



Out of sight, out of mind? How electricity (un)reliability shapes residential energy transitions

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HIGHLIGHTS

- Concerns about power reliability reduce willingness to adopt electric appliances.
- Social dimensions of reliability modify prospects for residential electrification.
- High-income homes look to batteries and generators to counteract unreliability.
- Low-income homes favor changes in the energy utility to ensure reliability.

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ABSTRACT

Social norms on household energy consumption practices have been historically fostered through ideas of comfort, cleanliness and modernity, underpinned by reliable and affordable energy services. Contemporary discourses on energy transitions require households to conform to new expectations of “sustainable” living, calling for energy users to participate in the electrification of energy end-uses, provided sufficient economic incentives. Yet, a combination of emotional and social responses to the increased frequency of power outages complicate this account. Despite expectations of consumer cooperation in the clean energy transition, limited research explores how differing capabilities and lived experiences with energy infrastructure modify perspectives on these changes. Through semi-structured interviews with sixty Northern California residents, we explore how residents cope with energy unreliability and whether—or how—they envision transitioning to higher levels of electrification of their homes. By centering users’ lived experiences, this work goes beyond formulations of “customer choices” to focus on how everyday energy practices are reimagined in the context of residential electrification policies, climate imperatives, and power outages—or the fear thereof. We argue that the emotional, social, and relational dimensions of grid reliability should complement the predominantly techno-economic lens through which electricity reliability is studied, highlighting the implications of this framing for electricity-intensive residential energy transitions.

1. Introduction

“If I thought about it, I probably wouldn’t say I’m not going to [buy] an electric stove, just because of a potential power outage that could affect me for like two days in my life. But... It’s like shark attacks... It’s not going to happen, but you know, every time you go into the ocean [you] think about sharks.” — Oakland homeowner.

In the wake of a power outage in 2019, a homeowner in Oakland, California, decided to install rooftop solar panels and battery storage in

her home. She was concerned about the impacts of potential future power loss, despite not having personally experienced any outages. While she initially mentioned feeling uncomfortable about disconnecting from the gas network (fearing electric service interruptions would leave them unable to cook for the family), she later reconsidered because she believed that remaining “hooked” to gas services was antithetical to sustainable behaviors. These reflections exemplify concurrent trends among residents: concerns about fossil fuels, anxieties about grid unreliability, and policy pressures toward greater residential electrification.

Fears of power loss are growing among Northern California residents

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as the frequency and duration of electricity unreliability events have escalated over the past five years. In September–October 2019 Public Safety Power Shutoffs (PSPS) were widespread; these were controlled outages that electric utilities used as precautionary measures to reduce the risk of wildfires being caused by their electrical infrastructure. About three million people (predominantly those served by the utility Pacific Gas and Electric) were left in the dark for an average of two days, with some shutoffs lasting up to six days. California is not alone. Across the United States, extreme weather events are occurring more frequently and intensely [1]. They are becoming the “principal contributor to an observed increase in the frequency and duration of power outages” affecting an aging and already vulnerable grid infrastructure [2], with customers experiencing more electric power interruptions co-occurring with extreme weather or climate events [3]. Federal regulators have started to engage in discussions on grid hardening to prepare electric infrastructure against increased flooding, heat waves and wildfires, among other extreme climate events [4–6].

At the same time as the US power sector is experiencing higher electricity unreliability, households are being incentivized to deepen their dependence on electricity to fuel their daily lives. Electrification is a key decarbonization pathway, which complements a renewable electricity supply by converting energy demands from being from fossil fuels to electricity [7,8]. In the residential context, households are expected to gradually “fuel-switch” from fossil-fueled to electricity powered appliances (via heat-pumps, electric vehicles, and induction cookstoves) [9–11], while cities are attempting to ban natural gas infrastructure in new construction [12,13]. Berkeley, California, was the first US city to ban natural gas in new buildings in 2019, though the ban was repealed in 2023 following a suit by the California Restaurant Association [14].

For California residents, home electrification primarily involves choosing to switch from natural gas to electricity-based energy services, as natural gas is the predominant fuel for space heating (63 % of homes), water heating (65 % of homes) and cooking (60 % of homes) [15]. Traditional methods to encourage sustainable customer behavior include economic and informational tools, particularly through nudging [16–20]. However, despite economic incentives and reliable information, households may still resist electrifying their energy services. High electricity rates compared to gas prices (see S1), upfront costs for heat pumps and electric vehicles, and rising energy burdens (percentage of income spent on energy bills) pose significant barriers to electrification [9,11,21,22]. Additionally, the ability of households to benefit from and participate in electricity-intensive energy transitions also depends on socioeconomic conditions, preferences and habits [23], and the adequacy of the networked infrastructures that enable home energy services [24,25].

The strained relationship between citizens and the integrated monopoly utility, Pacific Gas and Electric (PG&E), further complicates households’ motivation to deepen their reliance on electricity. As the largest privately-owned utility in the US, serving 5.5 million electricity and 4.5 million gas accounts [26], PG&E is also regarded as the least esteemed energy utility by its customers in the US [27]. A general dissatisfaction with PG&E itself is not surprising given that sparks caused by their equipment were blamed for the catastrophic 2018 Camp Fire, which led PG&E to introduce Public Safety Power Shutoffs (PSPS) events in 2019 [28]. Compounding negative perceptions of PG&E are the hikes in electricity rates in the region, which are partly attributed to wildfire prevention costs that are being passed on to customers. These rates exacerbate the already high prices that Northern Californian residents face in comparison to state and national averages (see Supplementary data S1). PG&E remains responsible for electricity delivery, billing, grid maintenance, and outages, but communities in Northern California can procure electricity through Community Choice Aggregation, introduced by Assembly Bill 117 in 2002. In the East Bay, Ava Community Energy has served as the default electricity provider since 2018, and offering comparable rates to PG&E [29].

Overall, while economic and techno-centric perspectives on

electricity-intensive energy transitions in homes are well-documented, the lived experiences and psychosocial factors shaping responses to energy unreliability and electrification decisions remain underexplored, particularly in the Global North. This gap, especially in the context of climate-driven power outages, motivates our work. We hypothesize that experiences of power loss condition households’ attitudes toward relying more on electricity in the face of fears of more frequent extreme weather events. To investigate the nexus between coping with unreliability events and residential electrification efforts, we ask: Which and in what ways do emotional, social and relational dimensions of power (un)reliability shape users’ expectations and experiences of transitioning to electricity-intensive energy services? We explore how these dimensions affect behaviors, attitudes, and energy users’ willingness to embrace residential electrification in the context of increasing grid unreliability.

Our work shows that fears of power outages and users’ perceived reliance on the electric grid complicate conventional, cost-centric views of household electrification decisions. We show that reduced power service expectations are becoming normalized, and we discuss what the possible consequences of such normalization may be for sustainability and equitable transitions frameworks. Drawing on these findings, we advocate broadening mainstream techno-economic research on power loss to encompass perceptions and expectations of grid reliability.

2. Socio-technical dimensions of electricity unreliability

The concept of electricity reliability,¹ and perhaps infrastructure reliability more generally, has been predominantly analyzed in academic scholarship on technical and economic grounds [30] [31]. These perspectives rely on quantitative metrics, economic models, and technical evaluations to make claims about the value of reliability and its impacts on society. Yet, electricity (un)reliability understood this way limits our capacity to recognize its role in energy transitions more broadly, beyond determining its economic impacts. In this paper, we bring together a technical understanding of electric reliability with insights from Science and Technology Studies (STS) to offer a nuanced reconceptualization of unreliability. This approach allows us to concurrently explore the symbolic and relational dimensions of infrastructure [32], investigate how users’ experiences and expectations of power loss shape their understanding of the grid, and assess the uneven material conditions of California’s electric infrastructure.

