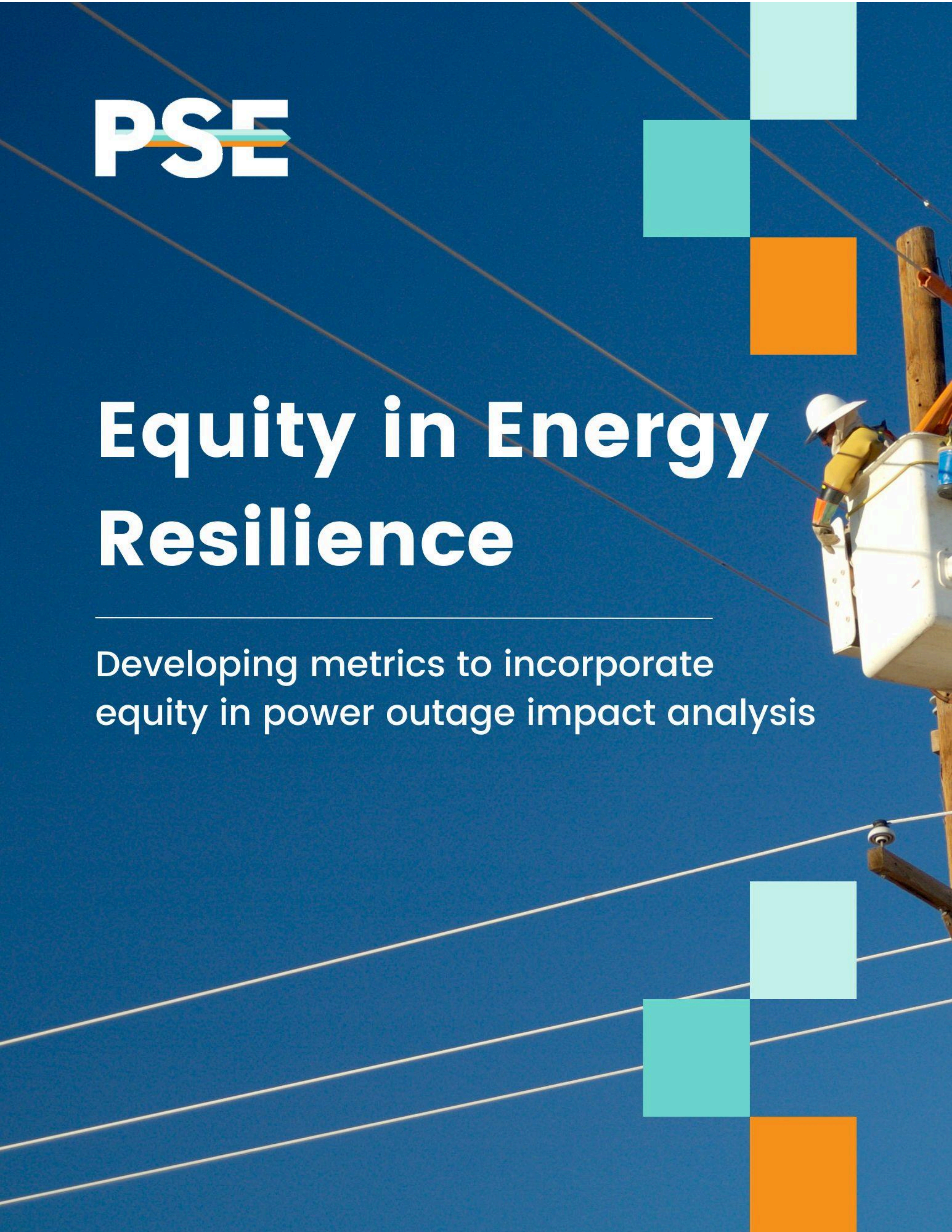


PSE

Equity in Energy Resilience

Developing metrics to incorporate equity in power outage impact analysis

Authors

Patrick Murphy, PhD | PSE Healthy Energy
Bethany Kwoka, MAS | PSE Healthy Energy

Acknowledgements

The authors would like to thank Chabot Community College and Teach Earth Action for their help collecting outage impact data across the Bay Area. The faculty team, including Sean McFarland, Eric Heltzel, and Tom DeWit, were instrumental to this work. But the greatest thanks go to the student leaders, Nayeli Torres Belloso and Cynthia Gucho.

Funding

This work was made possible through funding from the Alfred P. Sloan Foundation.

About PSE Healthy Energy

PSE Healthy Energy (PSE) is a scientific research institute generating energy and climate solutions that protect public health and the environment. PSE provides expertise in public health, environmental science, and engineering and brings science to energy policy through actionable research, communications, and advising. Visit us at psehealthyenergy.org and follow us on X @PhySciEng.

PSE Healthy Energy
1440 Broadway, Suite 750
Oakland, CA 94612
510-330-5550
www.psehealthyenergy.org
info@psehealthyenergy.org

Table of Contents

Introduction

Across California, 4.4 million households face an **energy affordability gap**[1] totalling $4.1 billion dollars, where energy costs in these households are greater than 8.5 percent of their net income. If the costs of dealing with power outages are included, another $900 million dollars in **resilient energy affordability gap** emerges for 4.9 million households. While the energy gap is emerging as an equity and affordability metric for energy policy decision making, considerations of **resilient energy affordability gaps** are so far lacking. Here we provide a method to measure the affordability gap incurred by a lack of resilient energy, using similar methods as those established for energy affordability analyses to account for equity in outage impact analysis.

Project Motivation and Background

Research on the health impacts of power outages, household energy cost burdens, grid inequities, and the connection between natural disasters and poverty traps all highlight the importance of incorporating equity into outage cost calculations. Power outages can cause serious health impacts, particularly for those who rely on electrically-powered medical devices (Casey et al., 2020). Households burdened by high energy costs may be less able to invest in energy resilience solutions, and households in Black-identifying and disadvantaged census tracts face grid infrastructure limitations to installing new solar panels and other energy infrastructure (Brockway et al., 2021).

Existing metrics used to evaluate the impact of power outages on residential households and prioritize investment in electricity reliability consistently underestimate the effects these events have on members of disadvantaged communities. These metrics, including the Value of Lost Load (VoLL) and Customer Interruption Costs (CIC), estimate the economic cost to customers when they experience an outage (NREL, n.d.). However, these estimations are often built using income and property values. This can result in equity gaps, as lost time or damaged property is automatically valued lower in lower income households. These calculations also use willingness to pay and revealed preference methods, both of which fail to appropriately incorporate equity into their measurements.

---

[1] The energy affordability gap quantifies the difference between affordable home energy bills and actual bills (Colton, 2021). The resilient energy affordability gap adds the cost of outages and outage mitigations to the energy cost. Calculation methods are presented below.

Utility investments in reliability and resilience that use these economic cost-benefit approaches are therefore biased towards wealthier neighborhoods. This can, in turn, deepen existing inequities, as the grid may become more reliable in wealthier communities as more investments are made in these neighborhoods. If this metric continues to inform infrastructure investments, low-income households may continue to be more likely to experience outages and the damages they cause.

Newer methods have begun to address this shortcoming by integrating a capabilities approach, which in this case focuses on a household's ability to access critical energy services during an outage.

However, these methods require intensive data collection after disaster events. Updating existing VoLL approaches to incorporate equity using publicly-available data offers a simple but useful metric of potential inequities in outage impacts and energy resilience outcomes. Power outages are increasing in frequency and duration, and these blackouts disproportionately impact disadvantaged communities and communities of color (Do, et al., 2023). This systemic energy injustice risks pushing already disadvantaged, underinvested communities further into poverty, further demonstrating a need for equity-centered VoLL calculations (Su, 2020).

Inequities in Established Outage Cost Calculation Methods

One of the most common metrics for valuing resilience is the Value of Lost Load (VoLL), which describes the costs associated with outages and represents the price consumers would be willing to pay for uninterrupted power. However, this metric is focused on economic measures, primarily reflects outages less than 24 hours, and does not account for how costs may vary over the course of an outage. For example, a short outage has less risk of food spoilage, while a long outage risks compounding costs such as missed work due to lack of childcare and the need to stay at a hotel because of extreme temperatures or medical devices that require power.

Utilities, regulators, and reliability planners also use Interruption Cost Estimates, which estimate outage costs based on outage duration and customer class (e.g., residential, small commercial and industrial customers, or large commercial and industrial customers). This metric uses Customer Damage Functions[2] developed through a series of 'value of service

---

[2] Customer Damage Functions relate average outage costs to outage durations, describing how the costs of an outage vary over time for different scenarios.

reliability studies' that surveyed customers' willingness to pay for uninterrupted power during different hypothetical outage scenarios. However, these estimates rely on data that is sometimes decades old, only consider outages less than a day, and use willingness to pay surveys—the latter of which is subject to some controversy and fails the equity test. (Baik et al., 2018) (Sullivan et al., 2009) Additionally, the documentation for these estimates notes that they are not appropriate for resilience planning. [3]

Focusing on residential impacts, costs to households include:

1. Lost work or leisure time,
2. Property damage,
3. Health and safety effects (e.g., reliance on breathing machines, air filters, mobility devices, etc.) (Munasinghe & Sanghvi, 1988) (Billington & Allan, 2013).

Lost work or leisure time is valued as equivalent to lost wages. Considering lost wages, the median income in the San Francisco Bay area among the bottom 10 percent of wage earners is $15,000 per year. Assuming a full-time work schedule of 2,000 hours per year, a low income household would lose $60 during an 8-hour outage. Comparatively, a top decile wage earner has a median annual income of $534,600, so would lose $2,138—nearly 36 times more—given the same working hours and outage.

Property damage, such as food spoilage or damaged appliances, also correlates with income. For example, a household may lose a week's worth of groceries to spoilage during an eight-hour outage. But while a higher-income household will have spent more money on food, this spending represents a lower percentage of their budget[4] (USDA, 2021). Replacing the lost food is an inconvenience for the wealthy household. For the lower-income household it may be impossible, or lead to cascading negative impacts such as unpaid bills and associated service shut-offs, potentially pushing families deeper into poverty. As a result, including property damage in VoLL calculations further increases the disparity in measured economic value and the impact of outages between households in different economic brackets.

