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De-energization as maladaptation: Uneven residential exposure to wildfire Public Safety Power Shutoffs and compound heat

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ABSTRACT

In response to growing levels of wildfire destruction, electric utility companies are adopting powerline de-energization as an adaptation strategy intended to prevent wildfire ignitions. While reducing wildfire risk, planned de-energizations also expose residents to electricity loss, potentially causing harmful consequences. We investigated the extent to which planned de-energization can be considered a form of *maladaptation*, in which an adaptive response to a climate-related hazard results in unintended, concurrent harms. To do so, we examined the co-occurrence of Public Safety Power Shutoffs (PSPSs) with extreme heat (temperature $\geq$ 32 °C) in California between October 2021 and September 2024. Our analysis revealed compound heat-PSPS outages throughout this period, including extreme temperatures exceeding 40 °C, during power shutoffs. Compound heat-PSPS events were geographically concentrated in census block groups with higher proportions of older adults and mobile home residents, both populations which may be at increased risk of heat-related morbidity and mortality. While they affected a relatively small proportion of customers de-energized by PSPSs, compound heat-PSPS outages raise concerns over extreme heat exposure when access to electricity-based cooling strategies is curtailed. Evaluating the maladaptive effects of institutional responses to climate change hazards is critical for comprehensively weighing both the benefits and harms of emerging adaptation strategies.

1. Introduction

Wildfire destruction has increased dramatically in the past decade, placing heightened importance on preventing wildfire ignitions near populated areas (Higuera et al., 2023). Electrical utility lines can spark fires when they come into contact with vegetation, especially during high wind periods. As a result, utility-ignited wildfires have caused high acreage fires and significant building destruction in recent years (Syphard and Keeley, 2019; Miller et al., 2017). Strategically de-energizing power lines, referred to by some utilities as "Public Safety Power Shutoffs" (hereafter "PSPSs"), is an emerging institutional adaptation to growing wildfire risk. During a PSPS, an electrical utility intentionally de-energizes electrical transmission or distribution lines during a period in which environmental conditions such as high wind speeds and low humidity increase the likelihood of electric lines sparking fires (Abatzoglou et al., 2020). In this paper we evaluate PSPSs through the lens of "maladaptation," assessing whether these events co-occur with periods of high heat, potentially exposing vulnerable populations to one climate hazard (heat) in an attempt to mitigate risk from another (wildfire).

1.1. Public Safety Power Shutoffs

We focus our analysis on California, a state with a very large population of residents living in fire-prone places (Greenberg et al., 2024) and one of the highest rates of wildfire-related structure loss in the U.S. (Higuera et al., 2023). California was also the first state to initiate PSPSs in the early 2010s (Huang et al., 2023), and PSPSs have been increasingly practiced in subsequent decades (Ptak et al., 2025). In the wake of the 2018 Camp Fire in northern California, Pacific Gas & Electric Company was found responsible for the fire's ignition and plead guilty to 84 counts of manslaughter (Penn and Eavis, 2020). The company's

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destruction-related financial losses totaled approximately $30 billion across the 2017 and 2018 wildfire seasons, much of which was due to the Camp Fire (Penn and Eavis, 2020). These legal outcomes are considered a turning point after which utility companies began using planned de-energizations across California to reduce wildfire risk, and, consequently, corresponding financial liability (Ptak et al., 2024). In the past six years, this institutional adaptation strategy has become a common wildfire risk reduction strategy across California, and is now being adopted in other fire-prone states across the U.S. including Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington and Wyoming (Ptak et al., 2024; Idaho Power; NV Energy; Bauer, 2024; Kate Ruder, 2024; Arizona Emergency Information Network; Public Service Company of New Mexico; Devin Oldroyd, 2023; Lee, 2024). De-energizations are also being used or tested as a fire risk reduction strategy outside of the U.S., in countries such as Canada (Canadian Electricity Association, 2020) and Australia (Victoria, 2025; Roy, 2021), suggesting their growing international prevalence as a wildfire adaptation strategy.

While PSPSs can reduce fire ignition risk and thereby protect human health, they have also been criticized for disrupting daily life, and impacting businesses, homes, and essential services (Huang et al., 2023; Wong-Parodi, 2020; Wong et al., 2022). Further, there is substantial evidence to suggest that electricity loss can lead to significant health risks including carbon monoxide poisoning, temperature-related illness, gastrointestinal issues related to food and water safety, and all-cause mortality (Casey et al., 2020; Anderson and Bell, 2012; Stone, 2023). Given these potential risks, it is unsurprising that a wide body of multidisciplinary literature explores technical solutions for reducing de-energizations. Much of this work focuses on the potential for micro-grids to function as a "resilience resource" (Kandaperumal et al., 2022) that can curtail the impacts of power loss. In contrast to conventional power grids, in which energy flows unidirectionally from generation site through transmission lines to end users, microgrids operate as decentralized networks of small-scale energy production, storage, and consumption (Yang et al., 2022). Localized energy production and storage are facilitated through battery energy storage (Hussain et al., 2017). Microgrids both have a smaller spatial footprint than traditional energy infrastructure (Kandaperumal et al., 2022), and can function independently of the larger energy network in which they are embedded, operating effectively as "islands" (Hanna, 2021). These characteristics mean that microgrids have the potential to reduce the extent of PSPS impacts, both because the spatial extent of a planned outages could be targeted to smaller regions of high risk power lines, and because microgrids could continue to provide electricity even if they were temporarily cut off from the larger energy network. Engineering scholars have simulated microgrid performance during planned de-energization events, for example testing grid scenarios during wildfire seasons in Australia (Yang et al., 2022) and California (Hanna, 2021), providing modeled evidence that microgrids can enhance energy resilience in the face of disasters and planned outages (Kandaperumal et al., 2022).