From a technical perspective, electricity unreliability is a spatialized phenomenon—constrained to either certain distribution system elements (feeders, circuits, substations) or to bulk power system interruptions (including generation and transmission lines and transformers).² Reliability is typically assessed at the distribution level, as the System Average Interruption Duration Index (SAIDI), which measures the duration of interruptions, and the System Average Interruption Frequency Index (SAIFI), which measures their frequency [30]. These utility-level, “top-down” measures help identify problem areas, prioritize infrastructure upgrades, and plan maintenance to improve overall system reliability. These metrics reflect the experience of the *average* customer across a utility’s service area but do not capture the variability in reliability impacts for households. More customer-centric metrics like Customers Experiencing Long Interruption Durations (CELID) and Customers Experiencing Multiple Interruptions (CEMI) focus on identifying pockets of poorly performing circuits, identifying groups of customers facing prolonged or frequent interruptions [33].

¹ “Reliability” is defined by the US Department of Energy report as “the ability to maintain the delivery of electric power to customers in the face of routine uncertainty in operating conditions” [79].

² Large scale outages are mainly attributed to falling trees, fires, wildlife, and traffic accidents in the first case, and to unplanned losses in power supply to specific areas in the second case [30,80].

These tools are not designed to capture differences in reliability experiences among customer classes, varying levels of vulnerability to outages, or the evolving expectations of “adequate” service as interruptions accumulate. Nor do they address the broader social and health costs borne by individuals living through unreliable events. Acknowledging these limitations, technical reliability assessments remain valuable for overall utility planning.

The economics literature on household-level outages centers on consumer preference frameworks, with emerging research beginning to examine how an increasingly disruptive climate shapes the evolving realities and imagined futures of increasingly electrified households. In particular, “bottom-up” studies that have examined concerns about reliability from the user’s perspective employ stated or revealed preference methods to assess willingness to pay to avoid outages [34–38]. These studies typically report a singular price point that an individual would be willing to pay to avoid electricity outages (called the Value of Lost Load, or VoLL). VoLL quantifies the economic cost of power service disruptions, providing a useful benchmark for utilities and policymakers to assess the financial impacts of service disruptions and guide grid investments. However, this metric cannot capture how diverse needs and capabilities among energy users influence their ability to cope with outages (cf. [39,40]). Recent research in California has also found that ownership of fossil fuel generators in homes correlates with a greater willingness to pay to avoid future outages [41]. Areas previously affected by power loss demonstrated higher intentions to purchase backup generators and reported reduced intentions to purchase electric vehicles [42]. These findings suggest that experiences of power loss can foster risk aversion and fear of future disruptions, shaping adaptive behaviors primarily through individual technological interventions. This literature, however, tends to frame the home as an isolated entity, paying less attention to the implications of individualized responses for broader collective strategies for mitigation and adaptation [43]. Overall, this body of work would benefit from a deeper exploration into how variations in energy users’ coping capacities, service expectations, and trust relationships shape adaptive practices in response to infrastructural disruptions.

Throughout our study, we theorize “infrastructure” as comprising both its physical elements and the interactions and relationships among those who design, build, use, and maintain infrastructural services [44]. This perspective emphasizes that infrastructure takes shape through organized practices [45], reflecting centralized planning power, conveying emotional and symbolic meanings linked to visions of modernity [46], and shaping public narratives about its role and functionality [47]. Traditionally, Science and Technology Studies (STS) literature has understood infrastructure as “invisible” until it fails [44]. More recently, Trovalla and Trovalla introduced the concept of a visibility continuum, where infrastructures operate imperceptibly when functioning but show “hyper-visibility” during interruptions, such as power outages. [46]. Degani builds on this idea by exploring how power outages shift energy users’ perceptions by altering their awareness of spatial and temporal disparities (“vital force”) and their trust relationships with utilities and governments (“social form”) [48]. Gupta expands the focus beyond complete breakdown to include the “partial presence” of modern infrastructure, where intermittency and poor power quality modify daily experiences, particularly in the Global South [49]. Similarly, Jacome et al. demonstrate how concerns around power quality services—from service interruptions to maintaining voltage within operation limits—are normalized by energy users, further embedding infrastructure performance into daily routines [50].

Breakdowns have also been seen as opportunities for reconfiguration of infrastructure dynamics, rather than as a mere interruption of service. Jackson offers this transformative lens to view interruptions as starting points for the creation of new systems through continuous maintenance practices [51]. Anwar distinguishes between spectacular malfunctions (c.f. [47]), which draw public attention, and the mundane, everyday repairs that are often rendered invisible [52,53]. Complementing often-

overlooked traditional repair work (c.f. [52,54]), households can actively modify the grid—understood as the assemblage of technologies enabling electric service—by responding to unreliable power through actions such as upgrading wiring, installing solar panels, or adopting batteries and backup generators. The emergence of differentiated energy technologies, such as rooftop photovoltaics, electric batteries and electric vehicles, exemplifies what Marvin and Graham describe as “splintering urbanism” by “unbundling” and commodifying energy services [55]. As the visibility of these arrangements increases with more disruptions, infrastructural inequities across energy users become more evident, underscoring the need to explore how such differences, in turn, impact users’ expectations of energy services.

Our study links the psychosocial dimensions of electricity service unreliability to energy users’ decisions about adopting electricity-intensive residential energy transitions. The psychosocial perspective brings together the internal, psychic dimensions of human experience and the external, social aspects of everyday life, treating them as mutually constitutive and intertwined [56–58]. Recognizing that individuals’ behaviors are shaped not only by rational responses to external conditions (i.e. socioeconomic factors, access to resources) this approach also integrates the unconscious motivations rooted in personal histories, emotional responses, and relationships.

In our work, we show how *emotional factors*, such as anxiety about outages and fears of future service interruptions contribute to skepticism toward transitioning to electric-only appliances. While emotional responses to power outages have primarily been studied in Global South contexts, previous research has shown how, during service failures, consumers experience a lack of agency leading to anger, frustration and blame attribution [59]. We also examine the role of *social factors*, recognizing that differences in adaptive capacities to outages, shaped by income, familial status, and health conditions, can result in uneven willingness and capabilities to adopt and benefit from electricity-intensive solutions. Existing research has shown how social disparities in power system restoration, with socio-economic status correlating with outage occurrence [60,61], and associated hardships [61,62]. Our work indicates that unreliable electric services may also foster a sense of urgency among some users to adopt decentralized systems like residential solar and storage, motivated by a desire for energy security, autonomy, and resilience. Here, *relational concerns*, such as trust and distrust in electric utilities, can significantly shape users’ decision to remain dependent on centralized actors or to self-provide electricity. We find that users’ sense of (inter)dependence with utilities, whether seen as cooperative partners or unreliable monopolies, significantly influences future electrification decisions.

Drawing on empirical insights from sixty semi-structured interviews with energy users across the East Bay, California, we explore how emotional, social and relational dimensions of outages influence energy practices and shape perceptions of the grid. We argue that studying the emotional, social and relational dimensions of grid reliability can complement conventional, technical metrics with user-centered understandings of reliable power. While typically reliability measures focus on technical performance, our approach focuses on how energy users experience and understand reliable power. We posit that a system is reliable when it meets users’ expectations and allows them to trust the electric grid and utility. Our approach centers users’ understanding of acceptable levels of electricity service, and perceptions of being *able to rely on* the electric utility. Unlike technical metrics in common use, the social dimensions reveal how power disruptions, and even the fear of them, are experienced differently across locations and communities. These dimensions explain how people’s experiences with power loss influence their expectations of future unreliability and willingness to adopt electric appliances and technologies at home.

3. Methods

3.1. Site selection

The study site, the East Bay, California, is a coastal region of the western United States. Comprising the Alameda and Contra Costa counties, it is the most populous and geographically diverse subregion of the San Francisco Bay Area, with approximately 2.8 million residents. Known for progress environmental initiatives and proximity to the tech hubs of San Francisco and Silicon Valley, the area has supported extensive demand electrification efforts for nearly two decades.³ These efforts culminated in the proposed language for Assembly Bill 1176, which codifies transport and building electrification considerations into city or county local planning processes [63] (see Supplementary data S2 for incentives for residential electrification). At the same time, East Bay residents pay among the highest prices in the nation for electricity. Currently, PG&E charges an average of approximately 30 cents per kWh for electricity, or about double the average US residential rate (see Supplementary data S1). These high rates are attributed to a combination of funding for wildfire mitigation and extensive bill assistance programs [64]. Residential electricity prices are projected to increase further as utilities deploy infrastructure hardening measures to mitigate climate risk, and to invest in significant capacity upgrades for transmission and distribution grids to accommodate the anticipated increase in electric loads due to electrification efforts. In the past five years, the region began facing higher occurrences of heat and wildfire-induced power disconnections.

