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ORIGINAL ARTICLE

Modeling and design of solar + storage-powered community resilience hubs across California

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Abstract

Distributed clean, reliable energy resources like solar plus battery storage (solar + storage) can reduce harmful emissions while supporting resilience. Solar + storage-powered resilience hubs provide energy for critical services during disasters while increasing human adaptive capacity year round. We studied where utility rates, local climate, and historical injustice make solar + storage resilience hubs more valuable and more challenging.

We modeled the economic and climate impacts of outfitting candidate hub sites across California with solar + storage for everyday operations and identified designs and costs required to withstand a range of outages considering weather impacts on energy needs and availability. We integrated sociodemographic data to prioritize the siting of resilience hubs, to focus potential policy and funding priorities on regions where solar + storage for resilience hubs is hard or expensive, and where populations are most in need.

We identified almost 20,000 candidate buildings with more than 8 GW of total rooftop solar potential capable of reducing CO_2 emissions by 5 million tons per year while providing energy for community resilience. Hub capacity for one of the most challenging missions—providing emergency shelter during a power outage and smoke event—could have a statewide average lifetime cost of less than \$2000 per seat. We identified regional challenges including insufficient rooftop solar capacity in cities, low sunlight in northern coastal California, and high costs driven by utility rate structures in Sacramento and the Imperial Valley. Results show that rates and net metering rules that incentivize solar + storage during everyday operations decrease resilience costs.

KEYWORDS
Climate justice, community resilience, energy equity, resilience hubs, solar and battery storage

1 | INTRODUCTION

1.1 | Background and rationale

Power outages are increasing in frequency and duration, driven in part by weather extremes caused by climate change (Mukhergee, et al., 2018; Intergovernmental Panel on Climate Change [IPCC], 2022). Distributed clean energy resources like solar and battery storage (solar + storage) can play a role in climate mitigation and adaptation by reducing greenhouse gas emissions and supporting local energy resilience. Until solar + storage or other renewable and resilient energy sources are available for all households, solar + storage at trusted locations in a community can provide resilient power to ensure access to critical services like communication, medical devices, and air conditioning. Such community resilience hubs serve as a resource during and after disasters and help to strengthen human adaptive capacity year round with community-driven programs and resources for gatherings, information sharing, social support services, health services, and training (Baja, 2018). Emergency centers—which do not offer the same wrap-around annual support as resilience hubs—can augment community resilience hubs, providing additional or alternative space and resources in the event of a disruption or disaster.[1] Candidate sites for resilience hubs and emergency centers include known and trusted spaces such as schools, community centers, and places of worship.

Interest in creating resilience hubs is growing, but there is limited research on the opportunities and challenges of equipping these sites with solar + storage to provide resilient power during emergencies. In California, as Public Safety Power Shutoffs (PSPS),[2] wildfires, heat waves, and extreme weather events increasingly trigger outages across the state, the need to support increased community resilience is pressing.

1.2 | Research summary

Here, we model the economic costs, benefits, and greenhouse gas emission reductions of outfitting candidate sites across California with solar + storage optimized for everyday operations. We then identify design modifications and additional costs required for resilient energy production and storage to support critical loads through a range of outage scenarios. Finally, we explore the impact of regional variation in solar irradiance, temperature profiles, and utility rates on design requirements. To analyze the everyday operations and resilience costs and benefits of solar + storage-powered community resilience hubs, we identify potential sites, estimate energy requirements, and design solar + storage for these sites, considering both everyday operations and resilience missions. We explore how utility rate design, including time-of-use (TOU) rates, demand charges, and net-metering rates, affects the financing requirements for these sites. We leave optimization of site selection to serve at-risk, disadvantaged communities for future work, with our results providing key cost and benefit inputs to that optimization function.

We find that solar + storage for everyday operations is often financeable and may not require additional funding, especially where sunshine and utility rates are favorable. Even with plentiful sunshine, however, modifying these designs to create resilient power systems may need additional financial support, incentives, or rate designs from local, state, and federal governments. We capture trends in the financial costs of resilience using the difference between the cost for the solar + storage design to survive an outage (e.g., a resilience scenario) and the solar + storage design for everyday operations. If the economically optimal design in either scenario has a positive net present value (NPV), it likely can be financed and would not require grant funding or other state support beyond loan guarantees. The designs to meet resilience scenarios, especially those of long duration and high critical loads, will have higher initial costs and lower (possibly negative) NPVs. For each site, the difference in cost between the resilience scenario and everyday operations is thus the marginal cost for that level of resilience for the site. Although resilience has value, there is no commonly agreed-upon approach to assigning it an economic value and there are fewer funding mechanisms for resilience-only operations.

Our localized analysis identifies particularly challenging locations where, for example, onsite solar generation has difficulty meeting summer cooling needs or utility rates fail to incentivize resiliency investments. Results indicate that solar input matters such that coastal northern California faces difficult resilience challenges in the rainy winter season and the Imperial Valley in southern California has its biggest challenge when summer heat outpaces rooftop solar input. But in many cases, utility rates matter even more for making resilience affordable, like in Sacramento Municipal Utility District where low demand charges make battery investments not cost-effective, especially during normal operations.

1.3 | Literature review

We review existing literature to understand what resilience hubs are, why they are needed, and what the body of research related to resilient energy and resilience hubs holds.

1.3.1 | Increasing power outage risks

Around the world, power outages—especially those driven by extremes in weather caused by climate catastrophe—are increasing in frequency and duration (Australian Energy Market Operator, 2017; Behnert & Bruckner, 2018; Mukhergee, et al., 2018). These outages disconnect medical devices, air conditioners, air purifiers, and other infrastructure critical for individual and public health. In 2020, the average American household lost power for over eight hours (MacMillan & Englund, 2021). In the last several years, millions of Californians lost power for multiple days, as power grids were shut down during weather in which they could spark wildfires (Murphy, 2019). The most vulnerable people and communities—the elderly, the young, those with underlying health conditions, and communities that have faced systemic disinvestment and environmental injustice—are less resilient to outages, and often lack resources to invest in resilience.

1.3.2 | Resilience hubs

Resilience hubs can serve as community resources during and after disasters, providing support during emergencies as well

[1] For more on resilience hubs, and the differences between them and other emergency centers and shelters, see the Urban Sustainability Directors Network work on resilience hubs: https://www.usdn.org/resilience-hubs.html.

[2] PSPS occur when utilities preemptively turn off power to parts of the grid in areas where wind, weather, and drought conditions increase the risk of fires caused by electric infrastructure.

as strengthening human adaptive capacity year round with community-driven programs and resources including information sharing, social support, and health services (Asian Pacific Environmental Network [APEN], 2020; Baja, 2018). Good resilience hubs should be capable of sustaining operations during a power outage of up to 72 hours and must be built on trust, strong relationships, and communication during everyday operations in order to strengthen communities year round and improve response capacity during emergencies (Baja, 2018). Evacuation shelters and emergency tents set up during disasters that have no programming, coordination, or relationship with the community fail to meet these criteria and therefore also risk failing to identify and serve the community's needs (Raval & Torres, 2021). Emergency centers—which do not offer the same wrap-around annual support as resilience hubs but are known to the community—can augment community resilience hubs, providing additional or alternative space and resources in the event of a disruption or disaster (National Academies of Sciences Engineering and Medicine [NASEM], 2022). Five essential elements of resilience hubs include resilient programming and services, resilient communication, resilient buildings and landscape, resilient power systems, and resilient operations (Baja, 2021). Not all sites will be capable of providing all services, so communities should choose sites with infrastructure that supports their resilience needs. Without planning and resources, sites will face staffing and operating schedule challenges during disruptions, especially when providing services outside of normal operating hours. Having plans in place for these situations could assist potential hubs in assessing what services and functions they can take on, consistent with capabilities, staffing, and infrastructure (Veil & Bishop, 2014).

1.3.3 | Resilience hub candidate sites

Resilience hubs should be chosen and led by the community, and local leaders can leverage almost any trusted site to host the day-to-day and emergency services of a hub (Baja, 2018). We ultimately leave it to communities to select the location and develop the necessary programming, but consistent with existing literature, for this study we considered community centers (including libraries and clubs), schools, and places of worship as potential sites for analysis. Community centers can serve as resilience hubs, especially given their existing local constituencies. Libraries already serve as public community centers, providing internet access and assistance in emergency relief applications and reporting, and some in Oakland, California, are pursuing solar + storage to support resilience missions (Veil & Bishop, 2014; Walton, 2023). A Lawrence Berkeley National Lab report (Barbose & Forrester, 2023) suggests that rooftop solar + storage in places of worship can provide energy for resilience hubs, and can also raise local awareness and acceptance of solar energy in communities where adoption has lagged. Glad Tidings International in Hayward, California, and Stillmeadow Community Fellowship in Baltimore, Maryland, serve as leading examples (Clean Energy States Alliance [CESA], 2022; George et al., 2022; NextCity, 2021). Schools, from elementary through college, can provide different scales of services given the wide range of sizes. However, schools pose challenges for managing student safety if long-term events require ongoing resilience hub services and education functions simultaneously (George et al., 2022). Elementary schools are deeply embedded in their local communities and can offer resources that are often within walking distance of constituents. Secondary schools offer more space but typically cover larger (not necessarily walkable) service areas. Community colleges may be even farther from constituents but often have space that could be reserved for resilience services during disasters. Multiple organizations are considering schools as hubs, but peer-reviewed analyses and reviews of outcomes are lacking (Collective Resilience, 2023; Communities Responding to Extreme Weather [CREW], 2023; Green, 2023).

Other locations not considered in this study include government buildings, stadiums, and armories. These sites face considerable staffing and programming challenges, and comprehensive statewide data sets for them are lacking. If the sites analyzed here cannot provide sufficient space or energy for resilience hub services, either statewide or in particular vulnerable communities, additional site categories may need to be considered.

1.3.4 | Resilient energy for resilience hubs

Although resilient power is only one of five essential elements for resilience hubs, buildings without resilient power will be unable to provide air conditioning, air filtration, charging ports for personal and medical devices, and refrigeration; communications will eventually fail; and other programming and resilience services will be extremely limited during outages. Ciriaco and Wong (2022) note that there is a lack of peer-reviewed research, metrics, and evidence to guide the design and implementation of resilience hubs, including power and energy designs; they begin to address the gaps by studying key transportation needs for resilience hubs. Roode and Martinac (2020) in their case study of resilience hub design and resilient power feasibility in Maui, Hawaii, argue that, consistent with Baja (2018), in addition to providing year-round critical community services, a site should be in good structural condition, located outside of natural hazard zones, and accessible by all members of the community. They identified resilient power design as critical, but the results of detailed resilient power feasibility studies for each of the selected pilot sites in Maui are not available yet (Roode & Martinac, 2020).