Micro-grids are only one part of larger technological and procedural initiatives aimed at optimizing power grid operations. Largely, these initiatives are aimed at selectively de-energizing the most vulnerable grid components during periods of highest wildfire risk to minimize the population affected (Vazquez et al., 2022). Procedurally, researchers suggest that the implementation of PSPS events can be optimized by modeling trade-offs between reducing wildfire ignition risk and minimizing outage impacts on communities (Lesage-Landry et al., 2023). Others have developed models to better predict wildfire ignition risk and thereby improve the accuracy of PSPS triggers (Huang et al., 2023). Such models might incorporate variables such as tree height and density, and fuel moisture content, among other factors (Arab et al., 2021). Identifying the most vulnerable aspects of a grid can also inform plans for maintenance or equipment upgrades (Muhs et al., 2020).

While microgrid and optimization approaches, along with proposals to underground powerlines and to insulate aboveground powerlines (Yang et al., 2022), have been proposed to limit the extent of wildfire-related de-energizations, we have yet to see large-scale policy changes that would systematically address the propensity of existing powerlines to ignite wildfires. In California, planned de-energizations have therefore continued in the face of ongoing wildfire risk. We therefore turn to social science and interdisciplinary research to understand how planned power outages have and continue to affect residents.

Social scientists studying de-energizations have drawn on survey-based methods to better understand residents' perceptions of PSPSs. For example, Wong-Parodi found that, while some California residents support PSPSs, they also express worry about planned de-energizations (Wong-Parodi, 2022), considering them to be an adaptive measure that may pose risks to health and wellbeing (Wong-Parodi, 2020). In Oregon, Zanocco et al. found general support for planned power outages (Zanocco et al., 2023). Others have used surveys to better understand residents' direct experiences with outages (Brown et al., 2022), and the connections between power outage experiences and behavioral changes, such as altering travel plans (Wong et al., 2022) and intentions to purchase alternative forms of energy generation (Mildenberger et al., 2022; Zanocco et al., 2021).

This study builds most directly on a growing body of interdisciplinary research that examines the spatial distributions of power loss and re-electrification, highlighting socioeconomic disparities in exposure. Much work in this area has studied power outages generally, without focused attention on wildfire-related de-energizations (Do et al., 2025; Do et al., 2023; Flores et al., 2023; Román, 2019; Liévanos and Horne, 2017; Coleman et al., 2023; Memmott et al., 2024). But in recent years as planned power outages have become more widely adopted as a wildfire adaptation strategy, research across a range of academic fields has emerged in response. For example, scholars have highlighted distributional equity concerns around the concentration of outages among specific communities (Kody et al., 2022) and disparities in above-versus below-ground power lines among lower-income communities (Wang et al., 2023). Our work builds most directly on Ptak et al. (2024) and Abatzoglou et al. (2020), who describe the populations exposed to de-energizations in California during 2019, with special consideration of socially vulnerable groups. For more extensive discussions of power outages in the context of wildfire risk, including consideration of the technical and engineering aspects of de-energizations, see recent reviews by Ptak et al. (2025) and Vahedi (2025).

1.2. *Compound hazards*

The public health impacts of planned de-energizations may be amplified if they occur simultaneously with other environmental conditions such as wildfire smoke or extreme heat (Do et al., 2025; Chen et al., 2024). Often referred to as "compound hazards," the co-occurrence of spatially and temporally overlapping climate-related hazards can lead to intensified impacts on human health, infrastructure, and ecosystems (Raymond, 2020; AghaKouchak et al., 2020). Recent research has highlighted a novel category of compound hazards comprised of intersecting climatic events (like extreme heat) and institutional events (such as power outages) (Stone, 2021). In this paper, we expand the concept of compound hazards to include the co-occurrence of extreme heat and PSPSs. For unplanned power outages specifically, researchers have documented historical instances of power loss coinciding with extreme heat (Do et al., 2025), and estimated that a major electrical grid failure during high-heat periods could double heat-related mortality in specific U.S. cities (Stone, 2023). In recent work, Memmott et al. (2024) examined the co-occurrence of extreme heat with utility disconnections due to nonpayment. Less research, however, has focused on utility-initiated de-energizations in response to wildfire risk. A recent study found that power disconnections due to non-payment in California were negatively associated with temperature, though they observed heterogeneity in this association by region (Memmott et al., 2024). No studies to date have specifically evaluated the co-occurrence of high heat and PSPS outages.

1.3. Maladaptation

Given their potential to cause harmful public health impacts, we conceptualize planned de-energizations as a form of climate change *maladaptation*, in which an institutional adaptation to wildfire risk results in concurrent exposure to a separate climate-related hazard, potentially resulting in harmful impacts (Juhola et al., 2016; Magnan et al., 2016). We use the term 'maladaptation' here to refer to a situation in which an intentional adaptation measure creates new risks, shifts vulnerabilities to different populations, or otherwise undermines adaptive capacity, in this case by increasing exposure (Barnett and O'Neill, 2010). This is distinct from a failed adaptation (Reckien, 2023), in that maladaptation may occur regardless of whether the adaptation strategy meets its stated goals (e.g., wildfire reduction, in the case of PSPSs), if, in doing so, it shifts or creates new vulnerabilities. The concept of maladaptation is borrowed from evolutionary biology and has been used in the context of climate change since at least the late 1990s (Scheraga and Grambsch, 1998), and has been used by the Intergovernmental Panel on Climate Change (IPCC) since the Third Assessment Report in 2001. Previous research has documented maladaptive interventions such as green infrastructure designed to prevent flooding that inadvertently created mosquito breeding habitats, shifting risk from one climate-related hazard to another (Brown et al., 2022). See Magnan et al. (2016) for additional case studies, including responses to both slow-onset changes such as droughts and sea-level rise, and sudden-onset exposures like tropical cyclones.