Our study area includes the towns of Richmond, Berkeley, Oakland, and Castro Valley (see Fig. 1). Richmond, known for its industrial background, has a median household income lower than the state average. Berkeley features a significant student demographic and higher median incomes. Oakland is the largest and most diverse. Castro Valley is more family-oriented, suburban and residential. Coastal cities like Berkeley and Oakland have a temperate climate, with mild winters and dry summers temperatures, while inner areas of Richmond and Castro Valley are more prone to extensive heat waves. The eastern hilly areas of these towns are particularly vulnerable to wildfire-induced power disconnections.

As in the East Bay, many communities across the US are experiencing climate-induced power outages (e.g. in Texas, Michigan, North Carolina, and Pennsylvania) [65], while local and regional governments are looking to electricity for their sustainability goals. Thus, the East Bay serves as an important and early case study to understand the pressures and impacts of the so-called ‘electrification of everything’ amid rising climate-related disruptions.

3.2. Interview content and analysis

In this study, we employed semi-structured interviews to gain insights into users’ energy practices, lived experiences of power outages, and attitudes toward energy transitions. The use of semi-structured interviews offered us the flexibility to contextualize interviewees’ responses and probe individual reactions to and understandings of the grid, the urban environment and energy services.

A total of sixty people across the East Bay participated in interviews between June 2022 and June 2023. Most interviewees were not Ava Community Energy customers, as their service agreements were established before the Community Choice Aggregator was created, and they did not opt in afterward. Participants were recruited through a

combination of community-based organizations, public outreach, and snowball sampling to ensure a diverse and representative sample. While some recruitment was supported by groups with explicit sustainability goals, such as the City of Oakland Sustainability and Environmental Stewardship Newsletter and the non-profit Green The Church (together accounting for 14 % of participants), broader outreach strategies were also employed. For example, Ava Community Energy, the community choice aggregator that is the default electricity provider for residents in Alameda County, disseminated study information through its newsletter, contributing 7 % of participants. To further reduce bias toward sustainability-minded individuals who tend to respond to newsletters or formal calls, we relied on snowball sampling. Initial participants referred their relatives, friends, and neighbors, sharing information about our study through word-of-mouth and social media posts. This referral-based approach accounted for 61 % of participants. We also partnered with the community-based organization East Oakland Collective to reach underrepresented, low-income residents. Additional interviews were conducted during food bank distribution events organized by the East Oakland Collective, enabling participation from individuals who might otherwise have been excluded. These efforts contributed to 16 % of the sample. Finally, posters placed in commercial streets and corner shops in West and East Oakland brought in 2 % of participants. This multifaceted recruitment strategy reduced potential biases and enabled a diverse sample across socioeconomic and demographic backgrounds (Fig. 2).

Our interviewees had varying experiences with power outages. Considering the ongoing COVID-19 concerns, participants were given the choice of in-person ($n = 31$), Zoom ($n = 24$) or phone ($n = 5$) conversations. Interviews ranged from 30 min to 1 h. The questions covered a range of topics, including which appliances interviewees used most frequently, their satisfaction with their energy provision (including affordability, sustainability, and reliability of gas and electricity services), and their experiences with power loss events and adoption of low-carbon technologies. Participants were also asked whether they anticipated more outages in the future, if they had taken precautionary measures in response to these events and their opinions on residential demand electrification. The semi-structured interviews were designed to adapt over time, allowing emerging themes to shape the process. (See Supplementary data S3 for the interview guide, though questions varied across interviews in response to interviewee comments and concerns). All interviews were conducted by the first author to ensure consistency, sometimes attended by the last author to ensure alignment with the broader research objectives.

We employed a grounded approach to interpret the interview data, integrating theoretical insights with interview findings to develop and validate concepts, which were further refined through subsequent interviews, and eventually informed our hypothesis generation [66]. Respondents provided information about the fuel type used by their main energy appliances, to the best of their knowledge. When interviews took place in-person appliances were inspected to corroborate the type of fuel in use. Respondents also self-reported whether they had been affected by outages or PSPS events. We classify homes as having been affected by a power outage in Figs. 2 and 4 based on their self-reported experiences of unreliability events lasting more than one hour in the past five years (see Supplementary data S4 for state-level unreliability over time). Interviewees provided their average monthly energy bill estimates based on recall and discussed seasonal variations within the last billing year. When respondents did not provide specific income estimates, we asked them to self-identify as belonging to one of three income groups (low, moderate, high), based on their assessment of their household’s financial situation. For example, respondents who felt they had limited financial flexibility often self-identified as low income, while those with more stable and flexible finances identified as moderate or high income. However, given the subjective nature of these self-reports and the hesitancy of some respondents to provide income figures, we recalibrated this self-classification using observable contextual factors, such as the

³ As early as 2007 Governor Schwarzenegger enacted the “California Alternative and Renewable Fuel, Vehicle Technology, Clean Air, and Carbon Reduction Act” (AB 118), which established the Air Quality Improvement Program. This program promoted the production and use of zero-emission vehicles including plug-in electric and fuel cell vehicles.

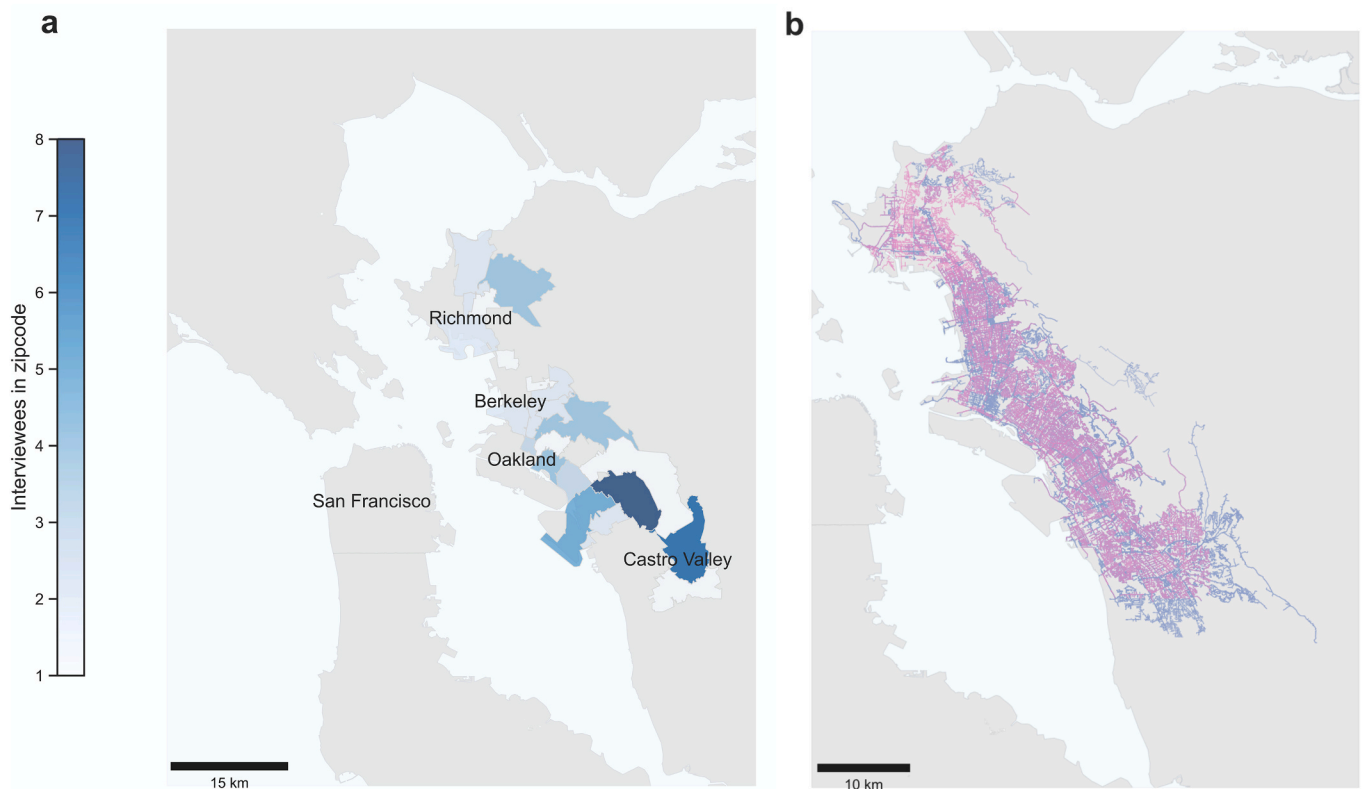


Fig. 1. Area of study encompassing zip codes in Alameda and Contra Costa county, a) number and location of respondents' homes, b) distribution feeders impacted by 2019 public safety power shutoffs events (in pink) and other feeders (in blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

occupation and education levels of household members, housing tenure, whether they were enrolled in income-qualifying bill assistance programs and the median income level of households in the respondent's neighborhood.