To date, power and energy analysis for resilience hubs have been specific to the selected location for the hub, incorporating specific local climate, renewable energy potential, and community resilience needs. The Urban Sustainability Directors Network (USDN) offers resources for designing and planning energy systems for resilience hubs and provides case studies for existing resilience hubs (Oxnam & Baja, 2019). The National Renewable Energy Lab (NREL) provides technical assistance to communities in Minneapolis, Minnesota, as part of the U.S. Department of Energy's Communities Local Energy Action Program (LEAP) (Department of Energy [DOE], 2024).

Fossil and hybrid fossil energy resilience and shortcomings

Hybrid fossil + solar + storage systems may be more economical than solar + storage alone, particularly when high levels of resilience are required (Baja, 2018; Marqusee et al., 2021; Mills, 2021; Murphy et al., 2014). But fuel-based backup has multiple shortcomings. It typically has no value outside of outages, pollutes when in use, and because it is used only during emergencies, it requires regular testing and maintenance—which also produces air pollution—or else tends to fail when needed. Half of poorly maintained generators fail within 48 hours during a long-duration outage, and regular failures of hospital backup generators lead to patient evacuations and rescheduling (CBS News, 2012; Marqusee & Jenket, 2020; Muoio, 2022). Additionally, fuel-based backup requires refueling. Often, during long-duration outages, refueling needs make fuel-based systems less reliable as fuel becomes scarce and fuel stations become inoperable (Mills, 2021).

Finally, and critically, hundreds of Americans die every year from carbon monoxide poisoning. Many poisonings result from improper use of generators, to the point that federal and state emergency managers distribute generator risk information to help prevent such accidents (California Governor's Office of Emergency Services [CalOES], 2023; United States Fire Administration [USFA], 2023). In fact, when Hurricane Laura hit Louisiana and Texas in 2020, carbon monoxide poisoning from generators killed more people than the hurricane itself (Powell & McGuinness, 2020).

Resilient energy equity

Zanocco et al. (2021) show that households experiencing outage events such as PSPS have increased intent to adopt resilient energy, independent of income level. However, despite this desire for in-home energy resilience, income and other factors present barriers to the adoption of home solar + storage. The adoption of distributed solar and storage by households in disadvantaged communities—who face barriers such as low rates of home ownership, lack of access to capital, and poor housing conditions (California Energy Commission [CEC], 2023a)—has lagged that of wealthier and less disadvantaged communities in California (Brown, 2022; Lukanov & Krieger, 2019). Studies have also shown that disparities in grid infrastructure hosting capacity threaten to limit the ability to integrate solar power and electrified household appliances in California's Black-identifying and disadvantaged communities (Brockway et al., 2021). Economic and structural barriers also hinder disadvantaged communities in the adoption of plug-in electric vehicles, which can serve as household energy storage (Canepa et al., 2019; Hsu & Fingerman, 2021).

For certain populations and in certain climates, power outages pose an outsized risk to health and well-being. The elderly and those with chronic health conditions are particularly vulnerable to heat waves, for example, and rely on cooling systems to prevent heat stroke; and those using electrically power medical devices require electricity to run their dialysis machines, respirators, and other essential equipment.

Logan and Guikema (2020) frame community resilience as equitable access to essential services, which can be measured as the travel distance necessary to obtain those services, providing a useful metric for resilience hubs. When resilient energy is not available at home, community-based resilience hubs and emergency centers outfitted with resilient electricity can reduce the distance to key essential services, including refrigeration, ice, communications, and shelter with clean, cool air. Bohman et al. (2022) analyzed community energy resilience for households and tested multiple scales of community energy solutions versus a resilience hub-based energy solution. They demonstrated that focusing on community strategies to serve critical needs during long outages can be 10 to 40 times less expensive than individual household options. This shows that community resilience hubs can serve as a cost-effective method to support community resilience, especially for disadvantaged communities that lack equitable access to essentials like resilient power and may lack acceptable levels of some services year round.

1.3.5 | Resilient energy analysis for resilience hubs

REopt has been demonstrated as a useful tool for evaluating off-grid and on-grid resilience for hospitals (Lagrange et al., 2020), clinics (Chowdhury et al., 2023), offices (Rosales-Asensio et al., 2019), public buildings (Farthing et al., 2021), and critical facilities (Krah, 2021).

But there is a gap in peer-reviewed resilience hub energy research, using REopt or other tools, to support a better understanding of varying utility rates, energy needs, solar availability, and their impact on priorities for resilience hub deployment and funding. NREL's technical assistance results have not been published or peer reviewed and are not geographically diverse (DOE, 2024). Murphy (2022) provided a blog post on the tradeoffs in energy design for resilience hubs, but this has not been peer reviewed and offers only general guidance to potential resilience hub planners. Farthing (2021) used REopt to analyze buildings, including those that might serve as resilience hubs, across 14 U.S. cities in multiple climate regions and utility service areas. However, the results have not been presented for peer review, and the reliance on climate zones for load estimates fails to provide the differentiation between California's microclimates that would be critical for a detailed, California-focused analysis (see Supplementary Appendix A).

TABLE 1 Outage duration ranges from various studies, highlighting minimum, baseline and maximum outage durations.

Reference	0	1	2	3	4	5	6	7	8	9	10	…	17
	Outage durations studied (days)												
Farthing (2021)	0.1	0.6	2										
DOE (2024)			2										
Murphy (2019)	0.1		2				6						
Gorman et al. (2022) model		1		3							10		
Bohman et al. (2022)			2			5					10		
Gorman et al. (2022) data		0.7			4					9		…	17

Outage durations and critical loads

Long-duration outage causes include hurricanes, seasonal storms, wildfires, and recently in California, PSPS. These outages drive the need for resilience hubs. Services necessary during outages then drive the amount of critical load that must be planned for in solar + storage designs.

According to utility reliability reports, the average outage duration for customers served by PG&E was 2 hours and 45 minutes in 2021 (Pacific Gas & Electric [PG&E], 2021), but outages can last much longer. Table 1 shows a range of outage durations analyzed and modeled in various resilience studies. Farthing (2021) modeled public buildings, including resilience hubs, in REopt for bill savings, climate, health, and resilience, with a baseline outage of 15 hours, and sensitivity analysis at 2 hours and 2 days. Communities supported by NREL technical assistance (DOE, 2024) expected resilience hubs to provide support for outages lasting two days. Murphy (2019) analyzed PSPS, which ranged from 2 hours to 6 days, with a mean duration of two days, a 90th percentile outage of four days, and the longest outage lasting six days. Gorman et al. (2022) analyzed 10 major historical events with a minimum of 0.7 days from a 2019 winter storm in Washington, and a maximum of 16.8 days from Hurricane Harvey in Texas in 2017. Recovery times for different customers in each event varied, with the average of minimum durations across the events at 3.8 days, and the average of the maximum durations at nine days. Gorman et al. (2022) used these data to motivate modeling household resilience from solar + storage in REopt with a baseline outage of 3 days and sensitivity analysis ranging from one to 10 days. Although not focused on resilience hubs, Gorman et al.'s (2022) outage durations are consistent with what resilience hubs should be designed toward. Bohman et al. (2022) modeled outages from 2 to 10 days long, focusing on minimum energy needs for households, at different scales of households served.

Given the durations of PSPS and storms analyzed in these studies, two-day outage designs from Farthing (2021) seem insufficient for resilience hubs. To cover a broader range, this study simulates outages between two and eight days.

Resilience hub planning must also consider the services to be provided during outages and how much power and energy they require. Roode and Martinac (2020) describe a resilient power spectrum covering the most resilient systems that provide little or no benefit during everyday operations but offer long-duration backup to critical loads during power outages to the most economic systems that provide environmental and economic benefits with less resilience. In addition to outage duration, how much power and energy must be available during an outage drives system design and defines the level of resilience. Clean Coalition (2020) breaks resilient energy needs into three tiers. Tier 1, about 10% of normal load, describes critical, life-sustaining needs requiring 100% uptime. Tier 2, priority load, considers the next 15%, requiring 80% uptime. Finally, Tier 3 describes the remaining 75% of load as discretionary, with 25% uptime. This serves as a useful guide, but specific needs for resilient energy will vary by community, climate, and mission at various resilience hubs (Baja, 2018). Farthing (2021) assumed that resilience hubs would need to serve 60% of normal load. Community members in Minneapolis desired at least 50% of normal energy needs to be met. Gorman et al. (2022) not only used appliance-level load shapes to determine energy needs for critical household needs but also considered whole-home backup of 100% of critical loads.

The wide range of critical loads induces us to also consider a broad range for analysis and understand the impacts on system designs for both individual sites and for statewide policy and funding requirements.

Value of resilience

REOpt does not have a built-in value of resilience but does include a method to calculate the cost of a lack of resilience by calculating the cost of an unmet load. The dollar value to put on unmet load, or the value of resilience (VoR), is a field of ongoing research, with estimates that range over three orders of magnitude, from less than $1/kWh unserved to more than $60/kWh in residential applications and more than $400/kWh in industrial applications (Gorman, 2022; Woo et al., 2021). Resilience hub critical loads may have an even higher value, given that some of these loads may be for storing expensive, lifesaving medicines for multiple people, and for providing clean, cool air for those who might otherwise die in heat waves or smoke events. Farthing (2021) puts the VoR for resilience hubs at $72/kWh, midway between emergency services ($140/kWh), and noncritical services ($4/kWh).

Ongoing research looks to account for disproportionate impacts of outages in disadvantaged communities, including a project at Lawrence Berkeley National Lab funded by the California Energy Commission titled "Estimating the economic, health, and safety benefits of avoiding long duration power disruptions in disadvantaged communities" (CEC, 2023b). North Carolina A&T and PSE Healthy Energy, funded by The Alfred P. Sloan Foundation, are also working on calculating an equity-adjusted value of lost load to account for the impacts of outages beyond capital costs and lost earnings (Sloan, 2023).

Rather than put a dollar value on these benefits, as they could be different for each resilience hub given differences in community needs, this analysis calculates the additional capital costs required to meet certain resilience levels (duration of outage and percent of normal load served) and the economic value provided in normal operations from systems designed to meet those resilience constraints.

1.3.6 | The research gap and motivation

Our research fills three important gaps in the literature. First, research is lacking in support of state and federal decision-making for where resilience hubs will be needed and where additional financial support may be necessary to support them. Second, we provide a roll-up to estimate potential costs to support resilience hubs statewide, especially for the most vulnerable populations. We focus on climate-vulnerable populations because the intersection of exposure with climate risk combined with a lack of resources to invest in household resilience indicates a need for community solutions. Third, we provide analysis to inform local stakeholders about needs, challenges, and opportunities for resilience hubs in their communities, prior to specific site selection and engagement of technical assistants or consultants.