In this study, we specifically measure the temporal and spatial coincidence of PSPS events with extreme heat conditions (hereafter as "compound heat-PSPS outages") as a form of maladaptation. Such compound events are especially concerning from a public health standpoint because they can remove residents' primary cooling mechanism, exposing them to dangerous heat conditions, and potentially interfering with electricity-dependent medical equipment. However, we do not measure the success or failure of PSPSs as an adaptive strategy to reduce wildfire risk given the lack of available data. Assessing the effectiveness and desirability of climate adaptation strategies involves weighing the relative success of intended outcomes (in the case of de-energizations, reduced fire ignition risk) against unintended, potentially negative impacts (Reckien, 2023). While there is a growing body of literature focused on de-energizations, this is the first study that specifically frames PSPSs as potentially maladaptive and investigates potential compound impacts. This means that there is very limited scientific evidence available to inform decision-makers who are weighing tradeoffs embedded in different approaches to addressing fire ignition risk. Existing cost-benefit analyses have focused narrowly on the potential financial losses of utilities and have not considered the health and wellbeing impacts of de-energization on exposed residents (Warner et al., 2024). Filling this research gap is especially pressing given that de-energizations are emerging as a proactive wildfire risk reduction strategy across a growing number of U.S. states and in fire-prone countries, even as their impacts on residents remain largely unexamined.

1.4. Social vulnerability

A large body of literature suggests that certain subpopulations may be at increased risk during periods of extreme heat (Li et al., 2023). In some cases, this elevated risk may be due to physiological differences: for example, older adults may be more likely to have pre-existing cardiovascular or respiratory conditions which can be exacerbated by high temperatures. Younger children may also be more vulnerable due to limited thermoregulatory capacity. In addition to psychological risk, social situatedness may affect individuals' ability to manage heat exposure. Socioeconomic status, for example, affects housing quality, material, and insulation, financial capacity to afford high costs of cooling, and access to medical care. Other social factors, including isolation, are strongly associated with adverse health outcomes during heat waves (Bouchama et al., 2007). Many of these factors may be exacerbated by systemic racism, leaving Black individuals and communities at elevated risk (Manware et al., 2022).

Previous research has also indicated that PSPSs are not experienced uniformly; for instance Ptak et al. (2024), found that Hispanic populations and households in poverty were significantly less likely to experience California PSPS outages in 2019, with Hispanic populations 18.3 % less present in shutdown zones, in contrast to commonly-observed patterns of heightened social vulnerability in regions of high hazard risk. In contrast, older adults (who may be particularly at risk during power outages), were consistently more affected by PSPS events. Our analysis builds off of this work to evaluate whether co-occurring heat-PSPS events vary across geographic regions with different socio-demographic compositions.

In this study, we use the Social Vulnerability Index (SVI) to identify key components of vulnerability. SVI is a composite measure developed by the Center for Disease Control, to identify communities that may need support before, during, or after disasters. Social vulnerability indices were first popularized by Cutter (2003), who created a composite score to identify populations with greater vulnerability to hazards (Cutter et al., 2003). There are now a number of different indices for measuring social vulnerability, and their various applications, utility, and limitations have been discussed in great detail in the extant literature (see for example, Hinkel, 2011 for a broad discussion regarding climate change vulnerability indicators; Ptak et al., 2024 on the use and spatial scale of SVI metrics in the context of PSPSs; Lambrou et al., 2023 on the use of SVI metrics in the context of wildfires). We use the CDC's score for two reasons: first, the CDC's SVI was developed as a tool for public health officials to use in disaster response and management situations (Flanagan et al., 2018), making it particularly applicable to our analysis. Second, the CDC disaggregates their SVI score into four domains – Socioeconomic Status, Household Composition & Disability, Minority Status & Language, and Housing Type & Transportation – which makes the tool more interpretable compared to social vulnerability indices that result in only one composite measure. We make no claim about the superiority of the CDC's SVI measure over other measures of social vulnerability; instead, we use it for its utility in illustrating the potential multidimensional impacts of compound hazards. We recommend future research explore different metrics or theoretical approaches to assessing vulnerability.

1.5. Project scope

For this study, we obtained data from the California Public Utilities Commission (CPUC) on all PSPS events in the state of California between October 2021 and September 2024. While PSPSs have been documented in states across the U.S., we focus on California in part due to data availability and in part due to the emergence of PSPS as a risk reduction strategy specifically in this state (Huang et al., 2023). First, using CPUC PSPS data, we examined the prevalence and spatial distribution of PSPS events initiated by three investor-owned utility companies: San Diego Gas & Electric (SDG&E), Southern California Edison (SCE), and Pacific Gas and Electric (PG&E).[1] Second, we investigated a specific maladaptive effect of planned de-energizations by measuring the prevalence and spatial distribution of compound heat-PSPS outages. Such co-occurrences could expose populations to elevated risk of heat-related health effects by reducing their capacity to mitigate these risks

[1] While other utilities do have PSPS protocols, no other utility company de-energized customers during the study period. These three utility companies provide approximately 75 % of California's electricity demand (California Energy Commission, 2015).

through common cooling strategies that rely on electricity, such as air conditioning units or fans. Finally, we describe the demographic characteristics of block groups exposed to both PSPS and compound heat-PSPS outages, assessing the extent to which these events impact socially vulnerable groups.