Fig. 3 compares electric and low-carbon technology penetration in the homes of interviewed participants with those across the PG&E service territory and California. Benchmarked against the 2019 California Residential Appliance Saturation Survey [15], the adoption rates are similar across all areas, except for lower air conditioning adoption among our interviewees, due to the milder climate in the study zone compared to the state average.

4. Results

We present three key results from our interviews. First, the fear of unreliable electricity supply exists even in areas with no direct history of shutoffs or outages; this "spillover fear" highlights the psychological impacts of grid fragility and usually not accounted for in conventional measures of unreliability. Second, socioeconomic vulnerabilities condition user responses to power loss, with significant variations in the ability and willingness to adapt through electrification or alternative measures. Third, trust in utilities' role in providing safe and reliable power vary across demographic groups, affecting their willingness to intensify their electricity use; this is also neglected in mainstream energy transition discourses. Together, these findings highlight the need for a more nuanced understanding of energy user perceptions to develop effective electrification strategies.

4.1. Perceptions of outage risk intensify amid the normalization of grid instability

Respondents' emotional responses to power outages were shaped by

a growing sense of anxiety about the increasing frequency and duration of power loss events. Approximately half of the respondents explicitly connected these disruptions to the broader impacts of climate change, while the majority also blamed deteriorating and unreliable electrical infrastructure.

Most respondents reported being worried about losing power during the late summer and early fall. All interviewees recalled the September–October 2019 Public Safety Power Shutoffs (PSPS), which affected 3 million people, and mentioned that that had made them aware of the electric grid's vulnerability. From September to late October 2020, PG&E also enacted five wildfire PSPS events, the last of which affected 345,000 homes and businesses, or about 1 million people in their service territory [67]. While these blackouts were significantly smaller in scope than those of 2019, the recurrence of these seasonal outages played into energy users' expectations for further power loss events in the late summer. Worries about recent and future power loss events were not confined to respondents who had experienced shutoffs. Independently of their history with outages, interviewees expected a growing frequency of power loss events in the coming years, especially in areas more susceptible to heat waves and at heightened risk for wildfires. One interviewee, who had recently moved inland to the Richmond hills from a more urban area close to the waterfront, reported feeling "tense" in the summers, in expectation of fires and disconnections: "[In the] summertime we just walk around with fingers and toes crossed, if you know what I mean." Indeed, a growing population living in the wildland urban interface (WUI) [68] exposes more people to wildfire risk and to wildfire-safety induced service shutoffs [28].

In interviews that took place after the severe winter storms in

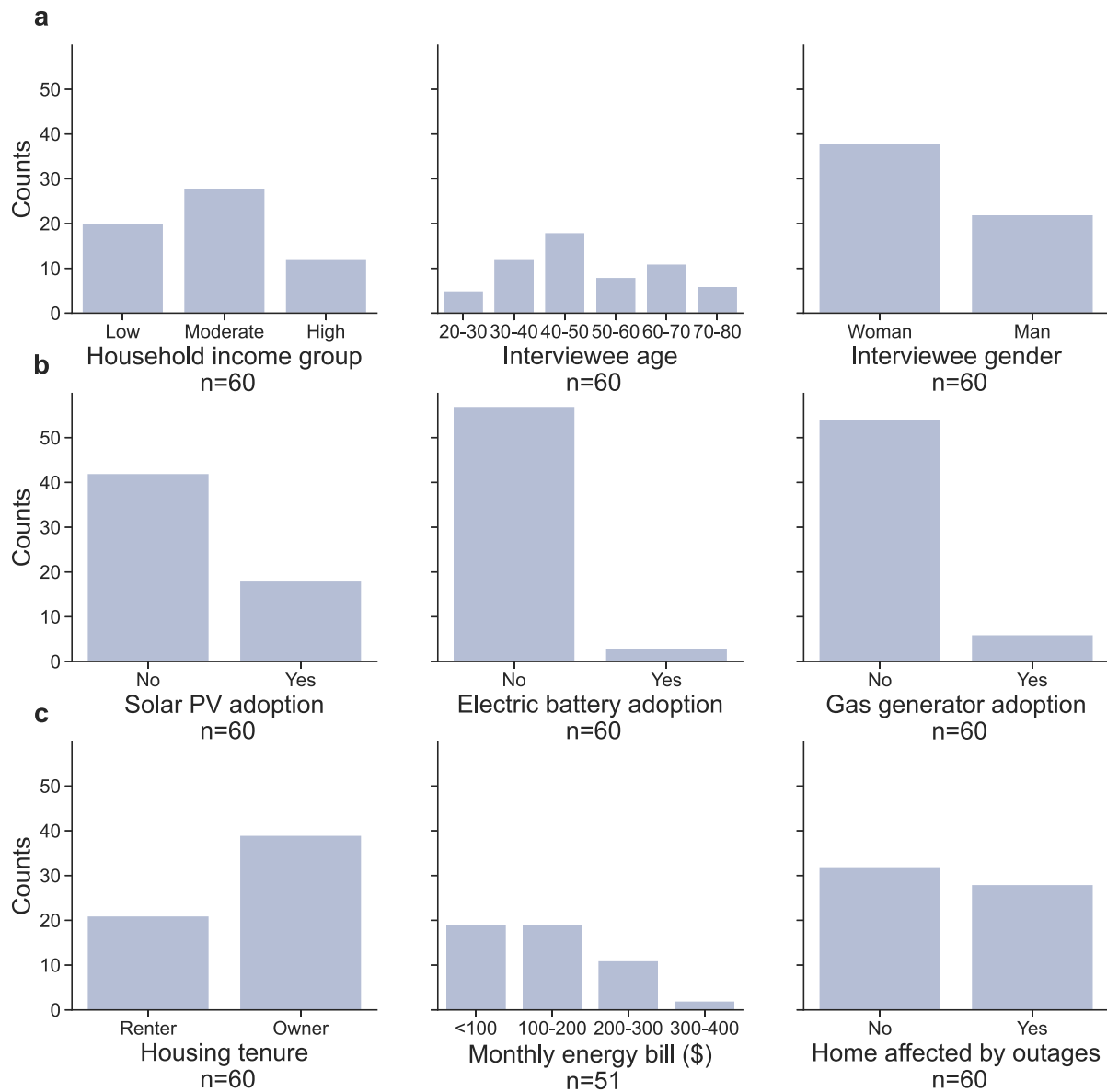


Fig. 2. Overview of interviewees' self-reported characteristics and experiences: a) socio-demographics, b) adoption of specific energy technologies and c) tenure status, experiences with energy costs and power interruptions. Each subplot displays the number of interviewees who discussed the respective topic.

Northern California of January–March 2023,⁴ respondents explained that the ensuing, and extensive, winter power loss events compounded the expectation of summer power loss. A long-term Oakland resident commented on the increasing frequency and evolving seasonality of power loss:

I lived in Oakland for about 20 years. And in all those 20 years, I never had, you know, these kinds of outages until the last three or four years [...] Yeah, I've kind of accepted that there is something called 'fire season'. And maybe this atmospheric river thing is also going to be a regular phenomenon. I mean, I'm not quite sure about that. But it wasn't a term that I [knew of]... Maybe they hadn't even coined the term until recently. I'd never heard it prior to about a year ago.