---

[3] Performance metrics for grid resilience have also been developed, which can be used to evaluate utility resilience investments. But these are focused on performance-tracking, rather than proactive planning. See Kallay et al. (2021).

[4] Annual food budget for households in the lowest income quintile in 2021 were $4,875 (30.6 percent of income); in the highest income quintile this increases to an average of $13,973 (7.6 percent of income) (USDA, 2021). The weekly budget estimate is then $93.75 and $268.71, respectively.

Those who rely on electrically-powered medical equipment such as breathing machines and mobility devices, as well as households facing extreme heat and/or bad air quality, face health and safety impacts from outages. The economic cost of these damages can be difficult to quantify, particularly since the U.S. grid has historically been very reliable, making revealed preference data on this scarce. (Gorman, 2022) Additionally, the rise in extreme heat events may have changed some of the health and safety impacts of these events since initial survey data was collected.

While revealed preference and willingness-to-pay survey methods attempt to quantify the value of these impacts, these methods center a household's existing economic situation. Not only is lost time and property damage valued lower in lower-income households, these households are also less likely to have money available to invest in outage mitigation solutions. Both revealed preference and willingness-to-pay survey methods are likely to reflect this inability to pay, rather than the actual cost of an outage for that household (Gorman, 2022). This may be what analyses of solar adoption (Lukanov & Krieger, 2019) and battery storage (Brown, 2022) have seen when they revealed that despite state efforts to encourage solar and battery storage adoption in disadvantaged communities, adoption of these technologies remains higher in higher-income households.

Income- or Equity-Adjusted Outage Cost Calculations Methods

Considering household budgets when making VoLL calculations can address some of the inequities inherent in these metrics. Doing so offers an estimate of outage impact severity—how severely an outage will impact a household, given that household's ability to absorb and bounce back from unexpected economic shocks.

Using the same lost food example from above: A simple, income-adjusted VoLL calculation indicated the total economic losses for this eight-hour outage come to $153, or 53 percent, of the weekly budget for the low-income household and $2,408, or 23 percent, of the weekly budget for the high-income household. Although the losses in the high-income household are nearly sixteen times greater than the lower-income household, the impact as a percent of weekly budget on the low-income household is more than double that of the high-income household.

Methods for addressing the equity concerns in willingness-to-pay methods have been considered for decades. Pearce (1971) developed cost benefit methods to adjust willingness-to-pay measures by the ratio of individual income to average income. Similar methods have been used to adjust climate change damages with damage estimates increasing significantly as compared to alternative methods (Fankhauser et al., 1997). Clark et al. (2023) have developed equity-focused metrics for quantifying the social burden of infrastructure disruptions like outages using the Capabilities Approach combined with costs to obtain certain capabilities like energy, water and food) during disruptions. The costs are based on the Travel Cost Method, essentially determining the fuel, time, and opportunity costs to obtain equivalents of or alternatives for the disrupted capabilities. (Clark et al., 2023) These methods are data intensive, and data collection is still ongoing in Puerto Rico for Hurricane Maria in 2017 (Clark et al., 2022), and Texas Winter Storm Uri in 2021.

Methods and Results

To measure the value of lost load through an equity lens, we adapted accepted energy affordability methods to frame a resilience-focused analysis (**Step One**). We then incorporated outage costs into these updated affordability methods, including some analysis of geospatial distributions of outages and the affordability of outage impacts (**Step Two**). Finally, we assessed the accuracy of our results and underlying assumptions against on-the-ground data from interviews and surveys (**Step Three**).

As with most exploratory analysis, this led to more research questions. We recommend additional study to address these questions and refine the analysis.

Step One: Adapting Affordability Analysis Methods for Resilience

Research and policy that considers energy affordability includes analysis of household energy costs with respect to gross or net income. Various methods and our updates to them are explained below.

Affordability and Equity Metrics

An affordability burden analysis based on gross income is broadly accepted and easy to apply (Colton, 2021) (Sovacool et al., 2024) (Makhijani, 2021). Energy Cost Burden (ECB) is the most widely used metric to identify areas, populations, and households experiencing excessive financial burdens from energy bills. ECB is calculated as the percentage of gross income spent on energy bills at home:

$$ECB \quad = \ (Annual\ Energy\ Bill) \ / \ (Gross\ Annual\ Income)$$

While common and straightforward to use, this metric is also relatively crude as it does not account for differences in disposable income across regions and households within regions. As such, it fails to account for locales with high cost of living, or demographics with high expenditures on housing, food, healthcare, transportation, and/or other essential expenses. We will refer to ECB as the Energy Cost Burden-Gross (ECB-G) to differentiate it from net cost burdens presented below.

The California Public Utilities Commission (CPUC) uses a slightly different ratio, updating Gross Annual Income to account for some of a household's non-negotiable expenses (CPUC, n.d-a). The resulting **Affordability Ratio (AR)** attempts to address the cost-of-living shortcomings of ECB-G by considering other essential home-related expenses. The CPUC calculates and publishes this AR using census data on household characteristics such as regional median income and twentieth percentile income. The CPUC aggregates this data at the geographical scale of Public Use Microdata Areas (PUMAs), census regions that aggregate census tracts into population groupings of no less than 100,000 people (Jain et al., 2021) (US Census Bureau, 2024).

The CPUC's AR is calculated as:

$$\begin{aligned}
&AR \quad = \ Essential\ Services\ Bill \ / \ (Gross\ Income \ - \ Non\ Discretionary\ Expenses)\\
&Where:\\
&\bullet\ Essential\ Services\ Bill \ = \ All\ or\ Selected\ Utility\ Services\\
&\bullet\ Utility\ Services \ = \ Electric\ ,\ Gas,\ Water,\ Communications\\
&\bullet\ Non\ Discretionary\ Expenses \ = \ Housing \ + \ Utility\ Services
\end{aligned}$$

Neither ECB-G nor AR were designed to set targets for policy tools, as they do not assign a directly comparable dollar value. This helps avoid inequities in comparison of wealthier households or regions to poorer households or regions on a dollar-for-dollar basis. However, it means neither metric can directly inform cost-benefit calculations.

To overcome this challenge, the **energy affordability gap (EAG)** assigns a dollar value to unaffordable energy bills by summing energy costs beyond a specified affordability threshold, either at the individual household level or for groups of households. The affordability threshold is typically set at 6 percent of gross income. The 6 percent threshold is derived from combining a 1981 amendment to the 1969 Housing and Urban Development Act—which states that housing costs, including utility bills, should not exceed 30 percent of gross income—with a conventional estimate that energy-related expenses should not exceed 20 percent of housing costs (Colton, 2021).

Importantly, the EAG captures the effects of demand-side investments on a home-by-home basis in a manner that also allows for consistent and simple aggregation of multiple households. For example, if an efficiency measure like weatherization decreases a single cost-burdened household's energy bill (and energy burden) by $500 annually, then this directly reduces the community, county, state, and national EAG by the same $500. However, EAG based on gross income continues to ignore the possible affordability impacts of high rents[5] or other expenses.

Recent, ongoing research merges EAG with AR, using estimates of disposable income, or income after essential expenses, with an adjusted energy affordability threshold. Essential expenses are those that cannot be avoided, such as housing or food costs, and represent the difference between gross income and net disposable income. Depending on what is included in essential expenditures, the energy affordability threshold percentage can shift. For example, if only household expenses (utilities and either rent or mortgage) are included, then the convention that housing costs should not exceed 30 percent of gross income indicates that non-energy housing expenses (either rent or mortgage) should not exceed 24 percent of gross income. This results in an adjusted **energy cost burden-net (ECB-N)** threshold whereby no more than 8.5 percent of income should be spent on energy bills. We can then calculate the **energy affordability gap-net (EAG-N)** as the sum across all households where those costs exceed 8.5 percent of net income after essential expenses including housing, groceries, taxes, transportation, and medical costs.

---

[5] The cost of housing—rent, mortgage, etc.—is particularly salient, as it typically accounts for the largest portion of a household's monthly costs. In California, this is often more than a third of a household's total expenses.

Additional EAG-Ns can consider these essential expenses such that:

$$ECB\text{–}N = \mathit{Annual\ Energy\ Bill} \,/\, (\mathit{Gross\ Income} - \mathit{Essential\ Expenses} + \mathit{Annual\ Energy}$$

