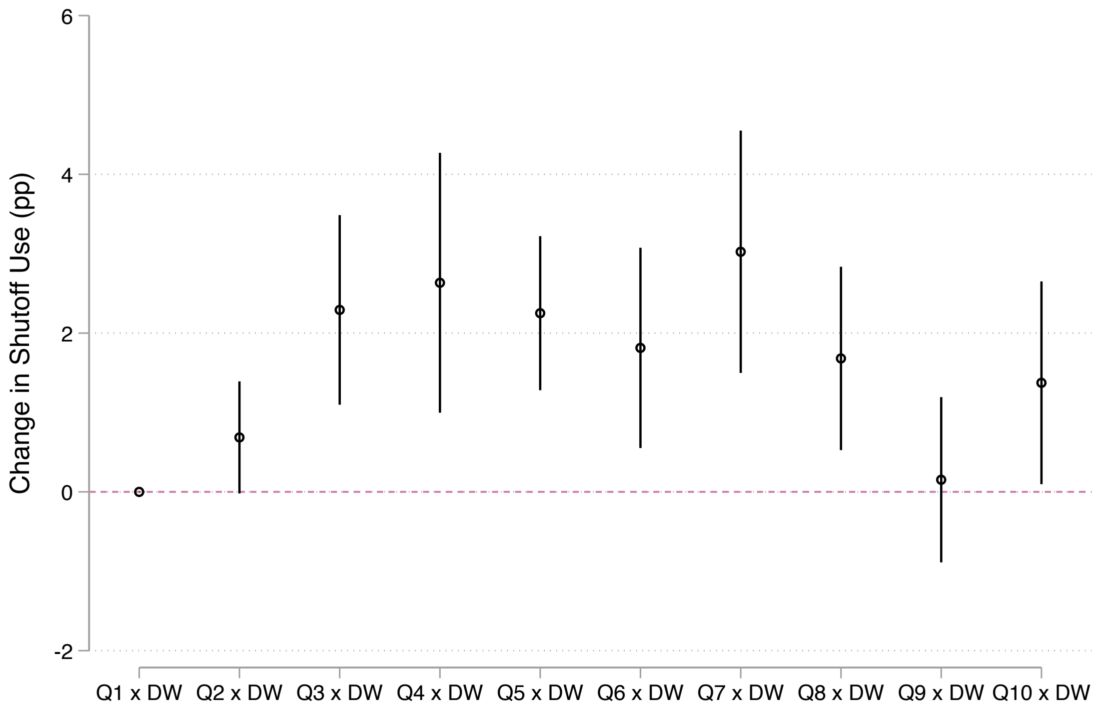


(a) Oct. 10, 2019

(b) Oct. 11, 2019

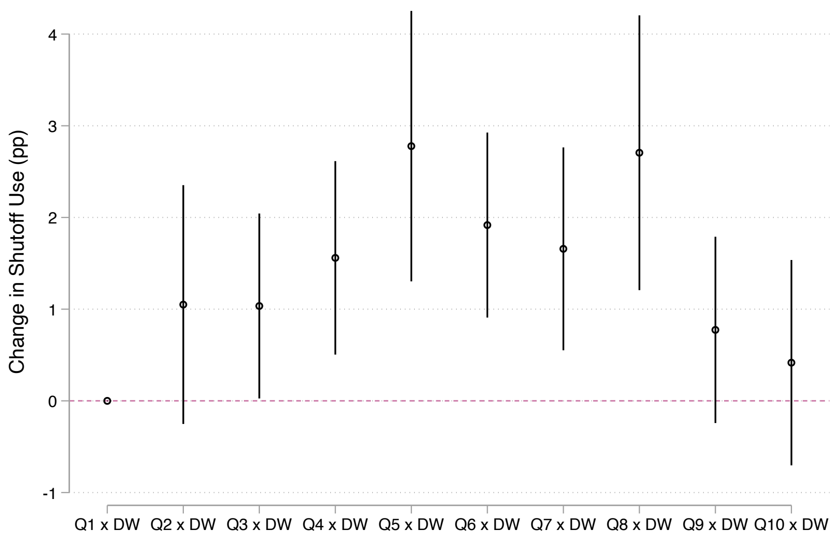
Notes: Daily variation in which zip codes are downwind of zip code 95917 (shown in tan) on October 10 and 11, 2019. The yellow and white shaded zip codes are the set of zip codes that are downwind of 95917 on any day between 2018 and 2020. The yellow zip codes are downwind of 95917 on a given day and the white zip codes are not downwind on the day shown. The black dot is the centroid of an electrical distribution circuit in zip code 95917 and the black line indicates the maximum daily wind direction and speed at the circuit on the day shown. The black line is using maximum daily wind speed and direction, an estimate of how far the wind can carry a lit ember from Albini, Alexander, and Cruz (2012), and several trigonometric identities. I calculate the total structure replacement cost for the yellow and white zip codes and changes in liability are generated by variation in wind direction and speed across days.