⁴ Sumeet Singh, PG&E's vice president of operations recognized that the storm was "the most impactful that we have seen in terms of customers out in a single day in the Bay Area, since 1995" [81].

The record-breaking outages due to winter storms (which re-occurred in February 2024) also made people hyper aware of the PG&E grid's fragility to the extent that no time felt safe from outages. Outages could seemingly occur whenever. In one instance, a resident of a wealthy neighborhood in the Oakland hills reflected back on the seasonality of these events.

This year [2023], we were pretty lucky. We didn't have the wildfire and the PSPS outages. But we had during the storms in the winter. [...] And so we were out for 48 hours on New Year's Eve and New Year's Day. [...] Prior to that in the kind of the worst of the wildfires that I think was like two years ago, we were having them probably at least three or four times in the first year. Maybe more times, and each one would be in the 24-to-48-hour range.

Despite experiencing fewer power outages that year, this resident purchased a fossil fuel generator in anticipation of potential year-round power loss. With first the fire season, and then the winter outages, respondents described a newly formed perception that they had to be

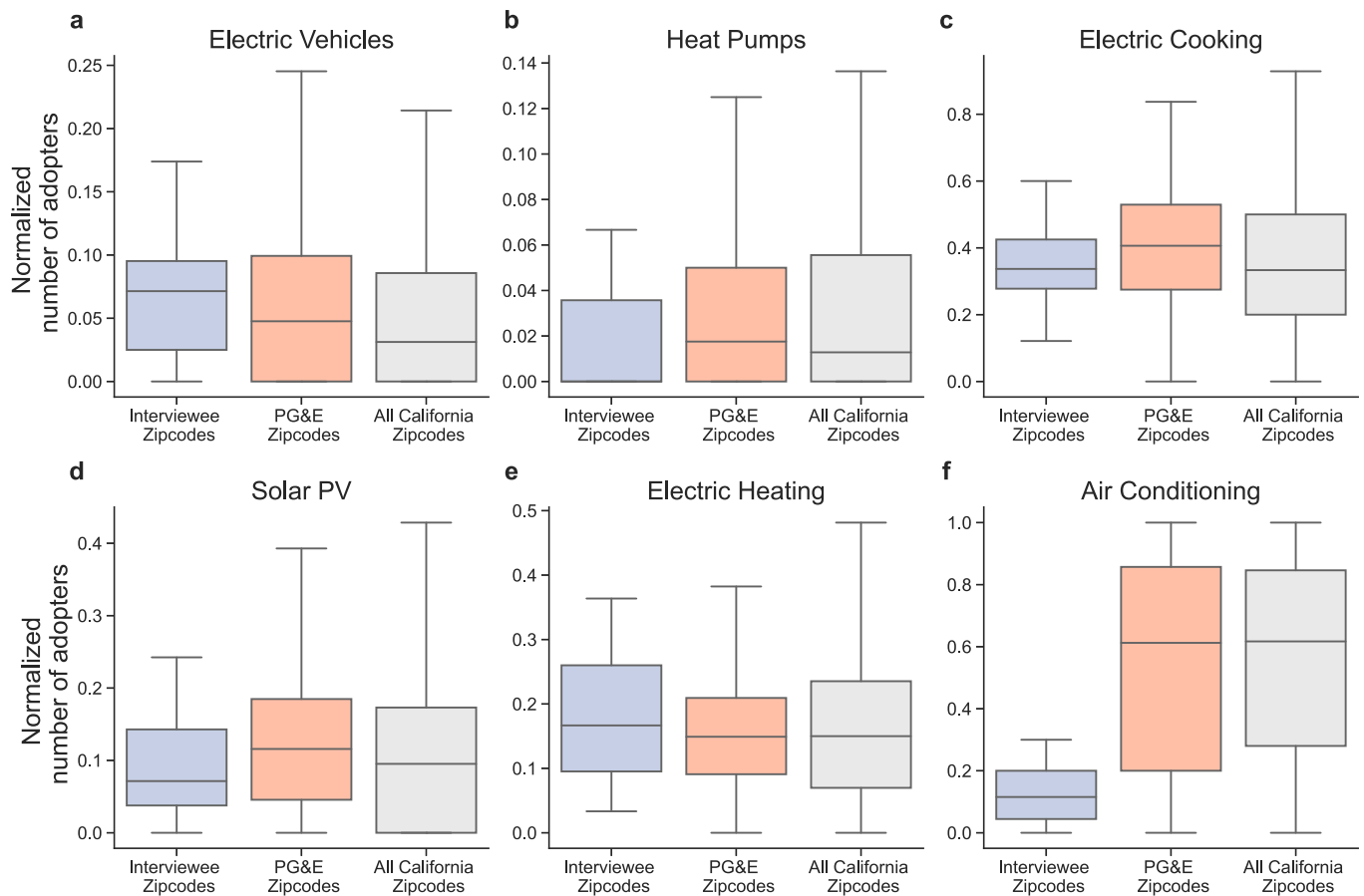


Fig. 3. Per capita comparison of the penetration of a) electric vehicles, b) heat pumps, c) electric cooking, d) residential rooftop photovoltaics, e) electric heating, and f) air conditioning in zip codes where interviewees reside, across the PG&E service territory, and statewide in California. All data are sourced from the 2019 residential appliance saturation survey (RASS). The PG&E data represent a subset of responses within the PG&E service territory, while the interviewee data further subset to zip codes containing adopters. Normalization was performed by dividing the number of adopters by the total number of households in each category. Following data quality verification, the RASS survey includes 21 households within interviewee ZIP codes, 478 households within PG&E ZIP codes, and 1409 households across all California ZIP codes.

“ready” for power shutoffs occurring at any time in the year, since outages were becoming a “chronic condition.”

The electric grid’s malfunctions heightened respondents’ awareness of infrastructural unevenness across different locations too. Spatial variations in outages and shutoffs left many respondents puzzled, describing them as a source of confusion or “mystery”, which played into their fears of maintaining sustained access to electricity. When asked about whether outages had occurred in her area in the past years, an interviewee who lives in May Valley (Richmond), said “my friend lives like 10 minutes away [in the Richmond Annex area], and she has brownouts and power outages all the time. [...] And we had surprisingly few, like, it does happen.” Across urban cores in Oakland, residents speculated on why their homes had not lost power in the recent de-energization events, while other homes around them had: “The power almost never goes out on this block. And it’s been a mystery. Why? I don’t know, maybe it’s like a hospital. That’s an elder care home [points] and there’s a reservoir. Just up at the top of the hill. Maybe we’re on some magical line that is critical. But all around, we still have power.” Other interviewees noted how outages divided communities, affecting those closer to the WUI and lightly populated areas more than urban cores, and even within hyper-local areas with protected circuits for critical loads like hospitals. These perceptions contributed to a sense of the lack of understanding over outage management, amplifying residents’ impression of vulnerability and dependence on an unreliable system.

Respondents from lower-income zip codes in East Oakland reported

more frequent power outages in their neighborhoods, often attributed to drivers colliding with utility poles or recurrent notifications of infrastructure maintenance from the utility. One interviewee in his late thirties, who had recently relocated from a rented apartment in downtown Oakland to a home he purchased through a low-income assistance program in the East Oakland neighborhood of Fruitvale,⁵ recalled being alarmed at a significant increase in the number of power shutoffs he started experiencing after he moved: “It didn’t feel normal. Because you know, I lived two miles away. And that never happened. [...] You know, it’s not like I moved to a different city. I just like moved two miles away. So I saw I was like this shouldn’t be normal or if this is normal this shouldn’t be normal. It didn’t feel like it was okay [for it] to be normal.” This respondent’s lived experience with power quality and its spatial fluctuations shows the recognition of unequal impacts of power outages across neighborhoods and a sense of frustration with infrastructural inequalities echoed by other interviewees.