We therefore focus this research on identifying challenges and opportunities for resilience hub power and energy systems across multiple climates, utility service territories, and building types. California offers a good test case for this analysis, as it provides a variety of climates and utilities to explore. Although resilience hubs should be chosen, developed, and led by the community, this research can help inform communities of risks and opportunities in their region and provide policymakers with tools to prioritize and maximize the benefits of resilience hub funding. Methods extend to other states and internationally but will require some adaptation to account for heating load in colder climates and additional cooling loads in more humid climates.

2 | ANALYTICAL METHODS

To develop inputs to future cost–benefit analyses of resilience hub sites, we identified potential sites, determined the optimal solar + storage designs for everyday operation of these sites, and calculated the additional solar + storage that might be necessary for various needs during different outage scenarios. We identified potential sites from multiple databases and online sources. The economics of everyday operations and resilience operations were modeled using the REopt tool, which optimizes energy costs considering electricity use, resource availability, and tariff structures, and for meeting energy requirements during various outage scenarios (Elgqvist et al., 2017). REopt also provides emission reduction estimates for carbon dioxide (CO_2) and other air pollutants based on hourly, local marginal emissions intensity data from EPA's AVERT model based on the 2020 National Emissions Inventory and projections of emissions from NREL's Cambium model (Anderson et al., 2022). We detail the inputs and methods for site selection and characterization in Section 2.1, modeling for economic operations in Section 2.2, modeling for resilience operations in Section 2.3, interpolating from sampled sites in Section 2.4, estimation of resilience hub capacity in Section 2.5, and comparison of capacity to disadvantaged community populations in Section 2.6.

TABLE 2 Input data for modeling economics and resilience of candidate sites.

Data element	Supporting data element
Location	Latitude, longitude
Load profile	Building category
	Building size (footprint and number of floors)
	Local climate (daily and hourly temperature profiles)
Utility costs	Utility (utility service area)
	Utility rate (building maximum load)
Outage scenario	Outage duration
	Critical load profile

2.1 | Site identification and characteristics

We identified over 18,000 potential resilience hub sites across California. We obtained place of worship and community college data through Open Street Maps inquiries (Open Street Maps [OSM], 2015). We obtained community center data through OSM, the California State Library website database (California State Library, 2022), and the National Shelter System Facilities data set (NSSF, 2019). We found school data from the California State Schools data set and OSM (California Schools, 2019). To model the economic and resilience potential for these sites, we used the input data shown in Table 2, some of which are directly available from the sources listed above (e.g., location by latitude and longitude). Methods of estimation for the remaining input data follow.

2.1.1 | Load profiles

REopt includes built-in energy use (load) profiles for schools, but not for places of worship, community centers, community colleges, or libraries. For these buildings, we developed custom load profiles.

Load profiles for churches (one type of place of worship) are available from the Electric Power Research Institute's (EPRI) Load Shapes Library (EPRI, 2022). Although places of worship from different faiths can have widely varying schedules and peak demand periods, this data set served as a reasonable proxy. Community centers, including libraries, also have widely varying schedules and use cases. We used a load profile for commercial small business, also from EPRI, as a proxy, although this may underestimate energy use on evenings and weekends. We found no examples of typi-

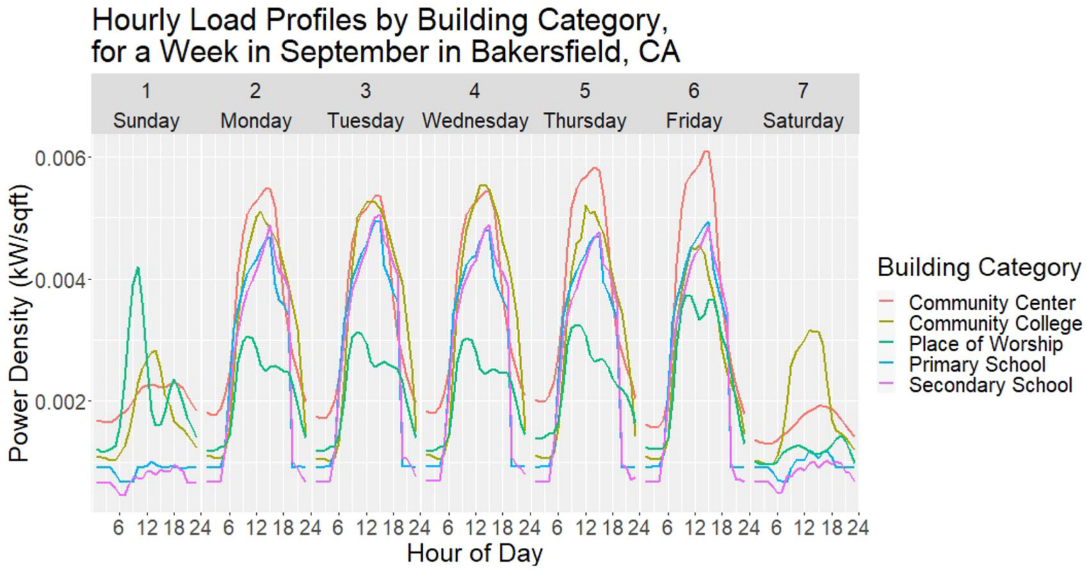

FIGURE 1 Example load profiles for each building category. Load profiles show the average power density (kW per square foot) used in each building type during each hour of the day for a representative week in September in Bakersfield, California.

cal community college load profiles but obtained multiple years of load data for a community college in San Mateo County and used these data as the baseline for the statewide analysis.

We adjusted each building type's load profile to its local climate by calculating the power intensity (kilowatts per square foot) for each building class based on weather data from the nearest of the 400 weather stations across California, overcoming known shortcomings in using only climate zones to differentiate electricity use patterns (Huang & Gurney, 2016; Wang et al., 2016). Details for this method are presented in Supplementary Appendix A, with example load profiles shown in Figure 1. Community centers tend to have the highest energy use per square foot, while places of worship have the lowest, except on Sunday mornings. Community colleges tend to have the latest evening operations, except on Fridays, when they appear to have fewer afternoon and evening classes and events.

To convert the energy intensity per square foot into a building energy load profile, we needed a building area. We calculated the roof area using OSM building footprints and estimated the building floor area from the roof area to account for multi-floor buildings. For this, we sampled 200 schools (124 primary and 76 secondary) and 50 community centers from the combined building data set and estimated the number of floors for each sample building using Google Street View imagery. We then averaged by building class and locale based on the National Center for Education Statistics locale classification (NCES, 2021). Significant differences were observed for community centers, primary schools, and secondary schools if the location was in a city or not (suburban, town, or rural) (Table 3). Buildings that were not found in OSM were assigned the mean building area from that building category.

TABLE 3 Average number of floors for each building class.

Building category	Average number of floors (In a city)	Average number of floors (Not in a city)
Community center	1.2	1.0
Community college	1.0	1.0
Primary school	1.3	1.0
Secondary school	1.4	1.2
Place of worship	1.0	1.0

2.1.2 | Utility costs

Utility rates impact solar + storage adoption. Higher grid electricity prices and higher payback prices from net metering rules (the price paid by the utility for distributed solar sent back to the grid instead of used on site) shorten the payback period for solar installations. Battery adoption increases with higher charges for peak power use, sometimes called capacity or demand charges, especially when those charges are greater than \$15/kW at 2017 battery storage costs. Decreased storage costs have also increased the adoption of batteries for peak power shaving (McLaren et al., 2017). In addition to high peak power charges, high energy costs (especially greater than \$0.40/kWh) combined with low solar sell-back prices during daylight hours (especially below \$0.10/kWh) can incentivize battery adoption (Barbour & González, 2018). We also expect that highly differentiated TOU rates, with evening prices higher than daytime prices and daytime sell-back rates, will incentivize battery adoption. To evaluate the economic value of solar + storage, electric utility rates must therefore be included in the analysis.

TABLE 4 California utilities selected for modeling.

Utility name	Utility abbreviation	Percentage of California customers
Pacific Gas & Electric Co.	PG&E	33
Southern California Edison Co.	SCE	31
San Diego Gas & Electric Co.	SDG&E	9
Sacramento Municipal Utility District	SMUD	9
Los Angeles Department of Water & Power	LADWP	9
Imperial Irrigation District	IID	<1
Modesto Irrigation District	MID	<1
City of Anaheim, California (Utility Company)	COAPUD	<1
City of Riverside, California (Utility Company)	COR	<1
Turlock Irrigation District	TID	<1
Total		**~95**

There are more than 40 electric utilities in California with different rates, rate structures, and net metering rules. These range from large investor-owned utilities, such as Pacific Gas & Electric Company (PG&E) and Southern California Edison (SCE), each with more than half a million commercial customers, to public utilities such as the City of Shasta Lake, serving fewer than 5000 commercial customers. The five largest utilities serve 90% of the customers in California, while no other single utility provider accounts for more than 1% of utility customers (Energy Information Agency [EIA], 2023). We include the five largest utilities and five additional utilities in our analysis to ensure statewide representation, coverage of urban and rural communities, and coverage of disadvantaged communities. Table 4 lists the utilities selected for modeling. Each of the five small utilities selected was chosen because it serves customers in census tracts ranking in the 90th–100th percentile of disadvantaged communities, as noted by California's environmental justice screening tool, CalEnviroScreen 40 (CES, 2021).

We identified specific rates in each utilities' service area from the International Utility Rate Database (URDB, 2023). In each region, we selected active or most recently available commercial rates covering a range of power service levels. Where TOU rates were available, we used these. In regions where TOUs were not available, rates with demand charges were selected. Supplementary Appendix B summarizes the selected utility rates in each utility service area.

2.2 | Economics for everyday operations

To explore the economically optimal solar + storage designs for everyday operations and various outage scenarios, we modeled the candidate buildings in REopt. REopt is a techno-economic decision support model designed to optimize behind-the-meter energy assets whose outputs include optimal system design given input constraints and objectives, economics (system cost, NPV), and environmental metrics (CO_2 and other air pollutant emissions) (Elgqvist et al., 2017). In addition to the site characteristics (load profiles, roof space available, utility rates) outlined above, some additional key inputs for economic analysis include solar and battery costs, rebates and tax incentives, and net metering rules.

We constrained this study to rooftop solar installations. Future work will add on-parcel off-roof potential (e.g., parking lots) and off-parcel (e.g., community microgrid) potential, and we discuss where such expansion might be most valuable in the discussion section.

2.2.1 | Installation and maintenance costs and incentives

Although solar and battery installation costs vary (generally decreasing over time and with installation size), we use constant installed costs with REopt defaults: solar PV costs \$1592/kW with annual maintenance costs of \$17/kW; batteries cost \$775/kW and \$388/kWh for initial installation, with replacement costs of \$440/kW and 220/kWh every 10 years. In addition, Inflation Reduction Act tax credits for solar and battery are 30% (0.3). As they are now applicable to nonprofits, we used this fraction for all sites.