Figure 4:
Results by Decile of Total Zip Code Replacement Cost

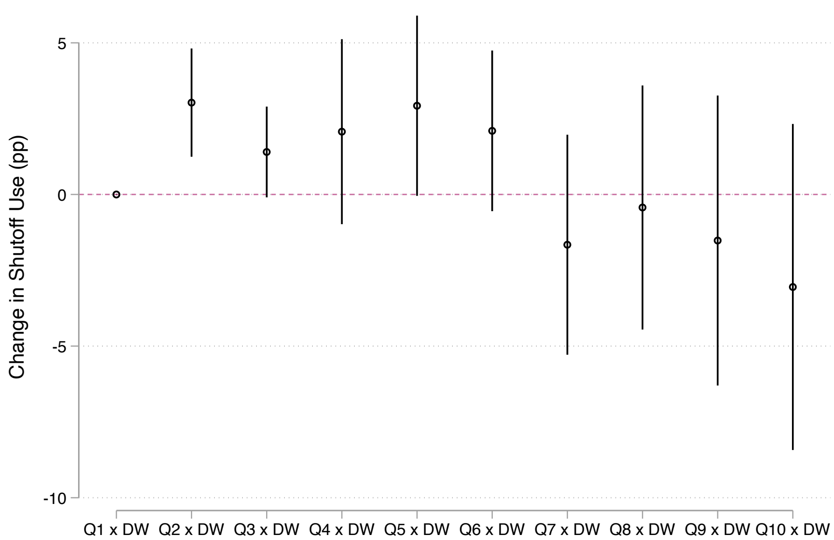


Notes: Wind and climate data is taken from weather stations operated by utilities in California and interpolated to each distribution circuit centroid using inverse distance weighting. Replacement costs are taken from the Zillow ZTRAX dataset. The underlying data consists of pairs of upwind, ever-downwind zip codes for selected days during 2018-2020. Only days with wind speeds greater than 20 mph and relative humidity less than 30% are included in the sample. The outcome is a binary variable equal to 1 if there is an active shutoff in origin zip code *o*. The variables of interest are indicator variables for whether the total replacement cost in each destination zip code *d* is in one of ten bins on days when it lies downwind of zip code *o*. The excluded category is decile one, so all estimates represent the impact of threatened property values in each decile relative to the first decile. Controls include daily average temperature, wind speed, humidity, and maximum wind speed binned by septiles for each origin zip code *o* and destination zip code *d*. Standard errors are clustered at the high fire threat district by calendar week level.

Figure 5:
Results by Decile of 2022 Firm Asset Damage Share



(a) Low/Moderate Fire Risk



(b) High Fire Risk

Notes: Wind and climate data is taken from weather stations operated by utilities in California and interpolated to each distribution circuit centroid using inverse distance weighting. Replacement costs are taken from the Zillow ZTRAX dataset. The underlying data consists of pairs of upwind, ever-downwind zip codes for selected days during 2018-2020. Only days with wind speeds greater than 20 mph and relative humidity less than 30% are included in the sample. The outcome is a binary variable equal to 1 if there is an active shutoff in origin zip code o. The variables of interest are indicator variables for whether the total replacement cost in each destination zip code d is in one of ten bins on days when it lies downwind of zip code o. The excluded category is decile one, so all estimates represent the impact of threatened property values in each decile relative to the first decile. Controls include daily average temperature, wind speed, humidity, and maximum wind speed binned by septiles for each origin zip code o and destination zip code d. Standard errors are clustered at the high fire threat district by calendar week level.