Although some respondents noted that certain areas appeared more protected from power loss, concerns about future outages were common among both two-thirds of those who had experienced shutoffs and over half of those who had not (see Fig. 4a). One person living next to a hospital, who’d never lost power expressed that outages were still

⁵ Fruitvale is the area with the highest concentration of Hispanic residents of any neighborhood in Oakland as of 2016 and a poverty rate of 22.5 %, according to the US Census in 2019 [82].

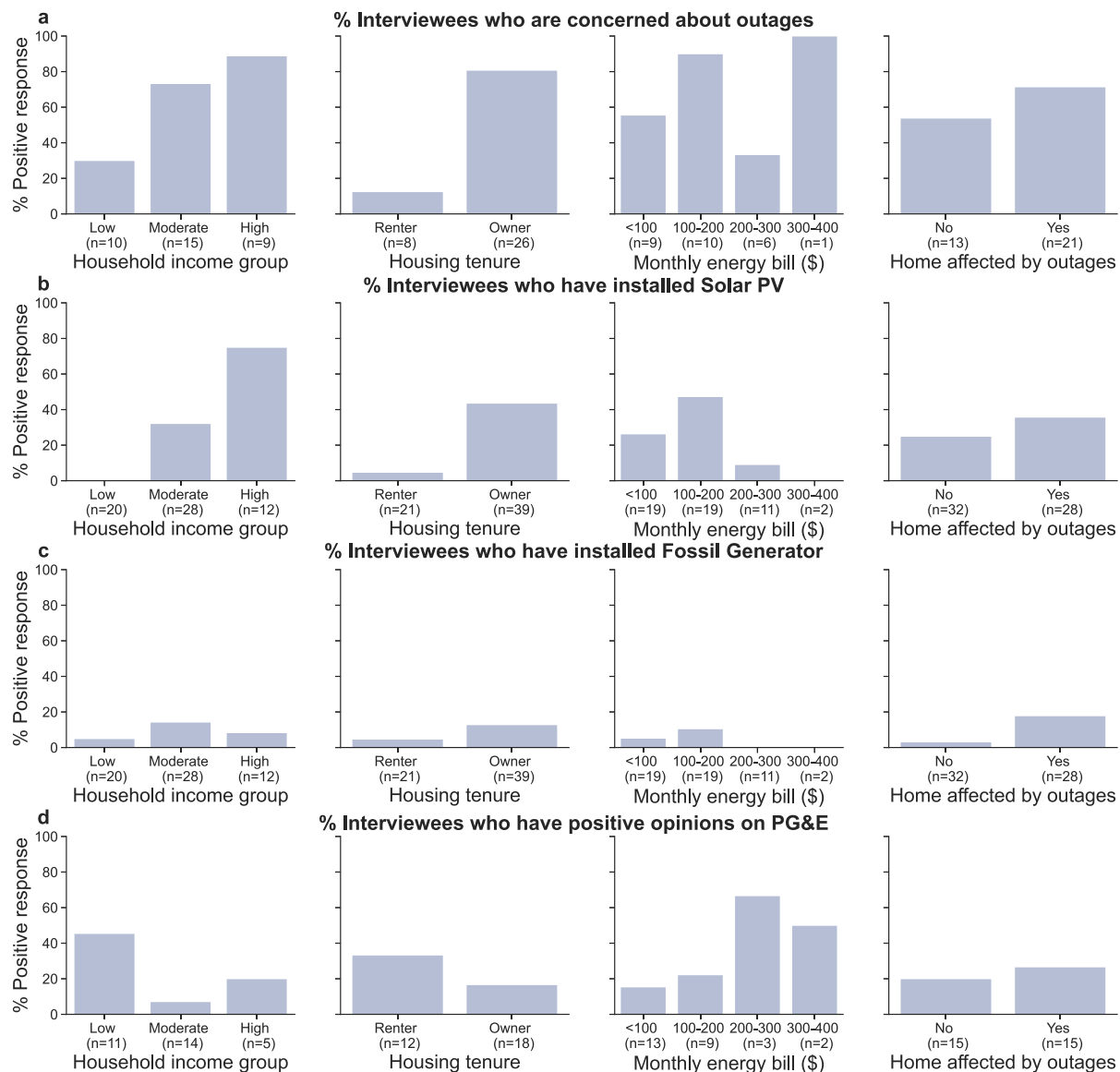


Fig. 4. Comparison of responses to a) prevalence of concerns for outages, b) adoption of residential solar photovoltaics, c) adoption of fossil fuel generator and d) positive opinions of PG&E, across respondents' characteristics. Each subplot displays the number of interviewees who discussed the respective topic.

“something that I’ve thought about and worried about.” As another interviewee who had not been affected by outages put it “just because my electrical has worked well in the past says nothing about the future.” For many others not impacted by safety shutoffs, the hyper-localness of the shutoffs became a source of confusion and played into a broader distrust among East Bay residents about maintaining sustained access to electricity.

4.2. Socio-economic factors condition responses to power loss

The capacity to respond to power outages was shaped by a combination of socio-economic factors, including income, housing tenure, familial responsibilities, and health conditions. These factors influence not only households’ ability to invest in solutions like solar panels or generators but also their willingness to do so. Our interviews explored how these dynamics create unequal opportunities for adopting and benefiting from electricity-intensive technologies, highlighting the interplay between practical constraints, environmental concerns, and the desire for energy resilience.

Socio-economic status and housing tenure significantly influenced

attitudes toward changes to home energy systems and residential energy transitions. Lower-income respondents often faced barriers to adopting renewable technologies, such as limited control over their housing or financial constraints. This group frequently prioritized immediate needs, such as affordable heating or cooling, over long-term climate goals, viewing electrification as an unattainable luxury. For instance, renters faced a “split incentive” scenario [69], where the benefits of investing in energy-efficient appliances were not aligned between tenants and property owners. This misalignment often limited their ability to make changes to their energy systems (“I’m a renter, I can’t afford a home to change all that, so I have very limited power.”) A renter enrolled in a bill assistance plan was dealing with issues like mold, drafty windows, and a broken heating system, but was reluctant to request repairs from her landlord for fear of rent increases, stating, “I kind of hesitate to ask her [the landlord] for stuff so it’s like, it keeps my rent lower if I don’t ask for things.” Given the East Bay’s high cost of rent, this concern about housing security hindered her ability to obtain adequate energy services in her home. This sentiment was common among low-income respondents, who viewed energy efficiency improvements as a risk that could lead to rent increases.

Conversely, (some) higher-income respondents displayed a willingness to invest in electrification to ensure energy independence, opting more frequently for electricity-intensive adaptation measures such as solar photovoltaic (PV) systems (see Fig. 4b). Higher and moderate-income homeowners often cited energy shut-offs as a primary or contributing factor in their decision to install rooftop solar or batteries. One homeowner who had just purchased a home electric battery pack shared, “The solar was first, and we got solar just for the reason to not rely, not 100% reliance on PG&E, like during the summer times we can create our own energy and use our own energy.” Many high-income respondents echoed this desire for energy “independence” and to decentralize power production, especially to ensure their electricity supply in the event of power shut-offs. When asked why she wanted to “get off the grid,” one interviewee responded, “Just so we’re not dependent on PG&E, the PSPS, the power safety shut-off... So we also have a battery as well.” This respondent’s desire for energy independence through home-generated power led her to adopt green technologies. However, for many more households, the high cost of electric batteries and limited familiarity with the technology led them to adopt fossil-fueled generators as a more accessible solution to service disruptions.

Generator adoption, in contrast to solar and batteries, appeared to be less influenced by socio-economic factors (see Fig. 4c). Respondents either considered purchasing generators or observed their neighbors doing so. An interviewee from the affluent Piedmont neighborhood in Oakland, adjacent to a high-risk wildfire area in the WUI, estimated that about a third of her neighbors, including herself, had bought generators. She noted that while the adoption of solar and batteries in her area occurred before the onset of power shutoffs, the acquisition of generators was a more recent development. “Most of the people got their solar and batteries before that whole era of the PSPS. [...] The generators came about definitely and totally as a result of the PSPS. They had never, we had never had any generators until it became like a chronic condition that your power was going off. Yeah, that was... That was new.” Further south in suburban Castro Valley neighborhoods, respondents also noticed this uptick in the use of generators: “We do get a lot of people that have generators here, we hear when the electricity does go off. And like, the whole neighborhood kind of like, you could hear like the zapping noises a couple of years ago, when that happened.” Indeed, the adoption of diesel generators surged in Northern California following the onset of power outages in 2019, with units priced around \$400 selling out at major retailers (see Fig. 5) [70] [71].