$$EAG\text{–}N = \sum_{h}^{households} max(0, X)$$

$Where:$

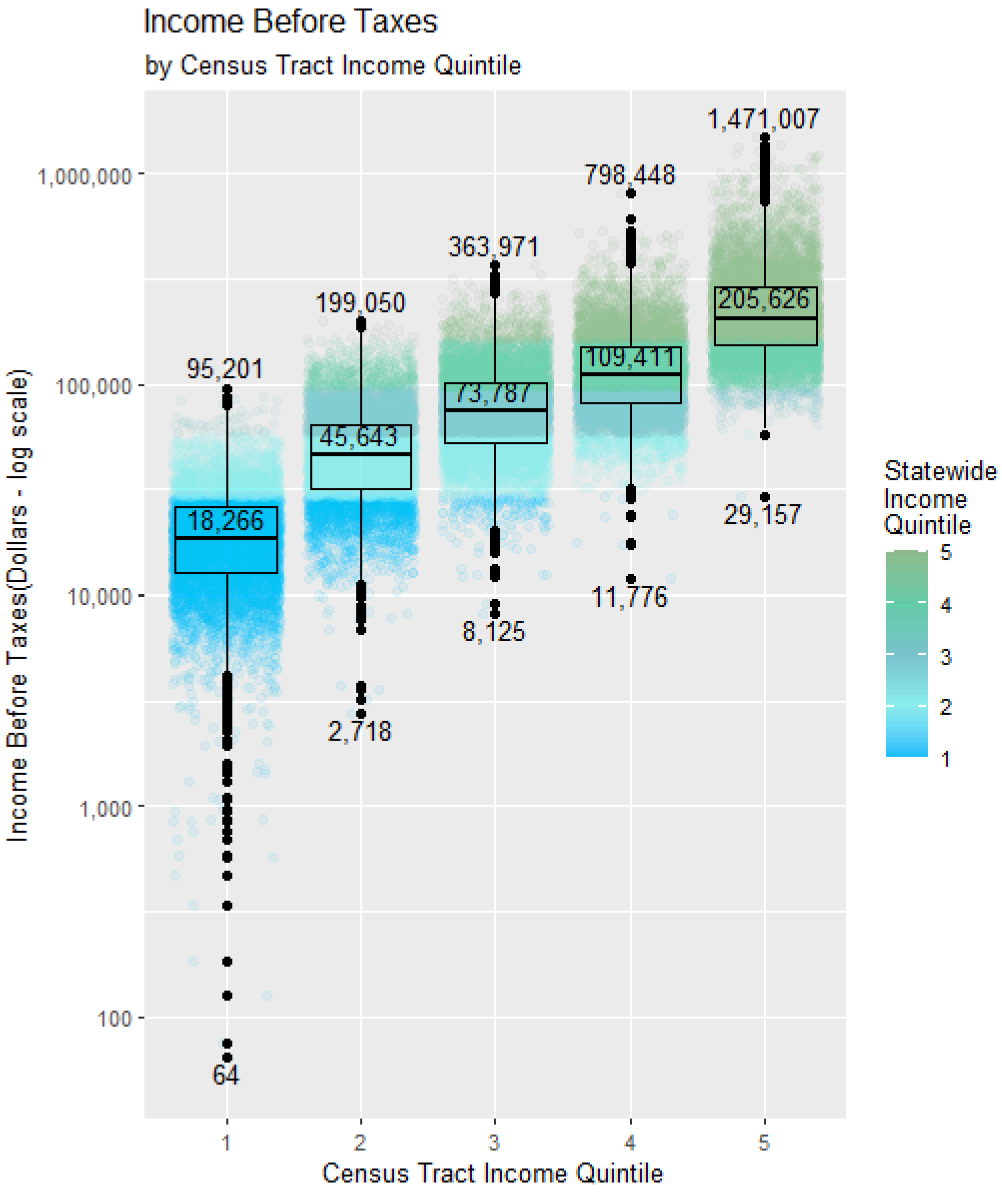
- $X = \mathit{Annual\ Energy\ Bill} - T(\mathit{Gross\ Income} - \mathit{Essential\ Expenses} + \mathit{Annual\ Energy\ Bill}$
- $\mathit{Essential\ Expenses} = housing;\ utilities;\ groceries;\ taxes;\ transportation;\ medical\ exp$
- $T = \mathit{threshold\ percentage}$

The threshold percentage for net energy should be higher than the typical six percent gross energy ratio, as the denominator is now smaller. While the six percent energy threshold for gross income stems from analysis where housing costs (including utilities) should not exceed 30 percent of gross income, the median household in California has a housing burden not including utilities that exceeds this 30 percent and a housing burden with utilities that exceeds 36 percent of gross income (Walker and Herman, 2024). For our analysis, we use a threshold percentage that is less than the median household net energy burden of 8.5 percent of net income after essential expenses.

Income Discussion

Income varies widely across California, both between geographical regions and within census tracts. In its Consumer Expenditure Surveys, the Bureau of Labor Statistics divides households into five income categories, or quintiles. But in California, mean incomes within each census tract quintile range from less than $100 per household per year (in a few census tracts dominated by university housing near CalPoly and the University of Southern California) to almost $1.5 million per household per year (in Atherton, one of the wealthiest communities in the U.S.). Figure A illustrates this, providing the full range of mean household incomes across census tracts. To capture this variation, each point in **Figure A** is a census tract's average household income in that quintile, with boxplots showing median and 25th to 75th percentile ranges. Labels on each boxplot show the maximum, median, and minimum average household income in that quintile. The color scale shows how these households fit into statewide income quintiles. The median household income in each census tract quintile is consistent with the statewide income quintile, but the actual household incomes in various census tract quintiles can vary widely. For example, for a census tract in San Ramon, the average income in the census tract's lowest-income quintile is over $95,000 per year, which is well into the third state-wide quintile. Conversely, a disadvantaged region of Los Angeles has a wealthiest quintile average income of $29,157, indicating the highest income quintile in this census tract is still binned in the lowest-income quintile statewide.

Figure A: Average Household Gross Incomes by Census Tract Quintile. Color scale shows where each household falls in the statewide income quintiles. Average household incomes can vary widely both across the state and within census tracts.



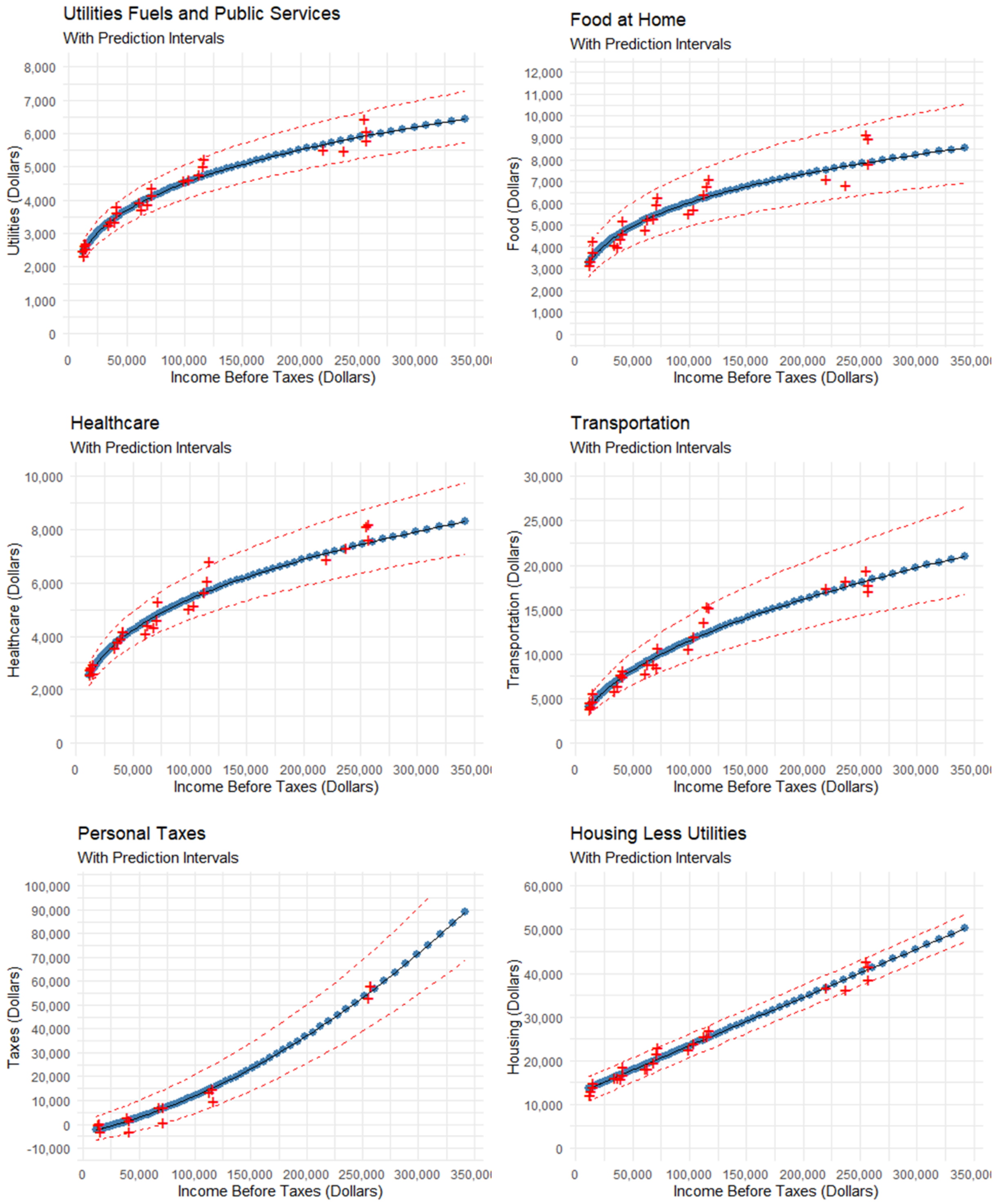
Income and Expenditure Analysis

We performed regression analysis on essential expenses to obtain expenses as a function of household income, using five years of data on California-wide income quintiles from the Bureau of Labor Statistics Consumer Expenditure Surveys (Bureau of Labor Statistics, 2019, 2020, 2021, 2022, 2023). **Figure B** plots prediction and prediction intervals for each component of essential household expenditures, including housing (rent or mortgage), utilities (including public services like trash and water), groceries, healthcare, transportation, and personal taxes.

All models were highly significant, with high coefficients of determination (R^2). All expenses modeled increased with increasing income. However, utilities, food, healthcare, and transportation all increased at a decreasing rate, with non-linear explanatory models. This means that wealthier households may spend more on these essential expenses, but they spend a smaller fraction of their income on essentials overall.

Personal taxes increased at an increasing rate with income, illustrating progressive tax brackets. They do not continue to grow indefinitely, as the highest federal income tax rate is 23 percent and the highest California income tax rate is 13 percent, for a total max tax rate of 36 percent. This rate isn't realized unless incomes are well into the top quintile at more than $500,000 gross income per year. Therefore, this had no impact on more than 90 percent of California households and is of minimal concern for our equity-focused analysis.

Figure B. Prediction and Prediction Interval Plots for Each Component of Essential Household Expenditures.