2.2.2 | Net metering rules

We conduct our baseline site analysis under the California Public Utility Commission's (CPUC) 2023 net billing regime (NEM 3.0) but compare outcomes with the previous regime (NEM 2.0). NEM 2.0 featured full retail price net metering, where the price of energy supplied to the grid was equal to the price of purchasing energy from the grid. NEM 3.0 reduces the price paid to distributed generators to a rate that reflects the value of that energy to the grid at the time of export. The value will usually be lower than the retail rate (CPUC, 2023).

The change was made to reduce cost shifting from those with solar to those without solar (CPUC, 2023). The sell-back price for electricity exports under the new net billing tariff will vary based on the utility value of energy at the time of export, with seasonal, daily, and even hourly fluctuation. To put a lower bound on the possible value of exports, we set the price to zero. The as-yet-undefined and likely volatile sell-back prices pose a significant challenge for solar designers; this analytical method provides a conservative estimate of the impacts on solar and storage sizing under this new net billing regime.

2.2.3 | Discount rate

We used a discount rate of 8.1%. REOpt uses this to calculate NPV from the initial cost and utility savings cash flows over the 20-year analysis period.

2.3 | Economics and resilience for outage operations

In addition to economic operations, we model resilience scenarios as a combination of outage duration and resilient energy needs during the outage. We study a range of outage scenarios across the economic-resilience spectrum, considering everyday operation economic optimization with no outages, and also design changes and costs incurred to provide energy for a range of outage durations and various levels of critical load.

2.3.1 | Outage durations

Although most outages are less than three hours, and most long-duration outages caused by extreme weather last less than four days, climate change is likely to increase the frequency, duration, and geographic range of severe weather and associated outages. As such, resilience hub design should reflect the uncertainty in this risk, and so be designed for extreme events; we model outages lasting two, four, and eight days (48, 96, and 192 hours).

2.3.2 | Critical loads

This study explores this spectrum by investigating tradeoffs between economically optimal solutions for everyday operations and various resilience-focused solutions. A challenge for a resilient solar + storage power system occurs when, over the course of an outage, solar energy input is lower than energy needs. For each potential resilience hub location, we combined data from the National Solar Radiation Data Base (NSRDB) (Sengupta et al., 2018) with load profile data for each site and generated a daily average ratio of solar energy versus energy needs for each month of the year. We assumed a solar conversion efficiency of 20%, consistent with current commercially available technology (Clean Energy Reviews, 2023). We also assumed that half of the roof space is available for solar panel installation, as commercial estimates for roof space available prior to detailed site studies assume 50% obstruction and shading (Station A, 2023). However, actual available roof space will vary by building as a function of shading, roof pitch, equipment obstruction, and other factors with regional estimated averages ranging from 22% to 95% (Wiginton et al., 2010).

For any given site, prioritizing energy needs to identify critical loads would be the role of site operators and stakeholders, which is beyond the scope of this work. Here, we estimate critical loads as percentages of normal load. For each site and outage duration, we selected critical load percentages (CLPs) to test how different ratios of solar production affect the site's ability to meet critical loads. If S_m is the daily average solar energy generated in a given month, and L_n is the normal-load daily average energy used in that month, the ratio of load-to-solar is $R_n = L_n/S_m$. To study a range of contingencies, we simulated a broad set of CLPs, with CLP being a scalar constant used to modify the normal load profile such that critical load $L_c = (\text{CLP})*(L_n)$. We select CLPs for each site in order to test a range of critical-load-to-solar ratios (R_c) such that the daily ratio of critical load over solar energy in ($R_c = L_c/S_m$) extends from solar energy providing half of the critical daily energy needs ($R_c = 2$) to solar providing four times the critical daily energy needs ($R_c = 0.25$), with a range of intermediate values also tested. CLPs selected range from 7% (low sunlight, high load) to 800% (high sunlight, low load) of everyday loads. We expected battery size and cost would increase with increasing R_c, and this range allowed us to study the implications on the cost of resilience for each site.

2.3.3 | Outage start times

All simulated outages start at 9 a.m. on the first Tuesday of the month, even though real outages are typically not scheduled. This consistent morning start time allows for comparisons of difficult design cases, as batteries will be at their lowest state of charge after serving nighttime load. We use monthly average load and average solar production to select scenarios and we model sites in REopt using realistic hourly load profiles developed using the methods in Supplementary Appendix A and solar data from the PVWatts database (National Renewable Energy Lab [NREL], 2022). We deterministically choose the first Tuesday of challenging outage months, which could miss the most challenging days in the most challenging month. In future iterations of this work, we will look at different weather events and resulting outages to better characterize design needs consistent with extreme weather events like heat waves and winter storms that coincide with long periods of poor sunlight. This type of reliability analysis is beyond our current scope, as the goal is to identify where there will be challenges in funding resilience, not to

TABLE 5 Key variables included in the statewide analysis.

Variable	Description
NPV	Net present value, the discounted worth of all costs (upfront, operations, maintenance, disposal) and benefits (bill reductions) over the 20-year lifecycle
$NPV_{everyday}$	NPV for the economically optimal design
$NPV_{scenario}$	NPV for the outage scenario design
$\Delta NPV_{resilience}$	Difference in NPV, or the NPV cost of resilience, given by $NPV_{everyday} - NPV_{scenario}$
CLP	Critical load percentage, or fraction of everyday energy deemed necessary for critical missions during an outage
S_m	Daily average solar energy generated for month m
L_{nm}	Daily average energy load for normal everyday operations for month m
L_{cm}	Daily energy load for critical operations for month m (CLP*L_{nm})
R_{nm}	Ratio of daily average energy to solar energy generated for month m (L_{nm}/S_m)
R_{cm}	Ratio of daily critical energy to solar energy generated for month m (L_{cm}/S_m); coincident with R_{nm}
P_{n_annual}	Average annual power, everyday operations
P_{nm}	Average power during the outage month, everyday operations
P_{cm}	Average critical power (P_{nm}*CLP)

calculate exact design parameters for every site for every contingency.

We choose the most challenging months for each site to stress resilience designs. When *net daily energy*—the difference between total daily energy consumed and daily solar production—is positive, the site is using more energy than can be produced by rooftop solar.

Table 5 defines some of the key variables for this analysis. We modeled outages in both the most challenging month at each site, where R_{nm}, the ratio of normal load to solar input, is highest (typically in winter), and the least challenging month at each site, where R_{nm} is lowest (typically in spring or early summer).

2.4 | Interpolating from modeled sites

We modeled a sample of 1097 sites out of the 18,000 potential sites identified. To minimize computation time, we used the modeled results to estimate key outputs for all sites by running a series of regressions on the modeled results and interpolating the results of these regressions back to the full set of potential sites.

We ran a series of linear regressions to characterize the influence of local building load and utility rate on everyday and resilience designs and costs. The key output variables included solar + storage system designs, financial metrics, and emissions reduction metrics. Financial metrics include initial capital costs after incentives (in dollars) and the NPV (in dollars). Emissions reductions were calculated for CO_2, nitrogen oxides (NO_x), and primary fine particulate matter ($PM_{2.5}$).

For the economic base case analysis, we performed regressions against annual average power (P_{n_annual}). Where there were enough sites in each category, utility, and utility rate to develop statistically significant regressions, we did so. For outage durations of 48, 96, and 192 hours, we performed regressions against critical average power during the outage (P_{cm}) for battery and financial variables. For solar installation size and emissions reductions, we continue to use P_{n_annual} as the regression variable. In addition to category, utility, and utility rate, we also grouped models by the critical-load-to-solar ratio (R_{cm}).

Each regression was performed considering a nonzero intercept and a zero intercept, and mean values for each output variable were also calculated. In many cases, we could assume that the regression constant must be zero, because the dependent variable in each regression could be assumed to be zero if average power or average critical power were zero. That is, if power equals zero, then no solar nor battery would be needed, no pollution would be emitted, and no costs would be incurred. In these cases, regression through the origin (constant equals zero) would be appropriate. But in some cases, assuming a zero constant would introduce errors. For example, if solar installation size were limited by regulation under an upper bound (as it is in California). Below this upper boundary, a linear regression through the origin fits best; above this boundary a constant term (the regulated maximum) with zero slope fits best. Textbooks caution against dropping the constant term from regression, but in some cases, as discussed here, regression through the origin is necessary (Eisenhauer, 2003).

From the candidate regressions and mean value models for each sample building set, we selected the model(s) that met significance thresholds of $p \leq 0.05$ for the regression parameter and the constant, as appropriate. If more than one was significant, we selected the model with the lowest standard deviation in the residuals. If multiple candidates still existed, we selected the model with the highest adjusted R-squared value. We then used the selected model to estimate the design, financial, and environmental outputs for all 18,000 sites.

2.5 | Resilience hub capacity

It is important to quantify how many people can be served by a hub simultaneously throughout an outage. We estimate resilience hub capacity, or simultaneous "seats" in two ways, first with an available building space constraint, second with building space and available energy constraints.

If grid power is available and critical services like clean, conditioned air for an emergency shelter are needed, we estimate this capacity by dividing the total square footage by the 70 square feet per person required for a bed and storage space for emergency housing according to the California Building Code (Weinert, 2018). We consider this an upper bound on hub capacity from these buildings, as not every event will require beds and storage space. However, we note that this rough estimate assumes that every room, space, and hallway in the resilience hub is available for emergency use.

We also considered an energy-per-person constraint. We do not have occupancy numbers for places of worship, community centers, or community colleges to determine energy use per occupant. However, we do have enrollment numbers for primary and secondary schools and can use those to estimate everyday operations energy needs at each school per person and use that energy intensity to constrain capacity at nearby locations. Methods are shown in Supplementary Appendix A5.

2.6 | Estimation of hub capacity serving disadvantaged communities

California uses CalEnviroScreen (CES) to identify disadvantaged communities (DACs) and prioritize funding. But CES misses some aspects of vulnerability, and in follow-up work, we will explore vulnerable communities outside of DACs. As an initial proxy, we looked at the overlay of DACs, poverty, and hubs. First, we grouped census tracts by their "approximate location," e.g., by their named city, town, or census-designated place as outlined in the CES data. This avoids falsely identifying census tracts as lacking resilience hub capacity when nearby neighborhoods might have enough hub space to accommodate people in nearby census tracts.

Using CES data, we calculated the total number of low-income residents (less than two times the federal poverty level) in these aggregated locations. To identify the hardest-to-serve communities, we filtered for locations where hub capacity is less than 10% of the low-income population and for locations where the NPV is less than -$1000 per resilience hub seat.

3 | RESULTS AND DISCUSSION

Here we will make observations regarding the optimal solar + storage system sizes for both everyday and resilience operations, and the marginal cost of resilience. We provide a statewide summary of solar + storage potential, estimating the economic benefits, emissions reductions, and costs for various levels of resilience for all potential sites in Section 3.1. We explore geographic differences in resilience capacity and costs driven by the interaction of weather, climate, and building load profiles in Section 3.2. We then examine regional differences in costs driven by utility service area and utility rate in Section 3.3. We briefly explore the impact of California's net metering rules changes on economic solar + storage designs, costs, and benefits in Section 3.4. Finally, we provide some initial insights about effectively building resilience hub capacity in the most vulnerable communities in Section 3.5.