Despite their functionality, generators were not without criticism. Some respondents expressed frustration with the noise and emissions,

raising concerns about their contribution to climate change (“Why have this thing contributing to climate change when climate change is the problem?”) and local air quality (“We have like fires, and terrible air, and now we are putting gasoline in all our homes?”). Others, however, viewed generators as a practical response to increasing grid unreliability, particularly during peak electricity demand periods like summer heat waves. For example, a mother in her thirties from Castro Valley shared her decision to purchase a gas generator after a summer outage left her family without cooling:

So I think the idea of gas flowing through the house is never a good thing. Although it is kind of contained to the garage [where the generator is stored], but still it’s not, you know, not great. The electric shutoff thing does really concern us though, because we have had several power outages over the past few years, and especially when it’s like super hot every day, just pumping the ACs and then all of a sudden, we have no power. That happened to us. I think it was last summer [...] It was a really hot day and the baby was supposed to be napping. And we couldn’t even get like any ounce of fan, we couldn’t even get a fan on and so it was just... We were desperate. It was really bad.

This sentiment of prioritizing family well-being by purchasing a generator was shared among those who chose this option. Interviewees who purchased a generator typically reserved it to power what they considered as priority energy uses, including security cameras, cooling devices during heat waves, water pumps in basements or refrigerators to store medications.

Even among environmentally-conscious residents, the perceived necessity of generators and the prohibitive costs of “green” alternatives often outweighed concerns about their environmental impact, underscoring the complex trade-offs households face when balancing energy resilience with climate goals. Residents struggled to navigate what they saw as contradictory imperatives: preparing for more power outages (which they saw as a reason to keep non-electric appliances) and electrifying their household energy demand to comply with climate change mitigation strategies. The social and political push for adopting or transitioning to more electricity-dependent appliances was viewed by many respondents as counterintuitive: “On one hand they are saying that to be more healthy and not create the gases that create climate change we need to move away from that [gas appliances]. But then it’s like a Catch-22, because if you rely on electricity solely, it’s very hard [given disconnections].” While many environmentally-conscious residents supported the

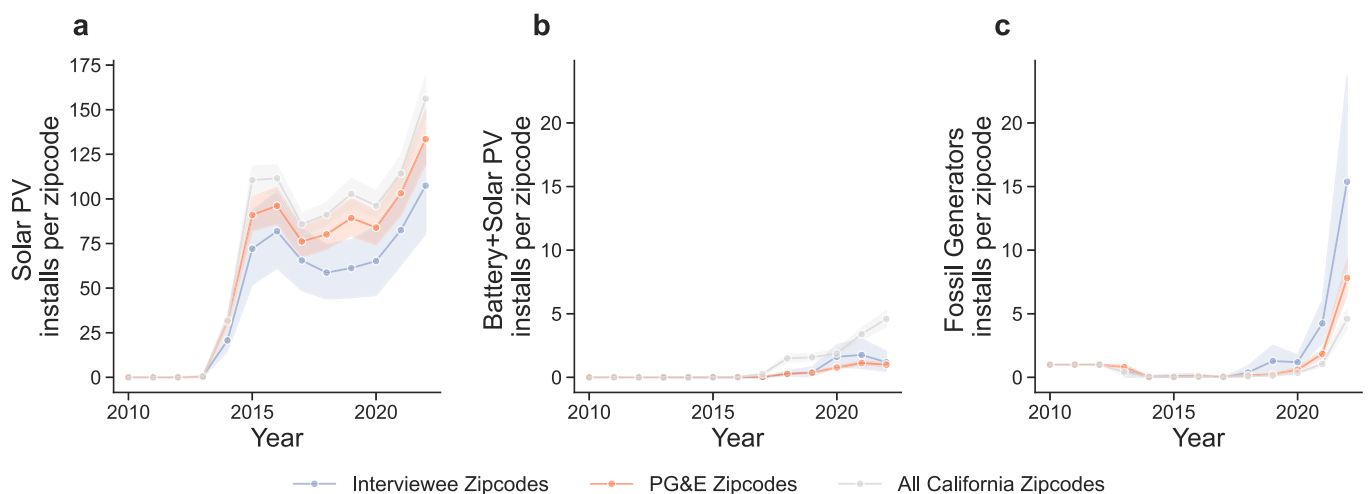


Fig. 5. Trends in the adoption of a) residential rooftop solar photovoltaics (PV), b) residential PV-plus-battery systems and c) fossil fuel generators in California, since 2010. Fossil fuel generator data compiled from the Bay area air district generator licenses database made available by M. Cubed (consulting firm). Battery and solar panel uptake from Lawrence Berkeley national laboratory’s “Solar Demographic’s tracking report” [72].

idea of electrifying their homes and were either obtaining quotes for significant upgrades or considering such changes, respondents overwhelmingly valued building in “redundancy” by having both gas and electric appliances, even those who had rarely experienced power disruptions. A homeowner in her sixties, seeking quotes for installing rooftop solar and a heat pump to help combat climate change, articulated this sentiment: “*One of the things behind my reluctance to give up gas is the idea of going to get redundancy. That if one doesn't work, the other power source does work.*” Echoing this desire for redundancy, a respondent who volunteered with an environmental group at her local church and was a homeowner and landlord had recently installed a gas generator as a backup for her fridge in case of a shutoff. She acknowledged that her choice to purchase a fossil-fueled generator conflicted with her environmental values but deemed it a necessary protective mechanism for future power outages.

4.3. Relations with the electric utility influence decisions about energy transitions

Trust in electric utilities proved to be an important component influencing decisions about energy transitions, with many respondents grappling with whether to remain reliant on centralized actors like PG&E or to pursue self-sufficiency through independent energy solutions. PG&E's reliability was a recurring concern across all income groups, though perceptions of the utility varied significantly. Higher-income respondents cited distrust stemming from PG&E's history of safety failures and infrastructure mismanagement, viewing the utility as an obstacle to further electrification. In contrast, lower-income respondents expressed more ambivalence, appreciating the utility's low-income assistance programs while feeling limited in their ability to explore alternative energy options. These differing perspectives highlight how socio-economic factors generate relational concerns that then shape energy choices and transitions.

The reliability of the East Bay electric utility, PG&E, has become a significant source of concern among residents, influencing their decisions and perspectives on residential electrification. This skepticism about energy users' ability to rely on PG&E for the provision of safe and reliable power is not just due to frequent service shutoffs; some residents recalled the 2010 San Bruno gas pipeline explosion—a catastrophic event resulting in eight deaths and numerous injuries, which led to PG&E's conviction on six felony charges in 2017 [73]. Additionally, respondents mentioned PG&E's role in igniting the 2018 Camp Fire, which devastated the town of Paradise and killed eighty-six people, and marked the first instance of a major utility being charged with homicide [74] [75]. These events underscored the utility's mismanagement issues, leaving infrastructure unmaintained and vulnerable, and deeply eroding trust.

While across all income groups respondents perceived there being “a lot of mismanagement” at PG&E, lower-income respondents had more positive, or at least accommodating, impressions of PG&E (see Fig. 4d). Many low-income interviewees described PG&E's role as an “impossible job” and appreciated how the utility facilitated access to low-income assistance programs for their energy bills. However, these same participants frequently noted their limited options for making energy choices for their homes, typically rented apartments, or adopting solar energy, resigning themselves to a reliance on PG&E: “*we just kind of surrendered to the fact that we are beholden to PG&E.*” Those from low to moderate income brackets often adopted a reformist stance regarding the utility's future role in providing safe and reliable power. Among this group, one respondent, who had bought her home with the help of a mortgage assistance program, acknowledged she would probably have to continue to rely on PG&E for energy services. She expressed a desire to encourage the utility to enhance its role in energy transitions and improve collective well-being, stating: “*The 'both and' exists for anything we are dependent on, we are now committed to this PG&E life. So I would like to continue to see them commit to more renewable energy, create safer neighborhoods*

and living conditions.” This accepting and transformative perspective starkly contrasts with that of higher-income respondents, who were more inclined to envision or actively pursue greater independence from PG&E's services as their expectations of power quality declined.