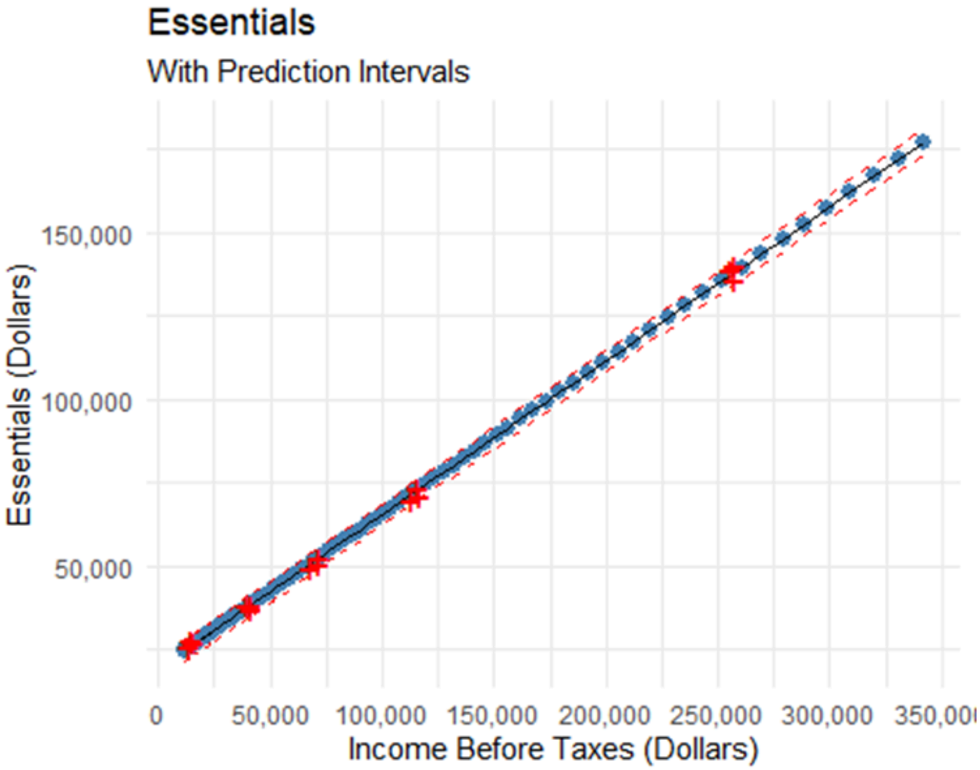


Housing costs increased linearly with increased income, and for most households is the most costly portion of essential expenses. The resulting estimate for housing costs indicated a particular challenge for lower-income households. Housing costs tended to be approximately $12,300 plus eleven percent of gross income per year. This means that a household making less than $13,800 per year would have to spend more than one hundred percent of their gross income on housing, which is clearly untenable. Households making less than $95,000 (which is more than 60 percent of California households) would be considered highly housing burdened by the aforementioned 30 percent threshold, assuming six percent of gross income is spent on utilities.

$$\boxed{Housing\ (rent\ or\ mortgage) \quad = \ (0.111)\ *\ \ (Gross\ Income)\ +\ \$12,300}$$

The combined total of essential expenses tended to be linear with income, as shown in **Figure C**, because housing expenses are linear and are such a large part of the total essential budget, but also because the non-linearities in components tended to cancel each other out in total.

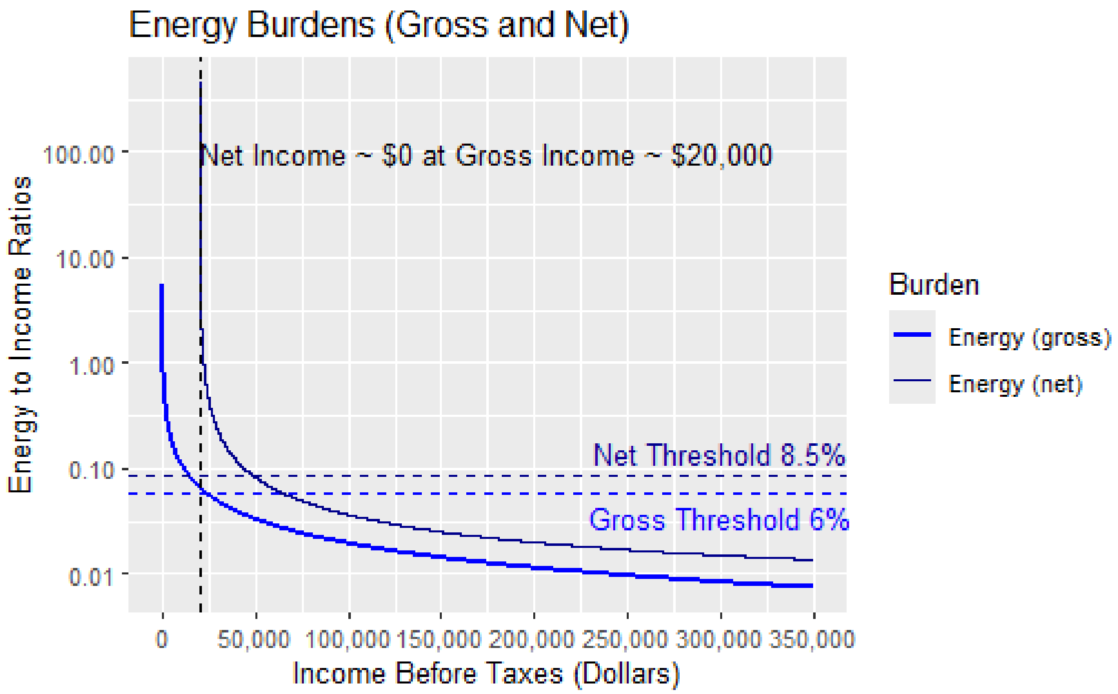
Figure C. Prediction and Prediction Interval for the Sum of Essential Household Expenditures. Despite non-linearities in the components, the sum is essentially linear with gross income. This is largely driven by housing costs, which increase linearly with income.



Using these statewide income regressions, we developed household spending profiles for the average household in each income quintile for each census tract in California. That is, in each of the 8,057 census tracts in California, we used ACS data on the average income in each income quintile for that census tract and the regressions above to estimate typical essential expenditures for each quintile in each census tract (40,285 representative households, five per census tract, one per quintile in each census tract).

We then calculated net income-based energy burden ratios given these essential expenses. The resulting energy burden ratios are shown in **Figure D**. Households with gross incomes below $13,000 per year were highly energy burdened when using the gross income ratio. But the highly burdened category moved to gross incomes of almost $50K per year when using the net income ratio. In fact, below a gross income of $20,000 per year, net income becomes negative after expenses (note the vertical asymptote in the net income ratio at gross incomes approximately $20,000 per year). While housing, energy, food and other support programs for essential expenses exist, we have not yet found data to separate these from BLS spending trends, and reserve detailed analysis on these programs for future work.

Figure D. Comparison of Gross and Net Energy Cost Burdens. ECB-G in bright blue versus ECB-N in dark blue. Highly burdened thresholds for each are also shown at six percent (gross) and 8.5 percent (net).



Step Two: Integrating Outage Costs Into Affordability Analysis Methods

While useful for capturing energy affordability challenges, the energy affordability ratio and energy affordability gap analysis methods outlined so far did not capture the impacts of energy reliability and resilience on affordability. The difference is apparent if we compare two locations with the same ECB-N, but where one experienced no power outages while the other averaged a week-long outage every year. The location that experienced outages has higher costs—the cost of potential damages from the outages and/or the cost to mitigate the impact of outages on the household. As households in that location must bear these costs, they can be integrated into the energy burden and understood as more complete metrics of resilient energy affordability.

To incorporate the cost of a lack of energy resilience into the affordability metrics above, we introduced a resilient energy burden and resilient energy gap: Resilient Energy Cost Burden-Net (RECB-N) and Resilient Energy Affordability Gap-Net (REAG-N).

These are simply the ECB-N and EAG-N with an added factor in the numerator: the cost of experiencing outages. For this analysis we focused on the cost of experiencing outages; future work will compare unmitigated outage costs to various mitigation methods.

Calculating Outage Costs

To calculate these resilience metrics, we used outage costs from a variety of studies and surveys on the topic that include lost income, food, property, and other costs.

We valued lost income such that an hour of income or equivalently valued leisure time is lost for each hour of outage (Gorman, 2022) (Shivakumar et al., 2017). This method has some challenges, including that it does not account for different impacts during different times of day (an outage at midnight might be less impactful than an outage at noon) and it can underestimate impacts on households with no reported income (Gorman, 2022). We mitigated the inequities in income-based outage cost estimates by converting these to burdens as a ratio of income.

Outage damage estimates come from an Argonne National Lab study and include lost food, physical damage to property, and other out of pocket costs including expenses for ice, fireplace fuel, batteries, and meals eaten away from home (Krohm, 1978). The study provides the damages to the average household in 1978, so we adjusted these for inflation from 1978 dollars to 2019 dollars, with a total inflation rate of 479 percent (Bureau of Labor Statistics, 2024).

Table 1. Outage Damage Losses and Inflation Adjustments.

Power Outage Losses and Adjustments			
Loss Category	1978 Value	2019 Value	Percent of household income
	($ 1978)	($ 2019)	(%)
Income losses	1,167	5,588	5.77
Food losses	25	120	0.12
Physical losses	16	74	0.08
Other costs	19	91	0.09
Total	**1,227**	**5,873**	**6.06**

Given that food, property, and other expenses scale with income, we also adjusted the damages relative to income using the values in **Table 1** as the baseline for the average household income. Data for the average California household is shown in **Table 1**.

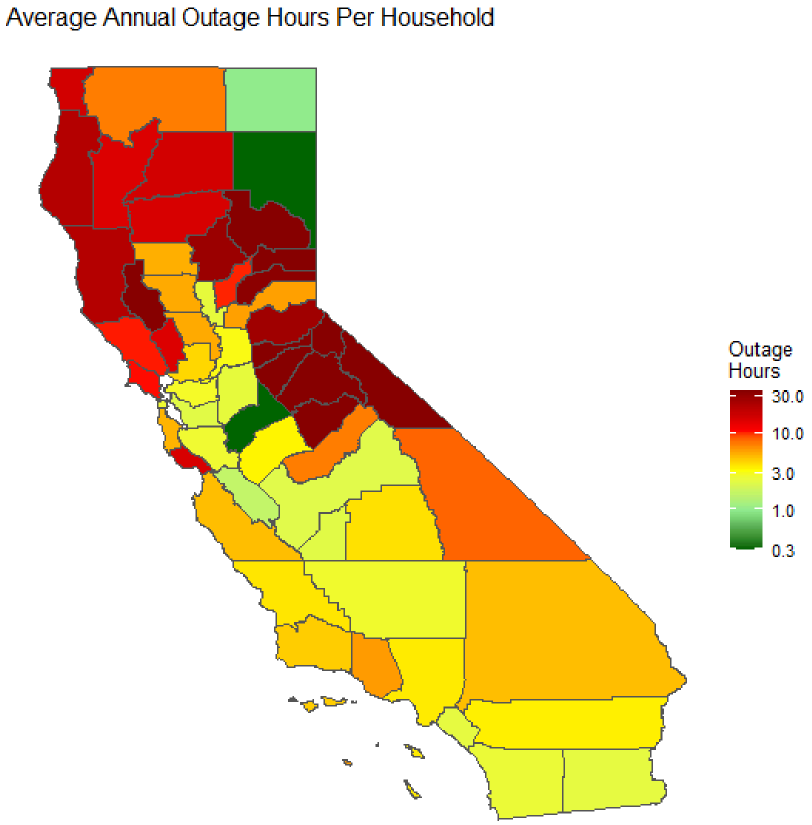
We see that a week-long outage impacting a household at the average statewide income in 2019 ($98,000) would put that household into the highly energy burdened category by the six percent threshold of ECB-G, even without including actual energy costs.