As wildfire risk increases under changing climatic conditions and the number of residents living in fire-prone areas grows, it is critical to understand the potential consequences of institutional efforts to reduce wildfire ignition risk (Abatzoglou et al., 2020; Barbero et al., 2015; Abatzoglou and Williams, 2016; Radeloff, 2023). Our analyses inform a broader understanding of planned de-energizations as both a form of institutional adaptation to wildfire risk and a form of maladaptation with the potential to compound with concurrent climate extremes. This approach allows us to evaluate a more comprehensive set of potential risks associated with de-energizations to inform more equitable and effective climate resilience policies. Our analysis further contributes to emerging research on the compounding of unplanned power outages with extreme heat (Stone, 2023; Do et al., 2025; Stone, 2021). To our knowledge, this study is the first to assess coinciding planned de-energizations in response to wildfire risk (as opposed to unintentional power outages or other utility-initiated disconnections) with heat exposure. We build on existing quantitative research on planned de-energization events (Abatzoglou et al., 2020; Ptak et al., 2024) by examining a more recent period of PSPS events than has been studied before, and by expanding the set of utilities examined to include SDG&E and SCE, in addition to PG&E. Given our expanded temporal scope and inclusion of multiple major utilities, this study represents one of the most comprehensive quantitative analyses of PSPS events to date.

2. Data and methods

2.1. Power outage data

Starting on 18 October 2021, CPUC mandated electric utilities to provide polygon GIS files with each PSPS post-event report. We obtained data for all reported PSPS events to date from the CPUC's PSPS Event Map on 1 October 2024 (California Public Utilities Commission, 2021). We used the consolidated map, which includes event-level polygons. Our analysis included the 23 PSPS events that resulted in actual customer power shutoffs during the study period, as indicated by the "De-energization Status" field. The dataset provided event dates, affected areas, and restoration times for each PSPS occurrence.

2.2. Environmental data

We obtained environmental data from the Oregon State PRISM Climate Group (PRISM Climate Group & Northwest Alliance for Computational Science and Engineering). This included gridded daily maximum and mean temperature at a 4 km x 4 km resolution across the state of California as well as humidity and precipitation. We then created daily block group-level temperature estimates for all block groups across the state (mean; maximum; and minimum daily temperature).

2.3. Social vulnerability data

To evaluate the association between de-energizations and social vulnerability, we obtained block group-level data from the 2022 American Community Survey, following Ptak et al. (2024) (Ptak et al., 2024; Manson et al., 2022). We then calculated the SVI by first determining percentile rankings for each variable within each block group, then averaging these rankings within each domain. The overall SVI score was calculated as the average of the four domain scores, resulting in a range from 0 (lowest vulnerability) to 1 (highest vulnerability). Levels of vulnerability range from low ($0 - <0.25$), low-medium ($\geq 0.25 - <0.5$), medium–high ($\geq 0.5 - < 0.75$), and high (≥ 0.75) (Flanagan et al., 2011).

In our analyses, we considered the composite SVI and each separate domain (Socioeconomic Status, Household Composition & Disability, Minority Status & Language, and Housing Type & Transportation). We also considered each individual variable within the SVI domains to better understand which specific aspects of vulnerability may have the strongest associations with compound heat-PSPS events. SVI components were scaled to per 1000 if their mean and median values were both below 5 %.

2.4. Statistical analyses

We first produced descriptive statistics characterizing PSPSs each year (2021 – 2024) based on total number of events, number of affected customers, utility company, duration of outage, and month of outage. We then cross-walked PSPS polygons to Census block groups using the *tigris* package in R using 2022 boundaries (n = 25,586 Census block groups in California, excluding islands) (Walker, 2016). Subsequent analyses were conducted using block group level as the unit of analysis. Each PSPS affected multiple block groups, and many block groups were affected by multiple PSPS events. Thus, the number of exposed block groups is much greater than the number of discrete PSPS events. We first calculated the percentage of block groups across the state that experienced any PSPS events during the study period and then evaluated the number of PSPSs that each affected block group experienced (e.g. accounting for block groups that were repeatedly exposed to PSPSs during the study period).

We next identified compound heat-PSPS block group outages based on the days when a block group was affected by a PSPS and when the maximum temperature exceeded an absolute heat threshold of $\geq$32 °C ($\sim$90 °F). As a sensitivity analysis we also used a relative high-heat threshold set at the 95th percentile of annual block level temperature. We then estimated the number of customers exposed to compound heat-PSPS events by calculating the proportion of each PSPS event area that overlapped with high-temperature block groups and applying this proportion to the number of de-energized customers in each event.

Finally, we evaluated the association between social vulnerability and compound heat-PSPS events. We calculated the mean and 95 % confidence intervals for SVI and its composite variables for each block group in California and compared block groups that were never affected by PSPSs, block groups that experienced at least one PSPS event but no events co-occurring with extreme heat, and block groups that experienced at least one compound heat-PSPS outage.

All statistical analyses were performed in R (version 4.2.1); results were considered statistically significant if p-values were < 0.05.

3. Results

3.1. Distribution of PSPS events

We observed 23 de-energization events during the study period (October 2021 – September 2024). Characteristics of PSPS events are presented in Table 1.

Over the 3-year period, over 170,000 customers were de-energized due to PSPSs. The number of customers de-energized decreased each year (though we only have data through September of 2024). Almost all events (91.3 %) took at least one full day for full power restoration. SCE initiated the most outages over the three-year period. More than half of all events occurred in October and November, with no events occurring from January – June.

To evaluate associations between compound heat-PSPS events and social vulnerability, we cross-walked PSPS polygons to the California census block groups. The 23 PSPS outages identified over the three-year period affected 736 unique block groups across the state. On average, each affected block group experienced 1.63 (sd: 1.25) outages during the study period, with 33.56 % of affected block groups experiencing two or more PSPSs during the study period. The maximum number of outages

Table 1
Characteristics of Public Safety Power Shutoffs (October 2021 – September 2024), by Year.