3.1 | Statewide analysis

One of the key goals of this analysis was to characterize effective and affordable resilience, such that solar + storage provides economic and resilience value without incurring untenable cost burdens. To that end, we tested multiple scenarios. Extreme resilience scenarios consist of 192-hour outages and require critical loads higher than normal loads. Hubs resilient to extreme scenarios require large, expensive batteries. Lower resilience scenarios consist of 48-hour outages and require critical loads that are less than 10% of normal. Under these low resilience scenarios, hubs offer limited services during an outage. Somewhere between these extremes are solar + storage designs where the critical loads selected can be met by the solar energy input during the outage and where the batteries do not need to store multiple days of energy for the site.

Figure 2 illustrates the decrease in NPV as critical loads and outage durations increase for an example site (a secondary school near Los Angeles). NPV for this site designed for economic optima with no outages is $1.3 million, or $3 per square foot for the 440,000 square foot building. We see that for low CLPs, NPVs remain high regardless of outage duration. As CLP exceeds 25%, we see NPV trends visibly diverge, with longer durations and higher R_{nm} having lower NPV.

To compare all sites and outage scenarios on a consistent basis, we focused on site designs that provide enough energy to sustain 50% of normal load throughout the outage. Although individual sites may choose smaller or larger resilience investments based on bottoms-up analysis of energy needs, comparing sites statewide at a design point where CLP is equal to 50% allows for a consistent comparison between climate regions, utility service areas, and building categories for reasonably effective resilience.

Statewide potential for rooftop solar + storage designs resilient to CLP-equals-50 is summarized in Table 6. We compare the solar, storage, and emissions reductions for economically optimal solar + storage designed to maximize savings during everyday operations and designed for various outage scenarios.

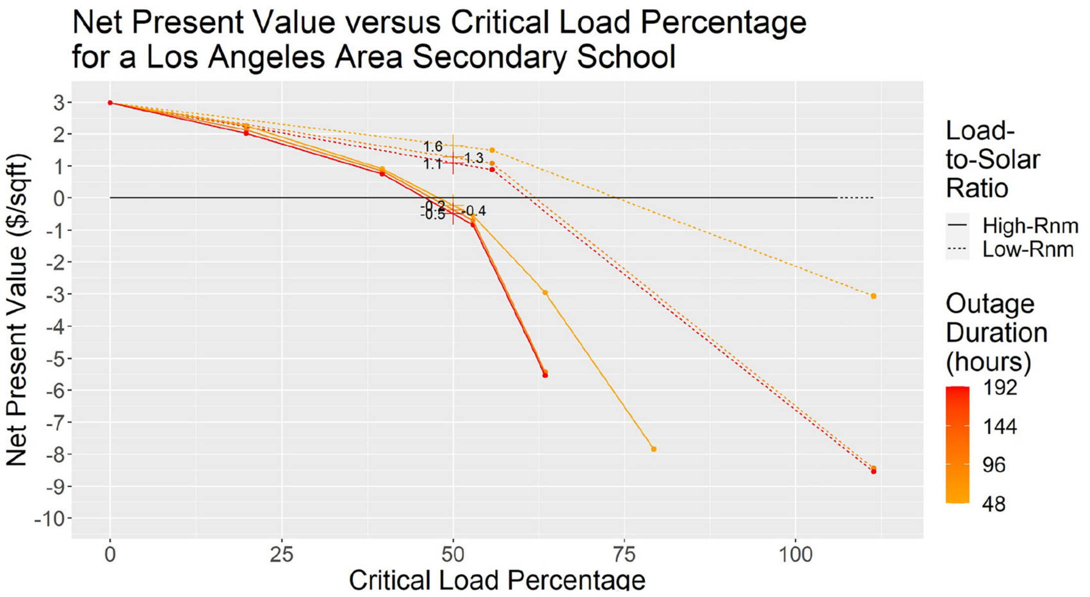

FIGURE 2 An example of NPV versus critical load percentage (CLP) for three outage durations (48, 96, and 192 hours) in low-R_{nm} (July) and high-R_{nm} (January). For each trace, the point at which CLP equals 50 is labeled with the NPV per square foot.

TABLE 6 Statewide summary of solar + storage potential, economic metrics, and environmental impact reduction.

Outage scenario	Everyday operations	Outage in highest-R_{nm} month			Outage in lowest-R_{nm} month		
Outage duration	**No outage**	**48-Hour outage**	**96-Hour outage**	**192-Hour outage**	**48-Hour outage**	**96-Hour outage**	**192-Hour outage**
Total solar (GW)	5.5	8.5	8.7	8.8	6.9	7.3	7.3
Total percent of solar rooftop potential (%)	59%	91%	93%	94%	74%	78%	78%
Total storage power (GW)	1.8	3.5	3.8	3.9	2.6	2.8	2.8
Total storage energy (GWh)	11	32	41	46	19	21	21
CO_2 emissions reduction (M Tons)	3.3	5.2	5.4	5.4	4.2	4.3	4.3
NO_x emissions reduction (tons)	200	360	360	360	280	280	280
$PM_{2.5}$ emissions reduction (tons)	190	290	300	310	240	250	250
Capital costs (after incentives) ($M)	7400	15,000	17,000	18,000	10,000	11,000	11,000
NPV ($M)	6000	2100	−140	−1400	5000	4400	4200
Return on investment (%)	81%	14%	−1%	−8%	50%	40%	38%
Resilience hub area capacity (M people) (% of CA pop)	15.8 (40%)						
Resilience hub mean energy-per-person capacity (M people) (% of CA pop)	NA	3.7 (9%)			2.5 (6%)		

3.1.1 | Total solar + storage for everyday operations and resilience

Solar installation size increases by more than 50% for resilience-optimized scenarios compared with the everyday economic optima; from 59% of total rooftop potential for everyday operations to more than 70% for low-R_{nm} resilience scenarios and more than 90% for high-R_{nm} resilience scenarios.

Battery power requirements also increase, doubling in high-R_{nm} resilience scenarios. Resilience requirements increase battery energy storage size even more, as total energy storage quadruples to meet energy needs for long-duration, high-R_{nm} scenarios. When sunlight cannot meet all of the energy needs, battery size increases with outage duration. For low-R_{nm} scenarios, battery energy size does not increase as much with duration, as solar input meets daily energy needs.

3.1.2 | Emissions

Emissions reductions increase with solar installation size, and so grow from 3.3 million tons of CO_2 per year to more than 5 million tons per year for designs to meet long-duration outages in high R_{nm}. NO_x and $PM_{2.5}$ emissions reductions also increase with solar installation size. Modeled emissions do not increase as storage size grows to provide increased resilience (either duration or CLP), though unless batteries are charged with emissions-free power, emissions may increase with larger storage systems, especially when they are cycled to minimize TOU or demand charges. We will explore this further in future work.

3.1.3 | Total costs for economics and resilience cases

Capital costs presented here include solar and battery incentives, which cover 50% of total costs. Upfront capital costs for the economic optima, without resilience, total \$7.4 billion. The lifetime value, including capital, operations and maintenance costs, energy bill savings, and residual value, comes to \$13.4 billion in 2023 dollars, giving an NPV of \$6 billion and a return on investment (NPV/upfront capital) of 80%. Thus, the total solar + storage for everyday use more than pays for itself with saved utility expenses. More upfront capital is needed to meet resilience needs, mostly for battery energy storage. After incentives, an additional \$3–4 billion is necessary for short outages in lower load-to-solar ratio seasons, with positive return on investments (ROI) ranging from 38% to 50%. In seasons when load-to-solar ratios are high, capital costs increase with outage duration, up to \$18 billion for 8-day outages, which reduces NPVs and ROIs below zero. When NPV and ROI are negative, financing alone cannot support the investment, and grant funding will be necessary.

3.1.4 | Resilience hub capacity

If grid power is available and critical services like clean, cool air for an emergency shelter are needed, the capacity of the candidate resilience hubs analyzed has an estimated upper bound of 15.8 M people (40% of Californians).

Adding energy-per-person constraints turns out to be more restrictive than space constraints. Using local energy per-person during the outage month provides a useful estimate for how many people the CLP-equals-50 design could support with normal lighting, HVAC, and plug loads. Results summarized in Table 6 show that this energy constraint cuts capacity to 3.7 million seats in high-R_{nm} and 2.5 million seats in low-R_{nm} scenarios. Although CLP-equals-50 requires less solar and battery in low-R_{nm}, each person requires more energy, and so CLP-equals-50 supports fewer people.

3.2 | Regional differences in capacity and cost

Regional differences exist across and within building categories driven by differing climates and different cooling loads. Figure 3 shows the critical load-to-solar ratio (R_{cm}) for the most challenging scenarios for each building category, broken out by building type and the season in which R_{nm} is highest. For all categories, Northern California, especially along the coast, has the highest R_{cm}, with CLP-equals-50 loads that are double the solar input in some cases. Community centers, with the highest energy intensity of the building categories, naturally have the highest R_{nm}. Places of worship have the lowest energy intensity, likely due to lower average occupancies, and thus have lower R_{nm} across the state.

Fall and winter contain most of the high-R_{nm} challenges across the state, but inland southeastern California, in Death Valley and Imperial Valley, experience high-R_{nm} in summer when, despite significant sunlight, high temperatures drive up cooling energy needs beyond the capabilities of rooftop solar. For schools, this challenge is somewhat mitigated by lower everyday occupancy and use in summer, but resilience hub needs do not drop off during the summer so further study on this is needed. Fortunately, the R_{cm} at CLP-equals-50 in these regions is near to or less than one, and the rooftop solar constraint should be relatively easy to overcome with ground-mount, parking lot, or other off-roof solar options in these mostly rural areas.

Community centers, primary schools, and secondary schools have more floors in cities than outside of cities (see Section 2.1.1), and for these another R_{nm} pattern emerges (Figure 4a and 4b). Multistory buildings have more floor area per roof area and thus will have more challenging R_{nm}. This can be seen in the higher R_{cm} in the more densely populated regions of the Bay Area, Los Angeles, and cities in the Central Valley as compared with surrounding suburban areas. These areas will have a harder time overcoming low R_{nm} than rural areas, as they are less likely to have real estate available for off-roof solar. Community solar and/or micro-grid solutions may be necessary to increase resilient energy supplies.