We converted weekly damages to daily and hourly impacts, in order to then multiply these losses by the average annual outage durations in each county, and thus generate the local outage losses. This may overestimate the impact of short outages, as some damages, such as food loss, only occur after refrigerators are left unpowered for several hours. That said, lost income (including lost wages and leisure time) dominated the function, and did not suffer from non-linearities in impact given different outage durations. We will explore nonlinearities in the daily and hourly damage in future work.

We calculated average annual outage damages using outage statistics from the Department of Energy's "Environment for Analysis of Geo-Located Energy Information" (eagle-i) record of electricity outages (Brelsford et al., 2023). Outage instances from this data set, with locational precision at the county level and covering 2014-2024, were converted to average number of outage hours per year in each county in California. Using the damage functions developed above, the outage durations were used to estimate average annual outage impacts in each county.

As shown in **Figure E**, county-level average outage hours range from less than one hour to more than 30 hours per year, with most of the highest annual outage hours associated with the forested areas of the mountain ranges including the Sierra Nevada Range (central eastern California), Cascade Range (north central), Klamath Mountains (north central), and the Coastal Range. The strikingly low outage totals in Modoc and Lassen Counties in the northeast and Stanislaus County in the Central Valley may be more explained by local municipal and co-op utility data availability for eagle-i than by actual outage statistics. This bears further study.

Figure E. County Outage Statistics from DOE's Environment for Analysis of Geo-Located Energy Information (eagle-i) data set (Brelsford et al., 2023). Mountainous, forested areas in California typically had the highest annual outage hours.



From the outage data, we then calculated the total energy and outage damage ratios, or the **Resilient Energy Cost Burden-Net (RECB-N)**, for each quintile in each census tract. These are shown in **Figure F**. This added damages from outages to the data from **Figure D**. The result is that households that were already cost burdened become even more so, and many households that were below the 8.5 percent net threshold were moved above it and would be considered highly (resilient) energy burdened. Households with negative net income must also be considered energy burdened and resilient energy burdened, as the affordability gap for these households was greater than their energy spend and outage damages.

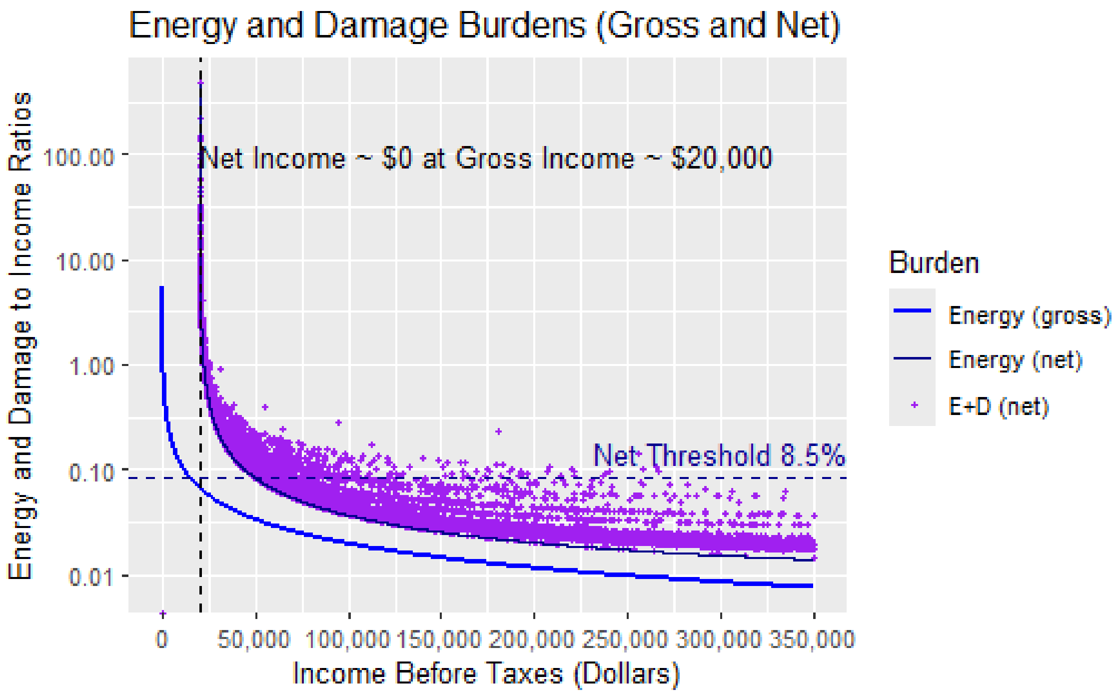


Figure F. Outage Costs Added to Energy Costs to Show the Net Energy and Damage Cost Burden or RECB-N. Many households that were below the burdened threshold without including outage impacts would now be considered highly burdened.

Overview of Results

Statewide Summary

High energy cost burdens are a widespread and long-term problem for low-income communities. From 2017 surveys, nearly a third of U.S. households struggle to pay their utility bills, and 14 percent have received a disconnection notice (EIA, 2018). Estimation of energy cost burden as a function of gross income (ECB-G) has been the most widely used metric to identify areas and populations experiencing undue financial burden from energy bills (Colton, 2021). While common and straightforward to use, this metric does not account for differences in disposable income, so here we will focus on ECB-N.

As shown in **Table 2**, Californians consume approximately $24 billion worth of energy each year. However, 4.4 million of California's 13 million households (34 percent) also faced high energy burdens such that they spent more than 8.5 percent of their net income after essential expenses on energy. The total energy affordability gap, or the sum of all energy expenditures above that 8.5 percent of net income, was $4.1 billion annually. Although energy spending increases with increased income—the top quintiles in each census tract use 1.8 times more energy than the bottom quintiles in each tract—the energy affordability gap was concentrated in the lowest income quintiles.

Similarly, most of the residential outage costs impacted upper quintile households, such that 67 percent of outage costs were concentrated in the top two quintiles, while only 17 percent were seen in the bottom two quintiles. But outage costs that contribute to resilient energy burdens that exceed household net income by more than 8.5 percent were once again concentrated in lower and middle quintiles. Of the $920 million resilient energy affordability gap state-wide, $640 million (70 percent) was concentrated in the two lowest income quintiles in each census tract, with only $90 million (less than 10 percent of the gap) in the top two income quintiles in each tract (40 percent of the state population).

Table 2. Summary of Energy and Resilient Energy Affordability Gaps.

Energy and Resilience Affordability Gaps						
	Energy			Resilient Energy		
Income Quintile	Total Energy Spend ($ million)	Energy Gap Households (#)	Energy Afford-ability Gap ($ million)	Outage Costs (# million)	Resilient Energy Gap Households (#)	Resilient Energy Afford-ability Gap ($ million)
1	3,400	2,500,000	2,900	310	2,600,000	310
2	4,300	1,400,000	1,000	610	1,500,000	330
3	4,800	450,000	230	910	620,000	190
4	5,300	56,000	18	1,300	140,000	72
5	6,200	500	0.5	2,400	14,000	18
Total	**24,000**	**4,406,500**	**4,149**	**5,530**	**4,874,000**	**920**

Regional Analysis

We analyzed cost burdens geographically across California to explore where local income disparities intersect with outage impacts. This allows us to recommend local resilience interventions where the resilient energy affordability gap indicates a lack of household ability to invest.

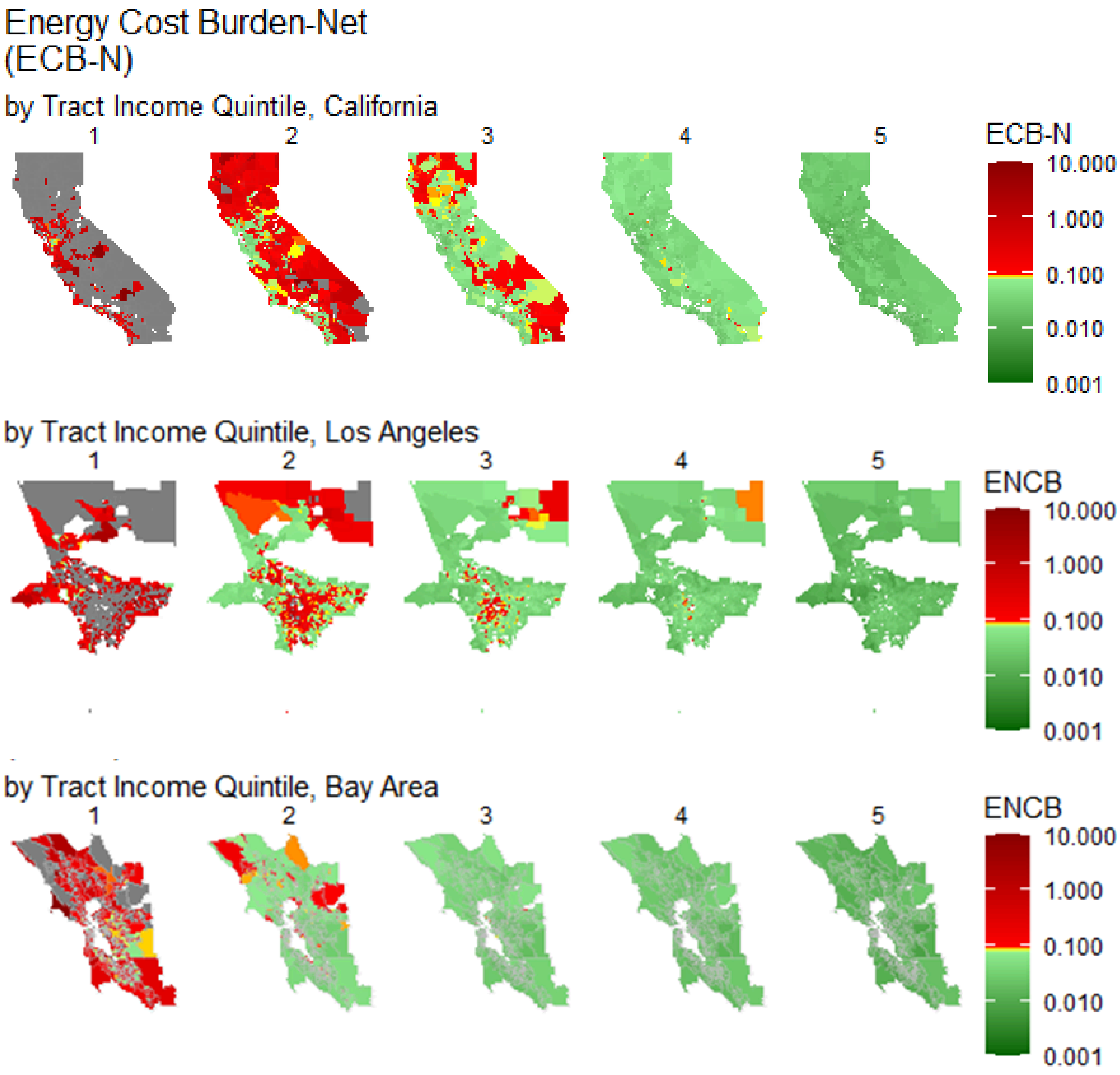
We began with energy and net income analysis to frame the focus of this analysis on resilient energy cost burdens. We continue to present results in terms of census-tract income quintiles. Additional local variance in food, housing, and utility expenses driven by local economics outside of the statewide income analysis were left for future study.