Characteristics	2021*	2022	2023	2024†	All years
Total events	8	3	7	5	23
De-energized Customers					
Total	115,178	15,784	39,037	2,567	172,566
Mean (sd)	14,397 (27,536)	5,261 (4,996)	5,576 (8,996)	513 (768)	7,503 (17,203)
Duration, n (%) ‡					
<1 day	1 (12.5)	0	0	1 (20)	2 (8.7)
1 day	4 (50)	3 (100)	4 (57.1)	2 (40)	13 (56.5)
> day	3 (37.5)	0	3 (42.9)	2 (40)	8 (34.8)
Utility, n (%)					
PG&E	2 (25)	0	2 (28.6)	1 (20)	5 (21.7)
SCE	5 (62.5)	3 (100)	5 (71.4)	4 (80)	17 (73.9)
SDG&E	1 (12.5)	0	0	0 (0)	1 (4.3)
Month, n (%)					
Jul	–	1 (5.6)	1 (5.6)	2 (8.7)	4 (17.4)
Aug	–	0	1 (5.6)	2 (8.7)	3 (13)
Sep	–	0	1 (5.6)	1 (4.3)	2 (8.7)
Oct	5 (27.8)	0	1 (5.6)	–	6 (26.1)
Nov	3 (16.7)	2 (11.1)	2 (11.1)	–	7 (30.4)
Dec	0	0	1 (5.6)	–	1 (4.3)

* October 2021 – December 2021.
† January 2024 – September 2024.
‡Duration is based on full restoration time; some areas may have been re-energized earlier.

per block group was 8. These repeat exposures resulted in a total of 1,119 block group level PSPSs during the study period across the 736 affected block groups, reflecting that block groups often experienced multiple PSPSs (Table 2).

3.2. Maladaptive compound heat-PSPS events

The average maximum temperature during a PSPS outage was 23.02 °C (±3.94) (~73 °F), which does not cross the established heat threshold to constitute a compound heat-PSPS outage. However, the highest maximum temperature during a PSPS was 42.95 °C (~110 °F), which occurred on September 7, 2024. Such compound extreme heat and PSPS events were rare. Of the 1,199 block group level PSPS events, only 52 (4.3 %) occurred on days when the temperature was above 32 °C (Fig. 1). These 52 compound heat-PSPS outages affected 45 unique block groups (some block-groups were exposed to multiple compound events). When using the relative high heat threshold (95th percentile maximum temperature), we identified 14 compound-heat PSPS block level outages (1.1 %). Results presented in Table 3.

Compound heat-PSPS outages were caused by six unique events (26.1 % of all PSPSs): an SCE PSPS on 07/22/22, a PG&E PSPS on 08/30/23, a PG&E PSPS on 07/02/24, a PG&E PSPS on 07/20/24, an SCE PSPS on 08/07/24, and an SCE PSPS on 09/07/24. Notably this includes four of the five PSPSs observed in 2024 (January-September). These six outages resulted in residents residing in 45 unique block groups being exposed to compound PSPS-extreme heat events (temperatures ≥ 32 °C). Full restoration for each event took at least 24 h. These six PSPSs resulted in a total of 6,701 de-energized customers; we estimate that of these customers, approximately 5,523 were located in block groups that experienced co-occurring high heat.

Table 2
Characteristics of public safety power shutoffs (October 2021 – September 2024) at the block group level.

Characteristics*	Block group level value (n = 25,586)
PSPS affected block groups	
Not affected	24,850 (97.1)
Experienced at least one PSPS	736 (2.9)
Range of PSPSs per block group	0—8
Mean PSPS count for affected block groups	1.63 (1.25)

* Reported as mean (standard deviation) for continuous variables and n (%) for categorical variables unless otherwise specified.

3.3. Demographic differences in residential exposure to PSPS and compound heat-PSPS events

Overall, block groups that experienced at least one PSPS during the study period or experienced at least one compound heat-PSPS event were significantly less socially vulnerable than those that did not experience any PSPSs (SVI score mean [95 % CI]: 0.41 [0.39–0.43], 0.36 [0.30–0.42], 0.51 [0.50–0.51], respectively). The only SVI dimension for which heat-PSPS affected block groups experienced higher vulnerability was the household score, but the difference was not significant: household vulnerability was 0.51 (0.43–0.59) for block groups exposed to compound heat-PSPS events, 0.50 (0.50–0.50) for unexposed block groups, and 0.50 (0.48–0.52) for block groups that experienced PSPS events but not compound heat-PSPS events.

Block groups affected by compound heat-PSPS events tended to have lower vulnerability for each of the individual SVI variables as well. The exception was the block group's percent of older adults, which was significantly higher in heat-PSPS affected block groups (0.24 [0.21–0.27]) compared to unexposed block groups (0.16 [0.16–0.17]), and block groups that experienced PSPSs without high heat (0.18 [0.17–0.19]). We also found that block groups affected by compound heat-PSPS events also tended to have higher percentages of residents living in mobile homes (0.10 [0.06–0.15]) compared to block groups that did not experience PSPSs (0.03 [0.03–0.04]). Results are presented in Fig. 2 with complete estimates provided in Table S1.

4. Discussion

4.1. Compound heat-PSPS outages and vulnerable populations

In this study, we investigated a maladaptive effect of planned de-energizations: the co-occurrence of extreme heat during periods of electricity loss. While de-energizations are increasingly used to reduce the risk of utility-ignited wildfires, we argue that such outages can have adverse consequences for affected residents, in particular when they coincide with concurrent hazards. Previous economic cost-benefit analyses of Public Safety Power Shutoffs (PSPSs) have centered on the potential financial losses that utility companies can avert through de-energization (Warner et al., 2024). What such studies have not weighed are the potential public health risks that de-energizations pose to exposed residents, including the potential for mortality, especially during a compounding heat-PSPS event. As such, existing evaluations provide an incomplete assessment of de-energization as a climate change adaptation strategy.