Distrust among higher-income interviewees often translated into reluctance to adopt technologies requiring utility cooperation, such as electric panel upgrades or EV chargers. Those who expressed interest in electrifying energy end uses or adopting solar panels were apprehensive about PG&E's involvement, fearing they could act as a “bottleneck” or “barrier” to many electrical upgrades, complicating the process or escalating costs. For instance, some worried that upgrading their electrical service panel to support higher electric loads in their home (e.g., for electric vehicles or electric heat pumps) could lead to modifications required by PG&E at the street level, significantly delaying or even stopping projects. According to respondents, with PG&E involved the project's timeline would increase significantly, or the project would have to be halted: “*PG&E will be like, well, we can't upgrade your service from the street because there's not enough electricity running through the infrastructure on your street. So you have to wait.*” Indeed, when interviewees had to deal with PG&E for these very service upgrades they found themselves in complicated bureaucratic processes, and were surprised to realize the costs and limitations of what could be technically done to their service panels (given strained distribution grid capacity limits in their area). One respondent, who was hoping to increase the size of her rooftop solar installation to accommodate an electric vehicle load, found out that her installation could only be sized slightly over her past year's peak power demand (limited to a 10 % increase) which was far below the anticipated demand increase with the adoption of an electric vehicle. She succinctly described her frustration, saying, “*So that was disappointing.*” This discontent contributed to her dislike of the utility, which many residents willing to electrify viewed as uncooperative at best and a deliberately obstructive at worst.

Disparities in perceptions of PG&E across socio-economic groups were also accompanied by complaints of differentiated and unfair treatment by the utility. For example, a man in his early thirties who rented an apartment in East Oakland considered “*PG&E being treated as an insurer of last resort*” for homeowners, “*especially [those more] affluent, whiter and richer*” living in fire prone areas. He expressed frustration with how planned safety shutoffs were implemented, believing that PG&E would overlook neighborhood vulnerabilities other than fire risk: “*Certain neighborhoods in those suburbs, like have the resources and ability to cope way better than poor minority neighborhoods like this.*” Referring to power outages implemented when demand for electricity is higher than supply, such as during a heat wave [76], he believed that higher energy users (which typically correlates with bigger homes and higher income households) should be prioritized for disconnection, claiming that “*it would be deeply inequitable to shut down power grids in like San Francisco or Berkeley or Oakland and not focus on places like Dublin, Pleasanton or Livermore or whatever. Just because the per capita energy use is so much higher [referring to suburban residents' higher energy use].*” In this way, outages revealed pre-existing socioeconomic unevenness and how this worked in and through energy vulnerabilities.

5. Discussion

Mundane experiences of energy use, and the perceptions, preferences and possibilities of changing energy practices as articulated by users, can reveal how electricity unreliability is as much a social as a technological or economic phenomenon. The prospects for household energy transitions depend on all these dimensions of (un)reliability. We find that intermittent outage or shutoff events do not end with the grid going back to “normal” functioning. These events are instead normalized and internalized across consumers, with varying consequences. In the East Bay, fears of power outages spread across neighborhoods where shutoffs affected only some (or even none) of the residents, complicating comparisons of “impact” between areas that suffered shut-offs and those that

did not. Trust in the grid and the utility is thus contingent on factors beyond experiencing disruptions and reflects differences across customers with varying degrees of socioeconomic vulnerabilities.

Our interviews explore social dimensions of grid reliability that remain unaddressed in the technical literature. For example, the categorization of homes as either affected or unaffected by power loss obscures spillover effects, such as the widespread fear of unreliability that our respondents reported. Similarly, reliability metrics such as SAIDI and SAIFI do not account for the diverse psychological, health, and economic impacts across different households. Finally, our findings show that residents predominantly attribute outages to flaws in the utility's management—despite root-cause analyses pointing to weather-related events or technical failures—profoundly shaping their trust in the grid and their willingness to rely on it. In these ways, California's climate strategies—which in turn “rely on California residents [...] to choose zero-emission vehicles and electric appliances for homes” [77]—are undermined by increasing grid unreliability.

Heat, storms and wildfire-induced power shutoffs have conditioned Northern California residents' expectations of electric service, but similar trends are evident across the United States [65] (see Supplementary data S5). In Texas, extreme weather events like Winter Storm Uri in 2021 exposed critical vulnerabilities in the grid, leaving millions without power for days and eroding public trust in utilities. Similarly, Michigan has faced frequent storm-related outages, such as those caused by severe thunderstorms in 2023, which disrupted power for hundreds of thousands and highlighted aging infrastructure failures. In North Carolina, hurricanes like Florence (2018) and Ian (2022) caused widespread blackouts, underscoring the grid's fragility during extreme weather events. In Pennsylvania, the grid has been increasingly strained by heavy snowstorms and ice, such as Winter Storm Jonas (2016) and Winter Storm Riley (2018), which caused prolonged power interruptions and raised concerns over grid resilience.

Grid unreliability has become a more prevalent and shared experience across diverse regions, exacerbated by extreme weather and aging infrastructure. This reliably-occurring unreliability moves energy users along the visibility *continuum* [46]: what was a once rare occurrence becomes part of a new normal, and systems now operate perceptibly—if imperfectly—within newly adjusted expectations of service. Such disruptions also make visible longstanding weaknesses in power systems and the inequities embedded in how disruptions are experienced and mitigated across different communities. In turn, these events catalyze a shift from taking the grid for granted as a facilitator of modern life to acute awareness of its critical role in everyday energy uses. This process is captured by STS scholarship, which has theorized breakdowns as crucial in making infrastructure visible [44,46,49], exposing the inequities embedded in breakdowns that are obfuscated in conventional measures of electric unreliability.

Building on this idea, we posit that the visibility/invisibility of the grid's imperfections—highlighted during outages and shutoffs—also make visible already splintered energy services (c.f. [55]). Thus, power loss can *shine a light* on a grid that has long been splintered, if just beneath the surface, waiting for a collective experience for public discussion. The splintered energy services that emerge during outages (whether through backup generators, batteries, or unevenly distributed resilience technologies) highlight disparities in access to reliable power today and preparedness for disruption in the future. Episodic shutoffs reveal residents' fragmented expectations of energy services and their varying abilities to respond, shaped by socioeconomic inequities deeply rooted in regions like the Bay Area but also applicable to other parts of the U.S. In an already splintered society, power intermittency further divides perceptions and responses to changes in electricity services delivered to homes. Increasingly wary of outages and utility mismanagement, wealthier consumers adopt individual solutions such as batteries or generators. Yet these localized and individualized responses risk perpetuating a cycle of diminishing collective expectations, contributing to “load defection” and underinvestment in the grid. This

shift from understanding sustained power access as a public service to a private product raises critical questions about equity and reliability in future power provision.

As residents adapt to the new reality of their electrical services, they reimagine the grid's, often through technologies that complement or supplant traditional grid functions, altering energy visibilities more broadly [78]. These technologies, once supplemental, are now positioned as substitutes for the “last-mile” electric grid, mobilized in response to growing grid unreliability. The commodification of reliable electric service, articulated through private investments in backup systems, challenges the social contract for high levels of reliability hitherto provided by centralized utilities. This transformation deserves attention in policy and regulatory frameworks to address the evolving landscape of energy equity and reliability, and the prospects for intensified electrification, not just in California but across regions increasingly affected by power disruptions.

Ethical approvals

All participants in this study provided informed consent. The Institutional Review Board at the University of California, Berkeley, granted approval for this study (Protocol ID: 2022-01-14974).

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CRedit authorship contribution statement

Cristina Crespo Montañés: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Isha Ray:** Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Veronica Jacome:** Writing – review & editing, Writing – original draft, Funding acquisition, Formal analysis, 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.apenergy.2025.125497>.

Data availability

The data that has been used is confidential.

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