Energy and Net Income Analysis

Energy Net Cost Burden (ECB-N) considers household income after essential expenses. We considered households to be highly burdened when the ratio of energy to net income is above 8.5 percent. **Figure G** shows ECB-N for California census tracts, broken out by census tract income quintile. Details are provided for Los Angeles County and Bay Area Counties (Sonoma, Napa, Solano, Contra Costa, Alameda, Santa Clara, San Mateo, Marin, and San Francisco Counties). For the lowest income quintile in each census tract, most areas were either highly burdened (red) or had negative income after essential expenses (gray). Only in the middle quintile and above did we start to see most census tracts dropping out of the highly burdened category. The total energy affordability gap—the sum of energy costs that exceed the 8.5 percent threshold—was $4.1 billion annually, as shown above in **Table 2**.

Across California, the lowest income quintiles in each census tract tended to be highly energy burdened, or to have negative income after essential expenses. The latter is even more challenging, as it indicates that solving the energy net cost burden may require solutions beyond the energy sector.

Figure G. Energy Net Cost Burden by census tract across California, Los Angeles County, and Bay Area Counties. Color scale breaks between red (highly burdened) and green (not highly burdened) at 8.5 percent of net income, with yellow indicating the ratio is exactly at the threshold. Gray areas indicate negative net income after essential expenses.

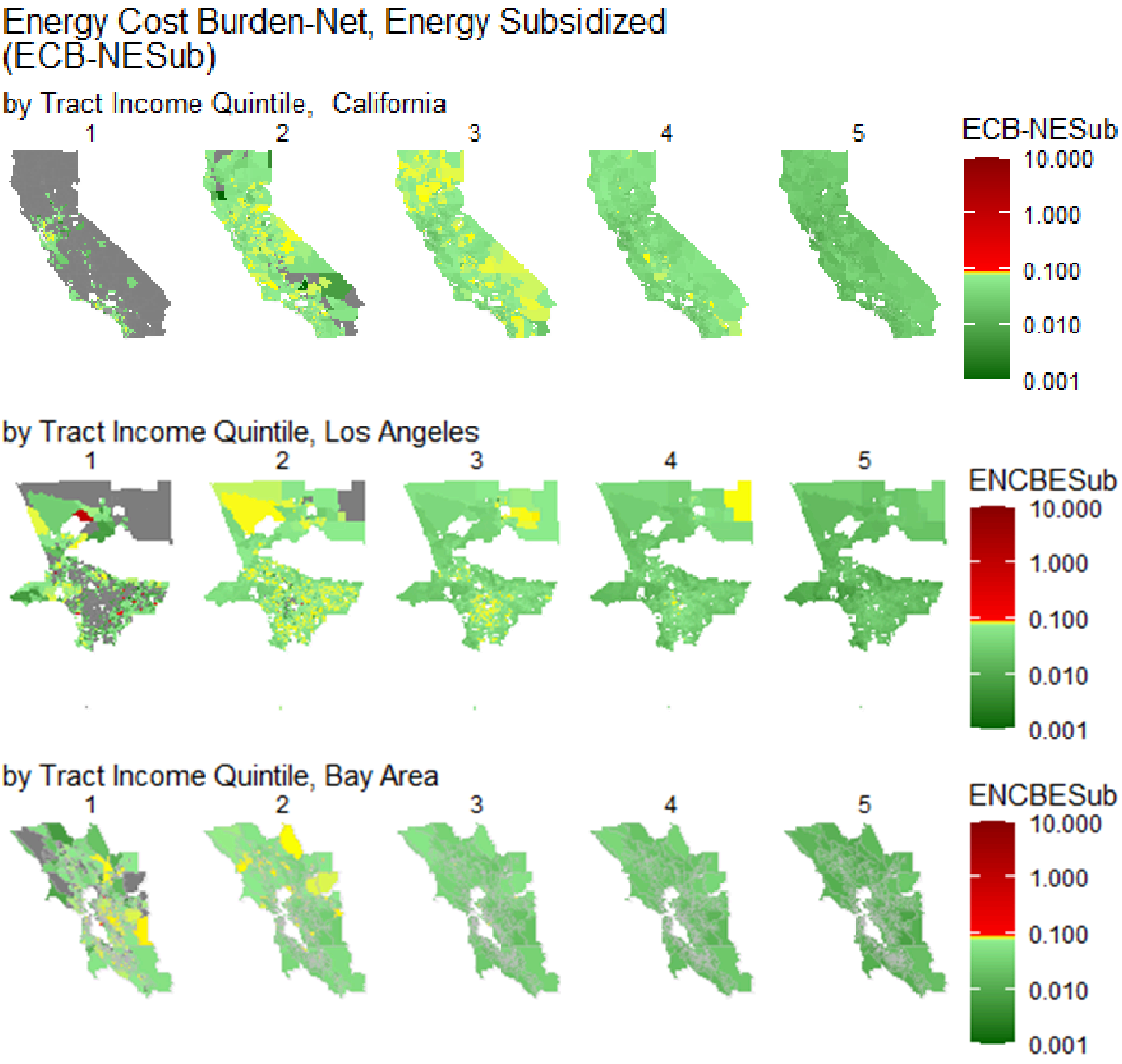


Energy and Net Income After Energy Subsidies Analysis

Energy Net Cost Burden after a theoretical energy subsidy (ECB-NESub) is shown in **Figure H** for each census tract income quintile in California, with more detailed views for Los Angeles County and Bay Area Counties. This presents the result of a theoretical subsidy that effectively cuts energy spending to a maximum of 8.5 percent of net income for each household. This eliminated the energy affordability burdens for each household and the total energy affordability gap state-wide. The required subsidy was equivalent to the Energy Affordability Gap shown in **Table 2**.

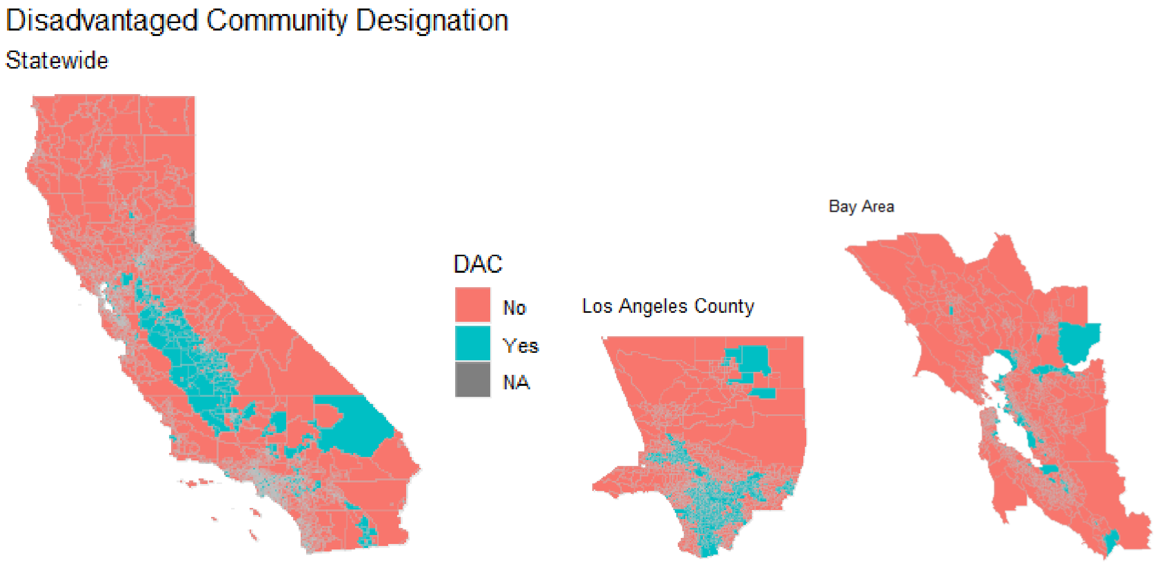
Where household net incomes were negative, the subsidy cannot address the total affordability gap, so many lower-quintile households still had negative net income (shown in gray). Several census tracts had high energy burdens even after this subsidy, as they had negative net income before the subsidy.

Figure H. Energy Net Cost Burden After Energy Subsidies. By census tract across California, Los Angeles County, and Bay Area Counties.



Negative net incomes and high energy burdens even after subsidies were not just a function of disadvantaged community (DAC) designations. **Figure I** shows DAC versus non-DAC stats for California, Los Angeles County, and Bay Area counties. (OEHHA, 2023) Especially for the lowest-income quintiles, these challenges exist in both DAC and non-DAC communities.

Figure I. Census Tracts Designated as Disadvantaged Communities (DAC) by California Senate Bill 535. DAC is one indicator of vulnerability, but it fails to capture local income variances that generate affordability challenges regardless of DAC status.