We conducted a comprehensive evaluation of all PSPS events that occurred in California between October 2021 and September 2024. We estimated that over 25 % of PSPSs resulted in compound exposure to heat and power outage for some customers, though this represented a small number of block-group level events (4.3 %), indicating that heat-PSPS events had relatively small spatial extents. We also found that these compound heat-PSPS outages affected populations with higher proportions of older adults and mobile home residents. This research represents, to our knowledge, the first evaluation of planned de-energization coincidence with extreme heat, as well as one of the most extensive multi-year analysis of PSPS events to date, drawing on a complete set of CPUC-mandated reports from all major utility companies in California. While this study focused on PSPSs in California, managed de-energization is an emerging institutional climate adaptation strategy becoming more common across the U.S. and in other parts of the world. Given their growing adoption, evaluating the benefits and harms of de-energizations through a maladaptive framework is critical to understanding the comprehensive scope of de-energizations' effects on

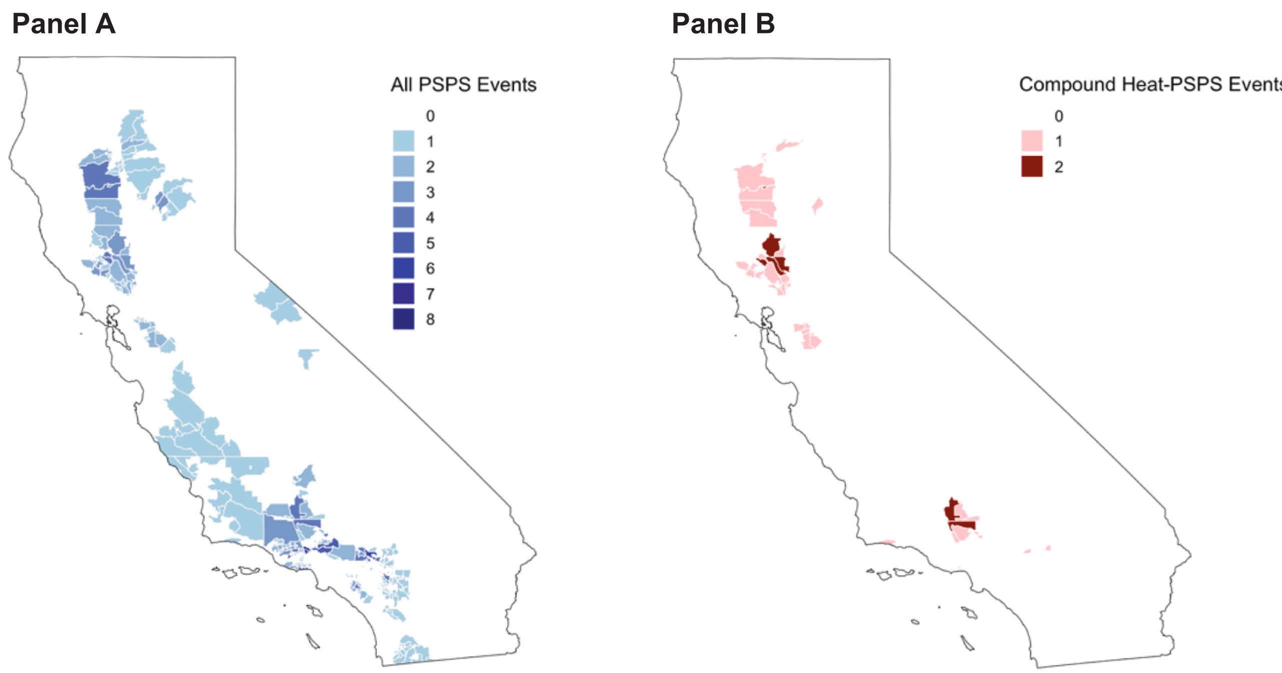

Fig. 1. Block group-level PSPS outages, October 2021 – September 2024 (n = 25,586 block groups). Panel A shows all PSPS events during the study period. Panel B shows compound heat-PSPS events during the study period.

Table 3
Compound heat-PSPS events (October 2021 – September 2024).

Temperature	Block group level PSPS events (n = 1,199)
Mean temperature (°C)	23.02 (3.94)
Max temperature (°C)	42.95
Compound heat-PSPS affected block groups, relative threshold †	
PSPS only	1,147 (95.7)
Compound heat-PSPS event	52 (4.3)
Compound heat-PSPS affected block groups, absolute threshold ‡	
PSPS only	1,185 (98.8)
Compound heat-PSPS event	14 (1.1)

† Relative threshold set to the 95th percentile of annual maximum temperature across block groups in CA.
‡ Absolute threshold set to 32 °C (~90 °F).

communities.

During our study period, over 170,000 customers were de-energized, with an average of 7,503 (± 17,203) customers affected per PSPS event. Notably, almost all PSPSs (91.3 %) required a day or more to completely restore power, which could lead to downstream impacts on food security or economic activity (which were beyond the scope of this study). We further found evidence of de-energization's maladaptive effects in the form of compound heat-PSPS exposure: six of the 23 PSPSs observed during the study period (26 %) resulted in customers being exposed to compound high heat-PSPS events (≥32 °C). These six PSPSs de-energized 6,701 customers, up to 5,523 of whom we estimate may have been exposed to high heat. Full restoration for all six of these outages took at least one full day. Notably, the highest maximum temperature observed during a PSPS was 42.95 °C (~110 °F).

While compound heat-PSPS outages affected a relatively small proportion of all PSPS-affected customers (approximately 5,523 out of 172,566 or 3.21 % of all de-energized customers), these events should be taken seriously, as blackouts during high heat periods are shown to amplify morbidity and mortality (Stone, 2023; Stone, 2021). This relatively infrequent co-occurrence of PSPS events with high heat likely reflects the somewhat distinct seasonality of wildfire occurrence in California, in which the Santa Ana Winds drive autumn ignitions (Abatzoglou et al., 2020; Westerling, 2011). However, geographic regions across the U.S. have different seasonal patterns of wildfire ignition, many of which are concentrated in summer months (Balch et al., 2017). While planned de-energizations emerged most prominently as a wildfire risk reduction strategy in California, recent news reporting suggests that this approach is now being adopted in states across nearly all of the western U.S.. The temporal signature of de-energizations in these states may differ from that of California, with potentially higher fire risk conditions occurring in summer months, during which we would expect a higher concentration of de-energization-heat events.