Figure 5a presents the resilience cost per seat ($\Delta NPV_{resilience}$) at resilience hubs designed for a 96-hour outage, with capacity constrained by typical energy per person as described in Section 3.1.4. The statewide mean cost per hub seat is \$1,700, but with wide variance across the state, from \$70 in rural San Diego County to more than \$9000 in Imperial Valley. High-R_{cm} remains a key driver, as can be seen by comparing Figure 5a with Figure 4a and 4b, with clear differences in cost in where multistory buildings are common. In cities, the mean cost per seat increases to \$2200, compared with non-cities at \$1300. Even without multiple stories, some rural areas face high-R_{cm} challenges, as can be seen in coastal North-Western California, having R_{cm} greater than 1.5 and resulting seat costs near \$4000. Cities in the Los Angeles and San Diego areas have higher R_{cm} than other surrounding areas, but because insolation is

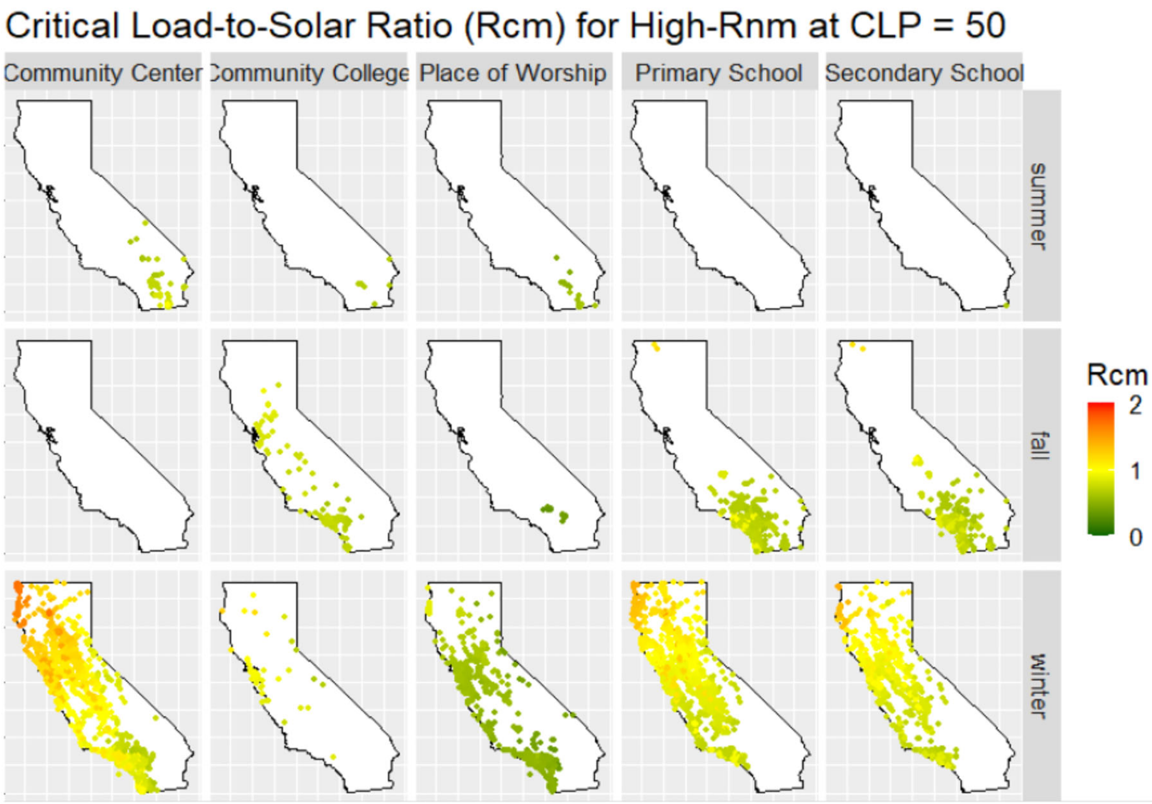

FIGURE 3 Critical load-to-solar ratios (R_{cm}) by building category and season.

good and temperatures are mild, the R_{cm} is still lower than more challenging locations like Central Valley cities and northern coastal California.

Two exceptions are not clearly explained by R_{cm} alone: the Central Valley (especially Sacramento) and the Imperial Valley (far southeastern California). Comparing Figures 5a, 5b, and 4a, these exceptions are explained by the boundaries between different electric utilities.

The Imperial Valley has the most expensive hub seats. Here the correlation between seat costs and the borders of the Imperial Irrigation District (IID) is clear. In addition, most of the sites where high-R_{nm} occur in the summer are in this region, and so outages here have the highest power requirements per person for any of the modeled outages (0.6 kW versus the statewide mean of 0.2 kW).

3.3 | Utilities, rates, and resilience cost

Different utility rates for energy, peak power, and payback for excess solar production cause differences in resilience cost.

From Figure 6 we see that PG&E and SDG&E have the highest NPV for solar + storage in everyday operations. PG&E and SDG&E have high NPV during everyday operations because they have high demand charges and high TOU rates, respectively. PG&E has the highest demand charges of all utility rates modeled, with some rates at nearly \$25/kW. These incentivize batteries for peak shaving and demand charge reduction. Although SDG&E has no demand charges in the rates modeled, it does have rates with evening TOU charges that are higher than daytime charges, incentivizing batteries to store daytime solar energy for use during expensive evening hours. As a result, PG&E and SDG&E have the largest battery sizes for everyday operations, capable of storing 10–12 hours of average load, compared with the other utilities with fewer than eight hours of storage. They also experience the smallest drop in NPV for resilience, with most sites maintaining positive NPV. Sites in other utility territories, with smaller batteries for everyday operations, must acquire significantly more storage for resilient operations, thus incurring higher upfront costs for resilient energy; and once acquired, these batteries have little or no everyday ROI.

IID sites have the next highest NPV in everyday operations, but in the resilience scenario, most sites transition to negative NPV. IID's fixed energy rates (with no TOU differentiation) and fixed net billing rate mean energy storage has no value in everyday operations. Resilience becomes extremely expensive in IID, both due to high energy needs during summer outages and because there is no mechanism for an energy storage investment to recover costs during everyday operations. The fixed net billing rate does make solar pay for itself in everyday operations, so sites in IID maximize their solar capacity.

SMUD has the greatest difference in NPV, with most sites dropping below −\$10/sqft. SMUD has some of the highest

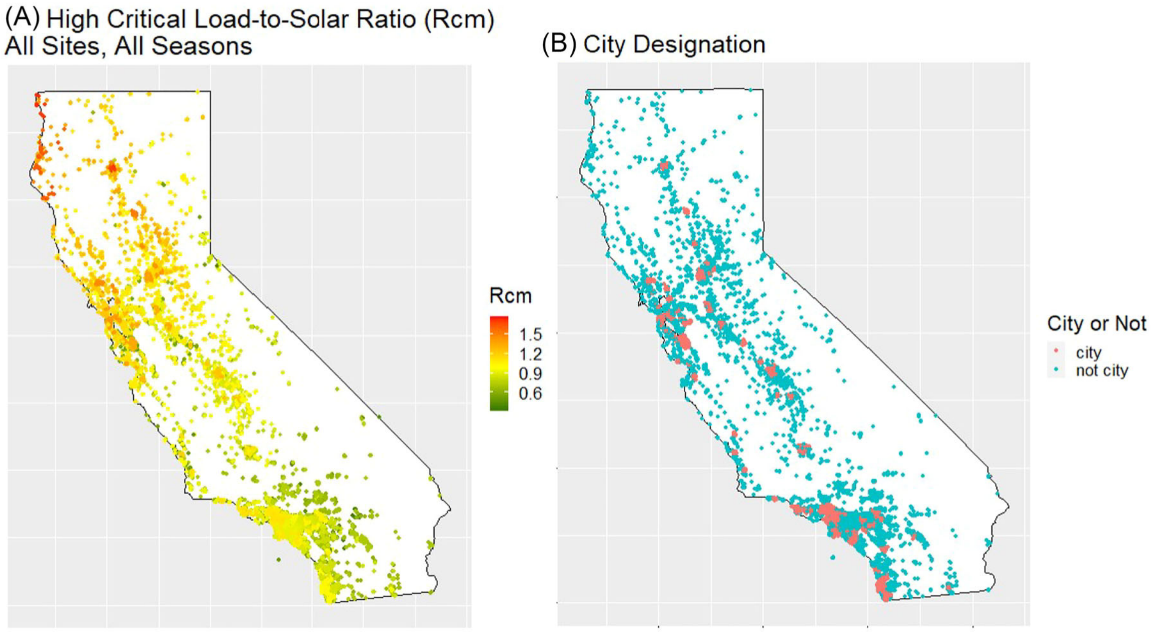

FIGURE 4 (a and b). Critical load-to-solar ratios (R_{cm}) for all sites and seasons (4a) compared with city designation (4b), highlighting the challenge for solar-powered resilience in cities where multistory buildings are more common.

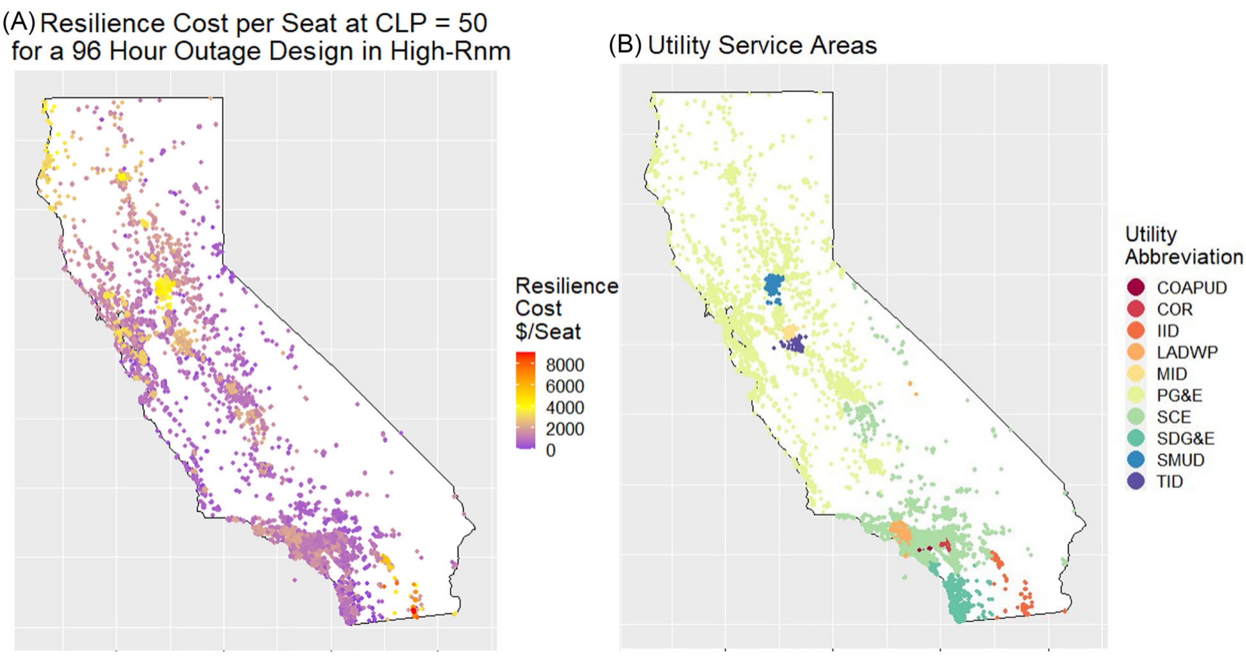

FIGURE 5 (a and b). Resilience hub cost per seat for high-R_{nm} (5a) compared with utility service areas (5b).