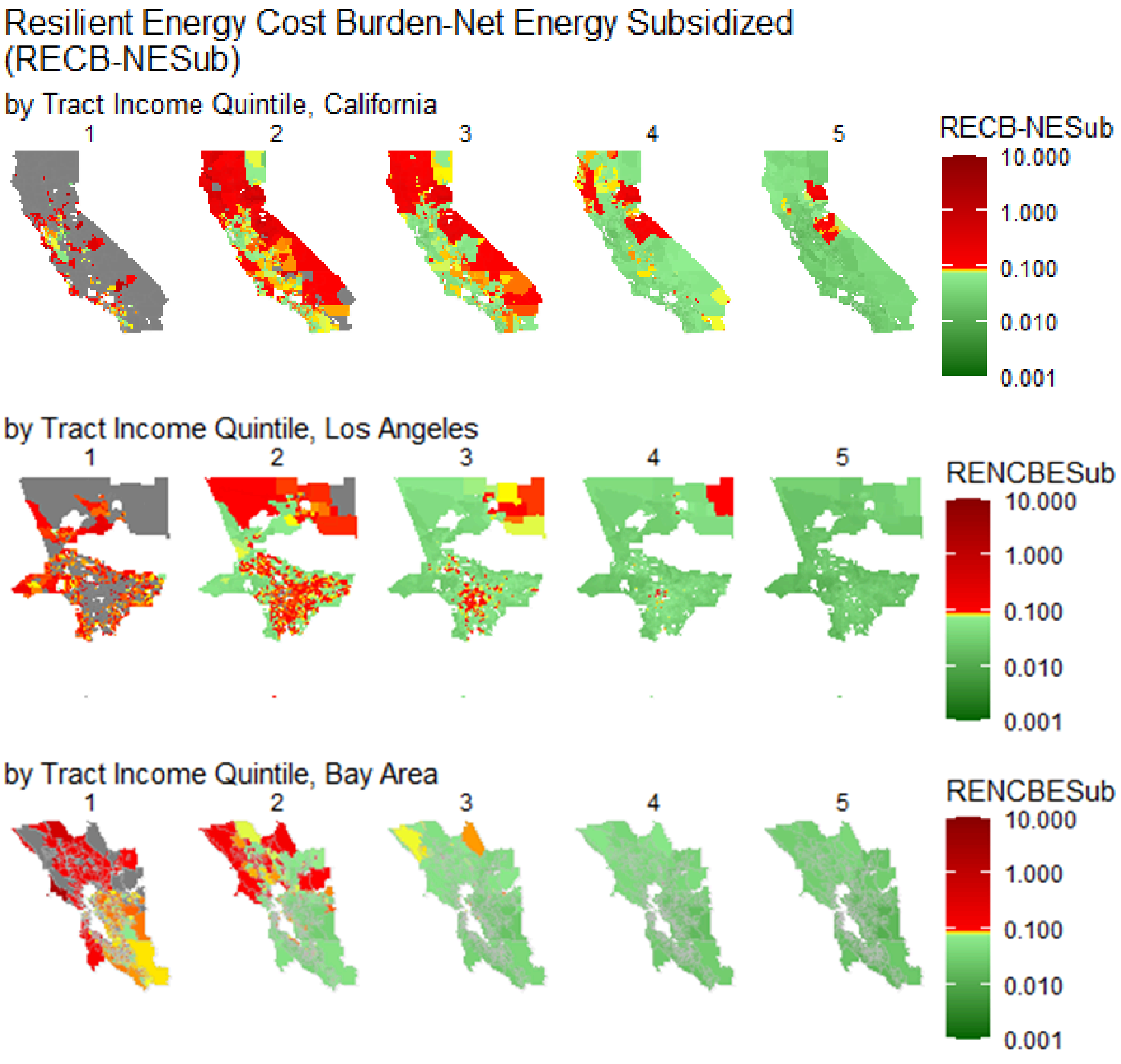


Resilience and Net Income After Energy Subsidies Analysis

Resilient Energy Net Cost Burden after Energy Subsidies (RECB-NESub) is shown in **Figure J** for each census tract income quintile in California, with details provided for Los Angeles County and Bay Area Counties. This presents the remaining resilient energy affordability challenges resulting from the theoretical subsidy addressing energy affordability gaps, but now incorporating outage costs into the ratio.

Nearly 4.9 million households were in the highly burdened category when outage costs were incorporated, even after subsidizing the energy affordability gap. More than half of these households were in the lowest income households in each census tract. An additional resilient energy affordability subsidy of almost one billion dollars would be required to address this affordability gap statewide.

Figure J. Energy Net Cost Burden After Energy Subsidies. By census tract across California, Los Angeles County,and Bay Area Counties.

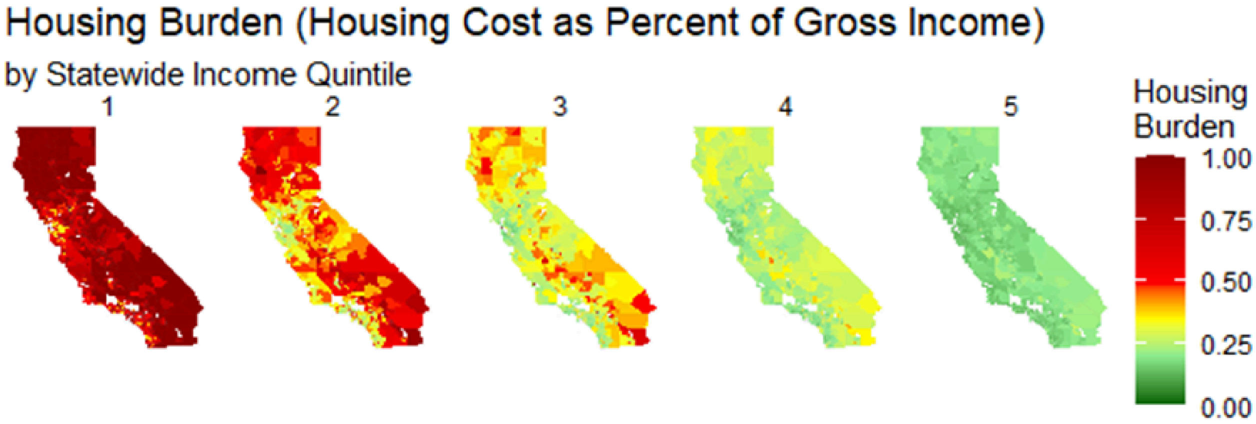


Housing Burden Analysis

While external to energy and resilient energy analyses, a key driver of affordability challenges was the burden of housing costs. For the lowest-income quintiles in each census tract, negative income after essential expenses remained a significant challenge for 1.6 million households. Combined, these households had a total negative net annual income of $6.5 billion. The largest component of household expenses was housing, such that across

California only the top-income quintile in most census tracts might be considered non-housing burdened with housing expenses above 30 percent of gross income.

Figure K. Housing Burden by Census Tract Across California. Only the highest income quintiles avoid widespread housing burdens.



Step Three: Using Local Survey Data to Ground Truth Methods and Results

The aforementioned data from the Bureau of Labor Statistics and American Community Survey represent real people facing energy affordability and resilience challenges. To ground truth the methods and results—in particular, to confirm we were considering the factors that actually mattered to people—we collected data from Bay Area residents. This took the form of a focus group with in-person surveys in Marin and distributed surveys conducted by local college students around the greater Bay Area. This also allowed us to uncover potential nuances specific to the Bay Area, and future work would benefit from additional ground-truthing surveys in multiple geographic regions.

Marin City Focus Group

We met with eight residents of Marin City, an historically black, working-class community between Sausalito and Mill Valley across the Golden Gate Bridge from San Francisco. We were connected to local residents through a community-based organization in Marin City, and a variety of ages and occupations were represented within the survey group, including a daycare owner, a county librarian, and an entrepreneur.

Surveys were distributed to collect demographic information, including income ranges, number and of residents per household, age, health risks; as well as outage data, including frequency and duration of outages over the past five years, outage damages and health impacts, and potential adaptations households had undertaken to prepare for outages.

The eight households surveyed averaged 3.25 people per household, with none having fewer than two occupants. This is a bit higher than the 3.01 or 2.88 average household size in California (for owner-occupied and renter-occupied units, respectively) (US Census Bureau, 2019). Five of the eight households also reported having children at home. This is important to consider because more people living in each household means more people impacted by outages, including those who cannot contribute to a household's income, like children. Roughly a third (3/8) of these households reported making less than $40k/year, while nearly two thirds (5/8) reported less than $80k/year. For context, in 2019 the mean household income was $98,000 per year in California, (U.S. Census Bureau, 2019) and the Area Median Income for the Bay Area for a 3-person household was $110,850 (San Francisco Mayor's Office of Housing and Community Development, 2019). Of the eight participants, seven were renters. This is significantly higher than is typical across California, where roughly 45 percent of households rent (ACS, 2019). It's also critical to consider that certain resilience solutions, such as installing solar and energy storage backup systems, are less accessible to renters. Five of the eight households also reported some type of health risk.

All eight households reported experiencing outages up to 24 hours, with half experiencing numerous shorter outages and more than half (5/8) experiencing outages greater than four days. For longer outages, households reported hardships—such as a loss of food—because of these interruptions. Multiple respondents also reported childcare needs due to daycare closures during outages as a significant challenge.

All participants also reported some reaction cost to outages, including flashlights, ice, and food. Most also reported some stress or worry caused by outages, with longer outages typically causing higher levels of stress. However, even outages under two hours were stressful for more than half of participants.

Along with surveys to record quantitative demographic and outage information, the session included a qualitative discussion of outages, outage impacts, and outage adaptation within the community. Anecdotally, people reported numerous and frequent outages. Many participants had vivid recollections of specific outages—memories related to missing work because of a lack of daycare, to unsafe situations experienced by their families or others, and to beneficial adaptation measures taken by the local library. However, participants found the specifics around outages difficult to remember precisely, and people had different recollections of when outages happened, how long they lasted, and whether the local utility or local library was responsible for popup outage mitigation measures.