Examining the demographic characteristics of block groups exposed to at least on PSPS or at least one compound heat-PSPS event, we found that, across most components of the Social Vulnerability Index, exposed block groups tended to have lower overall social vulnerability than unexposed block groups. This finding is in line with prior research examining PG&E PSPSs during 2019 (Ptak et al., 2024), and suggests that exposed populations may have reasonable capacity to adapt to planned de-energizations. However, for two SVI measures, we found the opposite trend; block groups with higher proportions of older adults (those 65 years of age or older) and with higher proportions of residents living in mobile homes were more likely to experience a compound heat-PSPS event during the study period. The exposure of these two groups raises concerns around the potential health impacts of compound events. Older adults are widely considered to be one of the most at-risk populations for heat-related mortality and heat-related illnesses, such as heat stroke, acute kidney injury, and cardiac arrest (Meade et al., 2020). While there is limited research on heat exposure among mobile home residents, one study noted that, in Maricopa County, Arizona, mobile home residents made up nearly 30 % of all indoor heat-related mortalities, despite only accounting for 5 % of the overall population (Phillips et al., 2021). This suggests that mobile home dwellers may also have heightened vulnerability to simultaneous power outage and extreme heat conditions.

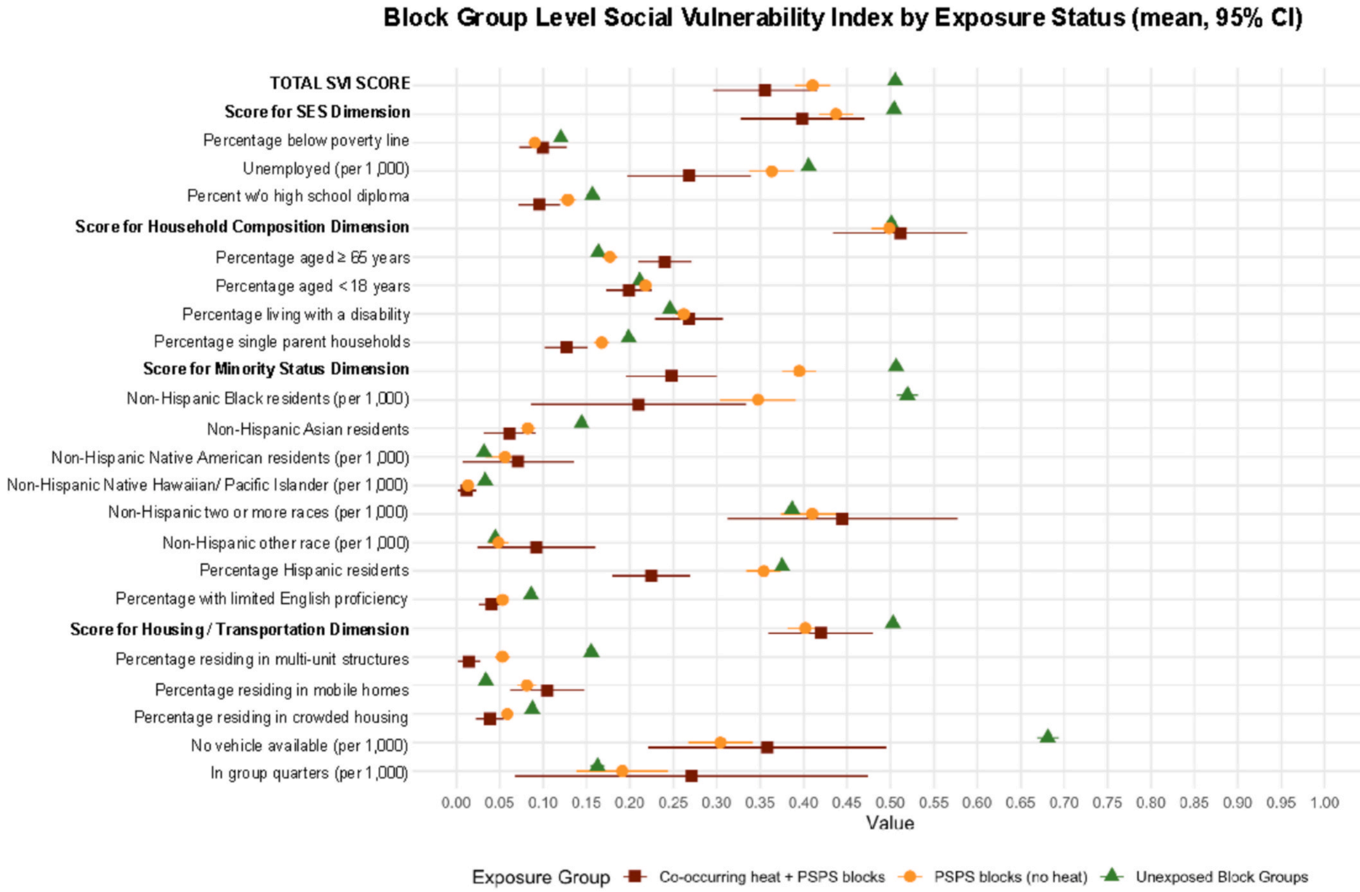

Fig. 2. Social Vulnerability Index (SVI) dimensions and components for California block groups based on their exposure status (n = 24,722 unexposed block groups; n = 691 PSPS exposed-block groups without compound heat exposure; n = 45 block groups with compound heat exposure*). * Based on an absolute threshold set to 32 °C (~90 °F).