TOU rate differentials from mid-afternoon (3 pm) to nighttime (11 pm), with daytime rates being $0.20 higher in some cases. Only SCE has a higher TOU differential, but SCE pairs this with high demand (kW) rates. SMUD's demand charges of $7/kW are not enough to incentivize energy storage. As a result, potential sites in SMUD have the lowest battery storage adoption for everyday operations and high cost of resilience.

The range of NPV for solar + storage is complex. Although demand charges and TOU rates matter, the interaction between such charges and the load profiles for each site, which are a function of the site category and seasonal and daily weather patterns, is difficult to predict *a priori*. This makes tools like REopt invaluable, especially for designs for outage operations, as can be seen in the large variance within a utility service area in outage scenarios.

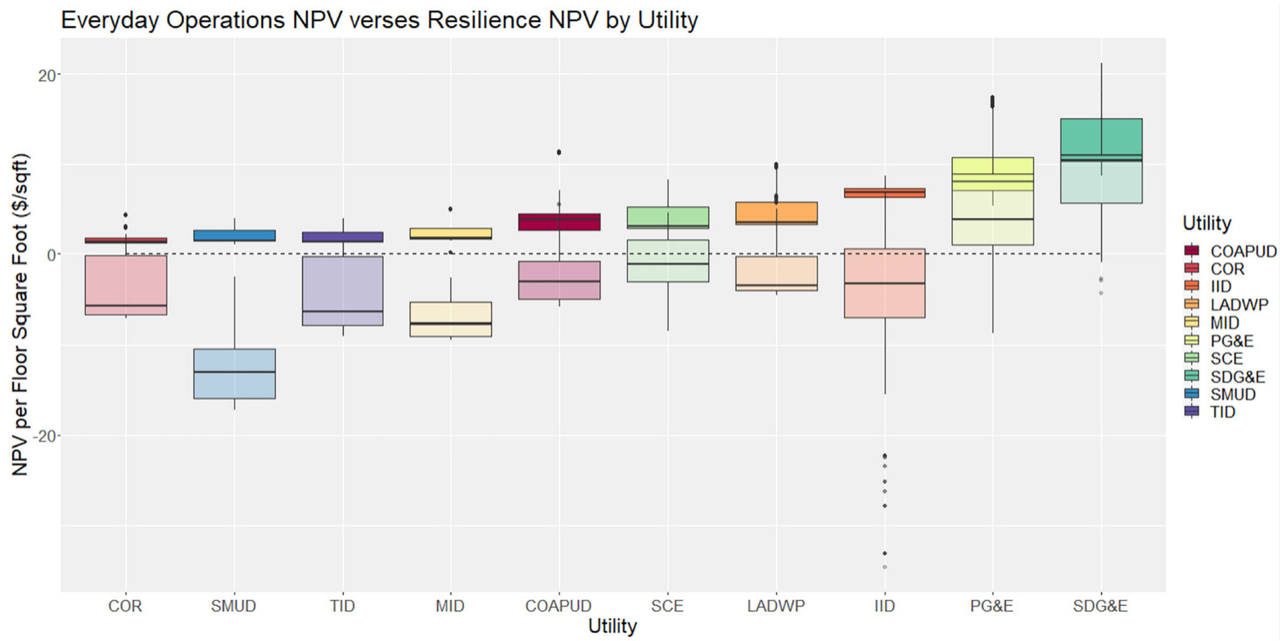

FIGURE 6 Boxplots of the NPV ($/sqft) by utility service area, comparing everyday operations (opaque) to CLP-equals-50, 96-hour resilience designs (semi-transparent).

That said, policies and rates that do not have mechanisms to pay back solar + storage during everyday operations essentially move the cost of solar + storage into the resilience budget. This could be considered a cost shift from battery nonadopters to adopters, as TOU pricing and demand charges are intended to reduce peak energy and power use when that power and energy is expensive to deliver. Utilities and rates that do not implement such charges are then spreading the cost of generation, transmission, and distribution infrastructure to meet these peaks across the entire rate base, regardless of their contribution to the peak demand. Where these costs are not explicit, resilience investments will be more expensive, as batteries will have less value during normal operations and become a strictly a resilience cost rather than a resilience, peak shaving, and TOU shifting investment.

3.4 | Net metering

The bulk of this analysis considered California's 2023 net billing tariff, the regime that will compensate for future solar installations in investor-owned utility (IOU) territories. The 2023 net billing tariff significantly reduces NPV compared with previous net metering rules. Although the total investment and solar + storage system sizes to meet 96-hour CLP-equals-50 scenarios are the same at $13 billion for 8 GW of solar and 30 GWh of battery storage, the economic value is significantly lower. If NEM 2.0 had remained in effect, NPVs at all sites in IOUs would be positive, summing to $7 billion. Instead, under the new net billing tariff, the total NPV is less than $1 billion, with many sites having negative returns on investment. The bottom line for resilience hubs is that the net billing tariff moves more of the solar cost out of the financeable, economically optimal portion of the budget and into the resilience cost. Although the new net billing rules will hypothetically incentivize more investment in battery energy storage, the NPV is limited by the lower and unpredictable value of energy exports.

3.5 | Energy equity and environmental justice

Table 6 showed that total CLP-equals-50 resilience hub capacity across all candidate sites could provide space for 9% of Californians for high-R_{nm} resilience events. Statewide, this indicates there is sufficient capacity to provide resilience hub services to at least the most vulnerable 9% of Californians. Economically and environmentally disadvantaged communities have historically been exposed to more health-damaging pollutants and face higher risk with less resilient infrastructure (Brockway et al., 2021; Nicoletti, et al., 2023). Even if probabilities and risk were equal, poorer communities lack resources to buy or finance self-resilience in the household and therefore face potentially greater consequences from outages, and so experience greater needs for resilience hub services. We will study whether or not the hub capacity found is accessible to the most disadvantaged communities in future work, as the spatial allocation optimization to serve the highest number of people, the highest number of vulnerable people, or the people who are most vulnerable requires additional analysis beyond the scope of this paper. However, we provide an initial analysis of some of the most vulnerable

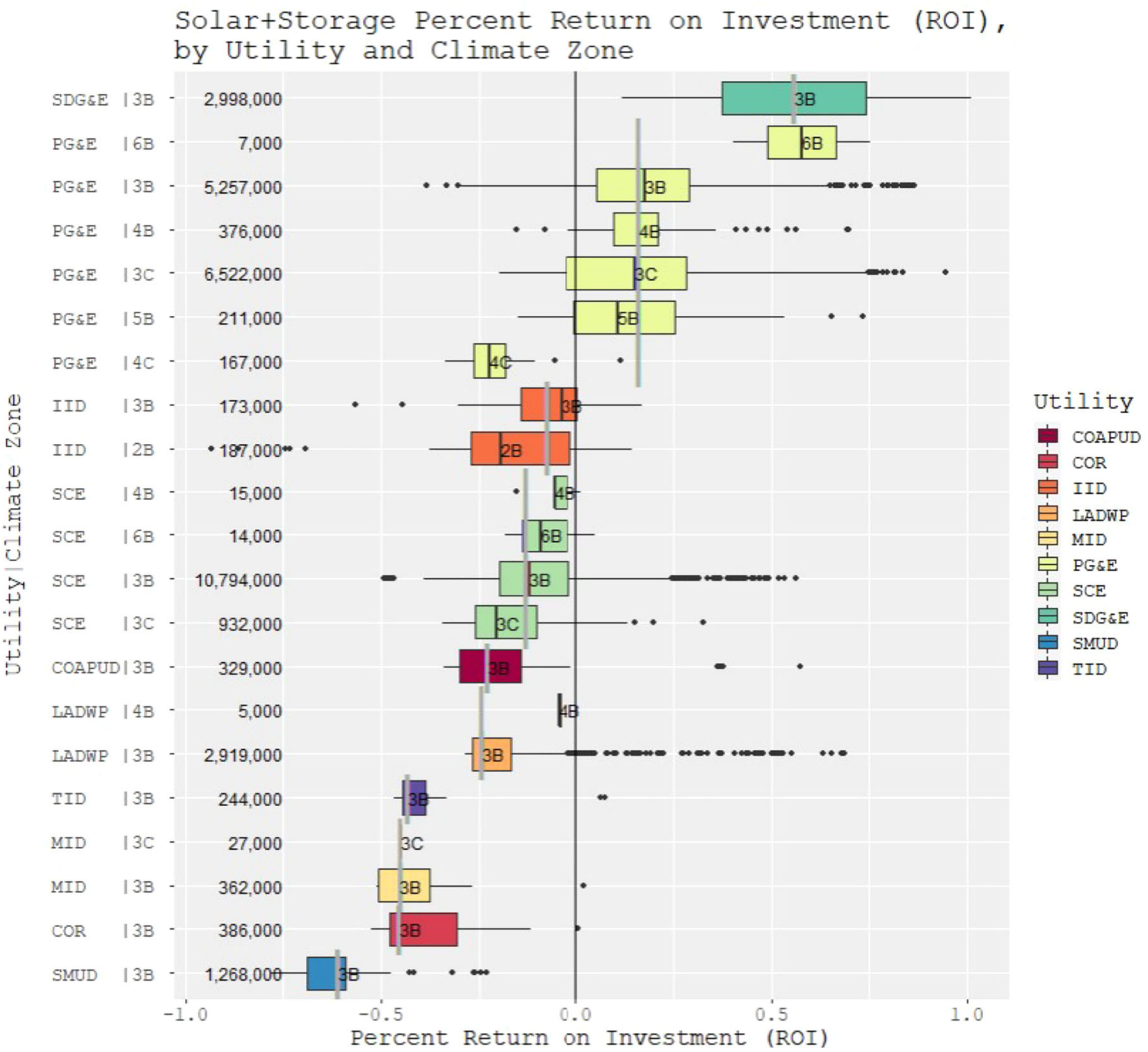

FIGURE 7 Solar + storage ROI compared by utility and climate zone. Boxplots are sorted by median ROI across the utility (gray line across each utility), and then by median ROI in each climate zone for that utility. Population in each utility and climate zone combination is shown next to the y-axis. Climate zones are detailed in Figure 8a, and utility service areas are shown in Figure 8b.

communities and communities with the lowest potential for affordable resilience hubs. Although hubs will be vital across California, resilience needs will be harder to meet where seats are few, costs are high, or ROI is low. Especially where these challenges compound, energy resilience at hubs will require policy change, additional funding, or both.

3.5.1 | Most challenging census tracts

The census tract with the lowest seat capacity (tract 6065044507 in Unincorporated Riverside County and SCE service territory) has space and energy capacity in the candidate sites found for only six people, despite more than 4000 people potentially needing hub services. The tract, though, has a positive NPV per seat at $715 per seat and an ROI of 10%, indicating that if additional candidate hubs could be found, they could be outfitted with solar + storage with loans that could be paid back with utility bill savings.

The census tract with the lowest ROI (tract 6025011803 in El Centro, Imperial County) and IID service territory has space and energy capacity in the candidate sites found for 103 people, almost 9% of the tracts 1166 people living below twice the poverty threshold. But sites in this tract have negative NPV at an average of −$7675 per seat and an ROI of −93%. The energy required to meet cooling needs during summer outages requires large solar + storage installations; combined with utility rates that do not incentivize solar + storage during normal operations, this reduces NPV and illustrates that solar + storage for hubs in this census tract cannot be funded with loans and would require grants to outfit them with resilient energy systems.

3.5.2 | Most challenging regions

Although climate zones were shown to not provide enough resolution for modeling energy use at each potential resilience hub, rolling data back up into climate zones high-

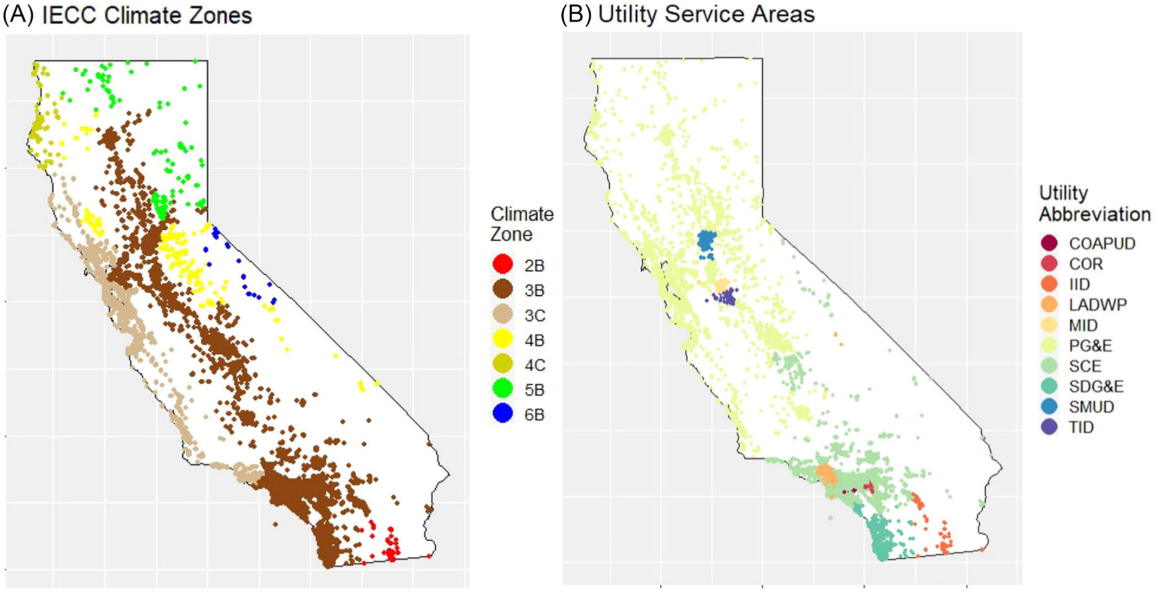

FIGURE 8 (a and b). Candidate resilience hub sites in California, coded to their International Energy Conservation Code (IECC) Climate Zones (7a) and Utility Service Areas (7b).

lights some of the regional challenges. The interactions of the utility service area and climate zone can be observed in Figure 7, which shows boxplots of ROI for solar + storage owners in each utility/climate zone region. ROI is the ratio of NPV to upfront capital costs, and where it is greater than zero indicates a good financial investment, and solar + storage can likely be supported with access to financing rather than grants. Where ROI is negative, grants will be required.

Starting from the top, SDG&E has the highest ROI across the state, where the median ROI across the utility exceeds 0.5, indicating that every dollar invested in solar + storage results in total bill savings of more than $1.50 over the system lifetime. The positive ROI across all of SDG&E indicates solar + storage is cost-effective, which is due to a combination of high utility rates combined with warm, sunny weather year-round.

ROI in PG&E territory is the next highest, earning back about $1.20 for each dollar invested in solar + storage. PG&E territory in climate zone 6B (Lake Tahoe and the Eastern Sierra Mountains) has the highest ROI in the state. Although PG&E rates are not quite as high as SDG&E's, abundant sunlight and mild temperatures make solar very affordable. For the more than 12 million people PG&E service territory in climate zones 3B (Central Valley and Eastern Bay Area), 4B (Coastal Cascade Mountains and Sierra Foothills), 3C (Central Coast and the Bay Area), and 5B (Northern Sierras and Cascade Mountains), median ROIs are all positive. Along with SDG&E territory, positive ROIs cover regions where more than 15 million Californians live and work.

PG&E in climate zone 4C (North Coast) is the first negative ROI shown, illustrating that despite PG&E's high rates supporting solar + storage, the lack of sunlight in this region makes solar + storage less cost-effective.

All remaining utility service areas have negative median ROI, and so will require grant support for solar + storage resilience hubs. Starting with IID in climate zone 3B, despite having the same climate zone as SDG&E, and bordering SDG&E territory, ROI drops to below zero because of IIDs lower electricity rates. ROI drops further in the hottest climate zone in California—2B—where despite plentiful sunlight, temperatures and cooling needs exceed the capacity of rooftop solar, and additional storage is necessary for resilience. However, the rooftop solar limitation should be relatively easy to overcome with ground-mount, parking lot, or other off-roof solar options in these mostly rural areas.

SCE, COAPUD, LADWP, and COR service territories include climate zones 4B and 6B in the Sierras, 3B in greater Los Angeles and in the Southern Central Valley, and 3C along the coast Northwest of Los Angeles. MID, TID, and SMUD all serve customers in climate zone 3B in the Central Valley, all with negative ROI for solar + storage. All of these have negative ROI, driven by utility rates. SMUD has the worst ROI across the state, losing $0.70 per dollar invested in solar + storage, indicating significant portions of funding would have to come from grants.

Note that this analysis did not consider electrical heating loads. The Sierras, Cascades, and the North Coast (climate zones 4B, 4C, 5B, and 6B) do not face electric cooling energy challenges but may eventually have to deal with decarbonized electric heating needs, which will challenge solar + storage resilience in low-sunlight (high-R_{nm}) winters. We defer that for future study.

4 | CONCLUSIONS

4.1 | Policy implications

Our findings inform the development of resilience hubs across California and future work across the country. Notably, we identify the everyday operations benefits of solar + storage, the economic design point for resilience supported by existing rate structures, and the additional cost and benefits associated with the larger solar + storage systems needed for resilience. We find that everyday operations designs are often financeable, and in many regions have high or at least positive NPV and ROI. Resilience designs for CLP-equals-50 illustrate that some regions have specific challenges driven by solar availability (a factor compounded in cities by multistory buildings) and utility rates that fail to incentivize solar + storage in everyday operations.

The actual design of resilience hubs requires input from the local community regarding desired services in normal times and during disasters. These services inform the critical loads necessary when the power is out. Communities also have different levels of risk tolerance that impact local preferences for the duration of outage resilience and cost. Analysis presented here identifies where those requirements may be challenging to meet.

4.1.1 | Rate design

The differences seen between utility service areas illustrate what policies and rate structures disincentivize resilient infrastructure. Utility regulators should ensure that resilience hubs are eligible for rates that increase the value of resilient infrastructure investments without increasing overal l bills.

Utility company costs to meet demand peaks are real. If these costs are not charged to customers explicitly through structures such as demand charges, these costs are amortized across all energy use. As shown, high demand charges incentivize infrastructure that can also help with resilience. Alternative mechanisms could also be designed to value the load flexibility offered by storage.

Similarly, TOU rates with high prices in the evening tend to incentivize solar + storage with larger storage to enable a time shift of energy from solar production hours to evening hours. These rate structures result in a higher NPV and ROI during everyday operations, reduce the amount of solar + storage that must be added for resilience, and reward investment in additional solar + storage for resilience. Utility rate design should not be the primary tool for promoting resilience, in part because rates that tend to incentivize solar + storage also tend to make energy more expensive.

Net metering at retail prices under NEM 2.0 incentivized larger solar during everyday operations and increased NPV. Net billing under the new tariff, with low payback prices, has lower NPV, and reduces optimal solar capacity during everyday operations. Net billing regimes that are transparent, predictable, and have high enough sell-back prices to incentivize maximum solar installation alongside high evening energy costs could further incentivize resilience-friendly solar + storage. In places without such rates, resilient systems will likely require additional funding.

4.1.2 | Challenging locations

Regions and seasons with high load-to-solar ratios (R_{nm}) will be challenging, requiring either more sites or more roof space to provide resilient energy for hubs. Northern California has solar production limitations, especially in winter, but also a relatively temperate climate. As Pless et al. (2018) noted, temperate climates require less solar capacity than very hot or very cold ones. But as heating systems become more electrified, this challenge in Northern California and the Sierra Mountains will become more acute, requiring additional off-roof solar and likely alternative renewable energy technologies beyond solar to meet resilient heating needs in winter.

4.2 | Future work

In addition to the billions of dollars in capacity development, design, building, and operation of resilience hubs to support vulnerable populations, much work remains to ensure equitable and efficient allocation of resources. First, prioritizing the most at-risk and vulnerable populations must take into account historical environmental injustice, varying exposures to pollution and cumulative health risks, and the likelihood of various climate-driven and other disasters. Projecting how climate change will impact the location, frequency, and severity of disasters will also be necessary, especially as increasing temperatures increase energy demand in everyday operations and increase the power and energy requirements for dealing with heat events.

Beyond statewide, regional, and national extensions of these analyses, deeper dives into community-partnered case studies will be necessary to understand key local requirements and challenges. A deeper understanding of energy use profiles in everyday operations and during disaster operations can improve the estimates provided here. Developing bottom-up critical load profiles and identifying power and energy needs per resiliency mission and per person served would improve cost estimates for solar + storage for resiliency planning.

Instrumenting and collecting usage data on existing and in-process resilience hubs will be invaluable for ground truthing and for learning lessons to improve future resilience hubs. A simple but important next step is to analyze where off-roof solar can augment economic value and resilience. This includes off-roof but on-parcel solar, especially in rural areas where space is available or urban and suburban areas where parking lots can be used. Off-parcel generation and storage face additional challenges, but research to overcome the technical and political barriers to multisite microgrids will help overcome the constraints on resilience imposed by lack of roof space.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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