5. Limitations

This study has several limitations that should be considered when interpreting results. First, while our analysis spans multiple years, the number of PSPS events is relatively small, because the available data does not include the peak PSPS year of 2019. During our study period, October 2021 through September 2024, we observed substantially fewer overall PSPS events compared to 2019. In 2019 alone, PG&E de-energized approximately 2.7 million customers (Huang et al., 2023), compared to 170,000 customers de-energized by all three utilities in our study period. A longer period of time would have provided greater statistical power to detect associations with vulnerable subgroups and improved our ability to characterize rare but high-impact compound events.

Second, during the study period, utilities introduced new forms of de-energizations that are not included in our data due to different reporting requirements. The reduction in PSPSs described above occurred simultaneously with an increase in the scale of what are known as "fast trip" outages in California. Between 2019 and 2022, PG&E, SCE, and SDG&E began reporting a different form of de-energization known as the "Fast Trip Program" (also referred to as "Enhanced Powerline Safety Settings," "Fast Curve Settings," and "fast protection settings program") (California Public Utilities Commission, 2023). Fast trips are de-energizations that, like PSPSs, are intended to reduce wildfire risk. The primary difference between the two is that fast trips are automated outages, designed to trip the power as soon as an object touches a powerline or a fault is detected, which can result in power being shut off in less than a second (California Public Utilities Commission). Thus, fast trips generally occur with much less advance warning to customers than PSPSs, quickly removing a potential ignition source but also potentially resulting in substantial disruptions (Hagler et al., n.d.). While lauded by some, (Penn, 2024) local stakeholders in California have criticized fast trips as having a "potentially debilitating impact on thousands of customers at a time," and have called for better monitoring and regulation (Peffer et al., 2022). Fast trip outages have come to affect a far larger number of customers than PSPSs during the study period, suggesting that the reduction in the scale and frequency of PSPSs in recent years (Abatzoglou et al., 2020; Ptak et al., 2024) may reflect a shift towards other forms of de-energizations. However, to the best of our knowledge, public data reporting infrastructure is not available for these events. While we anticipate that fast trips may have similar maladaptive impacts as PSPSs, due to a lack of data, we were not able to include them in this analysis.

6. Conclusion

Our findings underscore the need for policymakers to evaluate a range of potential maladaptive effects when evaluating climate change adaptation strategies. A more holistic approach to wildfire risk mitigation would consider not only the prevention of ignitions but also the potential consequences of preventive measures for vulnerable populations. Complementary approaches to risk reduction could include improving infrastructure to reduce the need for de-energization events (e.g. undergrounding power lines), developing targeted support systems for communities most affected by de-energizations, and enhancing communication strategies to better prepare residents for potential outages, especially during periods of high heat.

Future research should explore these possibilities in more detail, and should be expanded to geographic regions beyond California and in fire-prone countries around the world. However, in order to conduct this research, there is a need for more systematic data collection on de-energizations, which should account for shifting institutional de-energization practices and subsequent changes to de-energization categories (including the introduction of fast trips) and data reporting. Questions over de-energization data availability nest into broader concerns over tracking power outages, in which even the most comprehensive evaluation of power outages (both unplanned and planned) in the U.S. reflects substantial missing data in the Mountain West and Southwest –- two of the most fire-prone regions of the country (Do et al., 2025). Addressing this data limitation would likely require mandated reporting for investor-owned utility companies across the country, as well as the reporting of other forms of managed de-energization, including fast trips. Future research should also examine the political economy of utility decision-making processes, including how financial incentives, regulatory pressures, and corporate governance structures influence de-energization policies and their implementation across different communities.

We recommend that decision-makers take seriously the possibility of rare but potentially very high impact compound events, such as the co-occurrence of widespread de-energizations during a heat wave. Prior research suggests that compound heat-power outage events pose severe morbidity and mortality risks to affected residents, and so should be accounted for when weighing the tradeoffs of planned de-energization as an adaptive strategy (Stone, 2023; Stone, 2021). While we examined the co-occurrence of extreme heat and de-energizations as a particular form of maladaptation, future research may investigate other types of compound events. For instance, de-energizations may occur simultaneously with periods of heavy wildfire smoke; if residents open windows in response to loss of air conditioning during such an event, they may be exposed to higher levels of air pollution. Future research should quantify the downstream health effects of de-energizations, such as hospitalizations and mortalities.

De-energizations are an increasingly common tool used in wildfire ignition prevention around the world. As such, their implementation must be carefully considered and monitored to avoid exacerbating existing vulnerabilities or creating new ones. We find evidence that PSPSs may be maladaptive, in that some de-energizations result in customers being exposed without power on high heat days. However, this does not mean that PSPS programs are without value or should be stopped entirely. Rather, as climate change continues to increase wildfire risk to communities, it is crucial that adaptive strategies like PSPSs are evaluated comprehensively, considering their full range of both beneficial and potentially harmful impacts. This study lays out an analytical approach for investigating the maladaptive effects of such utility adaptations to hazard risk, highlighting the importance of detailed, localized analyses in understanding the complex effects of climate adaptation strategies.

CRediT authorship contribution statement

Kate Burrows: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Kathryn McConnell:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Nora Louise Schwaller:** Writing – review & editing, Formal analysis, Data curation, Conceptualization. **Chantel F. Pheiffer:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2025.103067.

Data availability

The data used in this analysis is freely available from the California Public Utilities Commission's Public Safety Power Shutoff (PSPS) Event Dashboard: https://www.arcgis.com/apps/dashboards/eccae0d91efc4cb1926507c0b5643f8e.

PRISM Group, Oregon State University, https://prism.oregonstate.edu.

Code used to process these data and conduct analyses is available at: https://github.com/kateburrows/Burrows-PSPS.

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