Additionally, imprecise recall of outages can make it difficult to say with certainty which neighborhoods experience the most frequent, or the longest, outages—adding another layer of difficulty for prioritizing funding. This can be improved by more transparent reporting from utilities around the frequency and duration of outages at a finer geographic scale than currently exists. While utilities report metrics such as System Average Duration Index (SADI), System Average Frequency Index (SAFI), and Customer Average Duration Index (CADI), these metrics are reported at much wider geographic areas than a neighborhood or census tract.

Bay-Area Wide Surveys

As part of their coursework under the guidance of Teach Earth Action professors, students at Chabot College in Hayward and College of San Mateo conducted surveys in neighborhoods around the Bay Area. Surveys captured demographic information such as age, ethnicity, and renter/owner status as well as information on income, household expenses, and outage impacts from the past five years.

Survey results for income and expenditures were reported in ranges.[6] **Table 3** shows the percent of income spent on different necessities for households with different incomes, as well as the percent of owners versus renters in each income category. For this comparison, the average value of each range was used, with the average between zero and the highest value for cost categories that began with ‘Less than’, the stated value for categories that began with ‘More than’, and $20,000 for the ‘Less than $20k’ income range. Weekly food costs and monthly utility costs were also converted to annual costs to calculate percent of annual income spent in each category.

---

[6] Costs of essential expenditures were reported in ranges of ‘Less than $50’, ‘51-$150’, ‘151-$250’, ‘251-$350’, and ‘More than $350’.

Table 3. Student-Led Survey Results: Percent of Household Income Spent on Essential Services by Household Income. Lower income households spend proportionately more of their income on essential services. Percentages for the lowest and highest income categories may be skewed by the use of the values used in the 'Less than' and 'More than' ranges, respectively.

Breakdown of Select Expenses by Household Income					
Annual Household Income	**Percent of income spent on essential services**				
	Food	**Electricity**	**Gas**	**Internet**	**Phone**
< $20k	40%	9%	7%	5%	5%
$20-40k	30%	7%	6%	4%	5%
$40-80k	20%	3%	3%	2%	3%
$80-120k	10%	2%	2%	1%	2%
$120-200k	7%	2%	1%	1%	1%
> $200k	7%	1%	1%	1%	1%

Income and spending data was reasonably consistent with the American Community Survey and Bureau of Labor Statistics data shown earlier, with some discrepancies that could be explained by the Bay Area's high cost of living. For example, the percentage of income survey participants spent on food was generally within a few points of the corresponding spending data, with the exception of participants in the $20K-$40K range. In this case, survey participants reported spending a significantly higher percentage of their income on food—averaging around 30 percent rather than the Bureau of Labor Statistics estimated 10-20 percent.

Household incomes reported in the Chabot-led surveys varied slightly from those reported in the Marin City focus group, with a smaller percentage of households reporting incomes under $40K and $80K per year (21 versus 38 percent and 44 versus 63 percent for under $40K and under $80K in the Chabot-led versus Marin City surveys, respectively). Household size was more consistent, with both groups reporting that roughly 50 percent of households had 3-4 occupants and 20-30 percent of households had either 1-2 or 5-6 occupants. However, both survey groups reported a higher average household size than the ACS estimates for California.

Data collected on outages was also segmented into seven buckets, this time based on length. Roughly five percent of those interviewed had not experienced any power outages they could recall over the past five years. However, roughly 80 percent had experienced at least one outage that lasted less than two hours, 15 percent had experienced at least one outage that lasted more than 24 hours, and four percent had experienced at least one outage that lasted more than five days. The frequency with which outages of different lengths were experienced is shown in **Table 4**.

Table 4. Frequency of Power Outages of Various Durations. More households experienced shorter outages, and experienced them more frequently. Longer outages impacted fewer households and were less common.

Frequency of Power Outages by Duration						
Outage Duration	**Number of Outages Experienced**					
	0	**1**	**2**	**3**	**4**	**5+**
0-2 hours	73	67	85	47	32	75
2-6 hours	147	90	67	32	13	30
6-12 hours	251	72	26	15	3	12
12-24 hours	304	43	16	8	1	7
1-2 days	330	29	12	3	1	4
2-4 days	344	22	7	3	1	2
5+ days	365	7	4	1	0	2

Those who had experienced outages reported challenges including the inability to use technology, loss of food and/or medication due to spoilage, missed work, and the inability to appropriately respond to extreme temperatures (e.g., use a heating or air conditioner). Similar to the responses from Marin City, loss of food was among the most commonly reported difficulties. However, in this more widespread survey group, just over half of those who experienced outages reported some loss of food, compared to all respondents from Marin City.

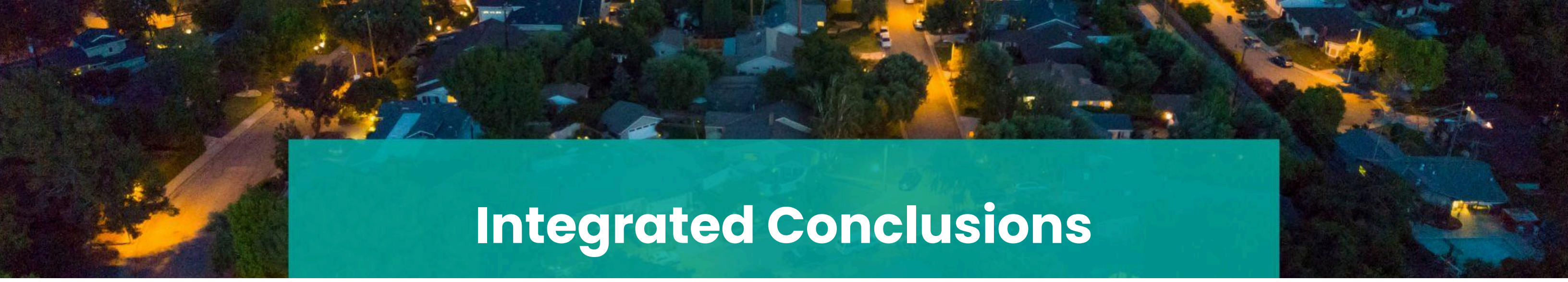
Narrative responses about difficult outages also highlighted where certain household demographics made outages particularly dangerous—for example, caring for a baby during a summertime outage when temperatures were high—or could compound inequalities, such as making it difficult to complete homework assignments. While 96 percent of respondents did not lose medication because of an outage, many still expressed concern over this possibility for family members and recognized the potential for serious consequences for those who rely on medication or medical equipment.

These outage damages generally reflected the expected damages, with a few additions such as people becoming trapped in their homes or housing complexes because of electric garage doors or gates.

Utilities do have existing programs to help some categories of customers through outages, for instance PG&E's Medical Baseline Program targeted at electrically-dependent medical device users. However, this doesn't cover all households where it could be medically dangerous to lose power (such as households with newborns or elderly residents) and relies on customers to ensure they are on the appropriate program list.

Roughly 40 percent of those who experienced outages reported spending more than $50 reacting to those outages, while a small fraction of (roughly three percent) spent more than $500. Reaction costs include buying ice to keep medication cold, purchasing candles or a flashlight, picking up batteries, going somewhere else where there is power available, and/or installing a generator. They do not include lost time or wages.

While this data collection was a productive benchmark, more extensive data collection is still needed. Increasing the sample size and including further questions, such as resilience costs to households, would generate more robust results. However, given recent increases in inflation, some damage costs may already be outdated. Additionally, survey results prompted numerous follow up questions, such as why many residents who endured difficult outages only responded by taking limited resilience action. Further questions are outlined in the Power Outage Survey Final Report prepared by Teach Earth Action about this data. (Belloso et al., 2024) These questions, among others, are worth exploring further to understand the connection between different demographic variables and resilience, which can help policymakers develop the most appropriate solutions.



Integrated Conclusions

High energy burdens, where energy costs are greater than 8.5 percent of net income, impact 4.4 Million households and generate a total affordability gap of $4.1 billion dollars in California. If the costs of dealing with power outages are included, an additional almost $1 billion in resilient energy affordability gap emerges, impacting 4.9 million households. Resilient energy affordability gaps should be considered in energy policy decisions and investments toward more reliable and resilient infrastructure, helping to reduce burdens for those least able to afford the costs of outages.

Surveys and questionnaires implemented in Marin City and across the Bay Area reinforce the statistical analysis in multiple ways. First, they reiterate that the high percentage of income necessary for essential expenses like food and utilities present a significant challenge for lower income households. Second, they show the elements we used to quantify outage impacts were felt within the community.

Importantly, the surveys and questionnaires also show some of the limitations of the publicly-available data from the Census Department, the Bureau of Labor Statistics, and DOE's eagle-i outage data.

County-wide average outage data can hide wide disparities in outage experiences. Survey respondents in the Bay Area experienced roughly 10 hours per year of outages, compared to an average of four hours per year across Bay Area counties in the eagle-i data. Eagle-i reported outage totals in Bay Area counties range from 2.3 hours in Alameda to 15 hours in Napa, while survey respondents in Alameda reported an average of almost 10 hours per year and the single survey respondent from Napa reported an estimated 45 hours annually over the last five years. Survey respondents in Alameda reported anywhere from zero to hundreds of hours of outages, indicating that averaging outages—and outage impacts—across a full county is likely to overestimate the impact on some households while severely underestimating the impacts on others. The average 10 hours reported by survey respondents also hides the significant impacts of multiple multi-day outages experienced by some respondents.

Surveys also showed that in addition to food and income losses, some more difficult to quantify impacts were also experienced, including damages to physical and mental health. These impacts should be addressed in future research, especially health impacts for those who are particularly vulnerable to climate-related health risks like extreme heat or poor air quality. Outage impacts become even more dangerous when power outages turn off air conditioners, air filters, refrigerators, and medical devices, especially for people with vulnerabilities (e.g. people with asthma or heart disease, people dependent on refrigerated medicines like insulin, infants, and the elderly).

Implications for Policy and Future Research

The resilient energy burden and gap metrics can inform future research and, in turn, future efforts to create more energy policy supporting both equity and resilience. The work is far from finished, however. This section discusses some of the potential implications for policy and research required to pursue these avenues.

The Goal: Improve Resilience by Reducing Outage Impacts

The goal of resilience is to ensure households can easily withstand and recover from the burden of unexpected shocks like power outages. If you can reduce outages to zero, you reduce outage burden to zero. However, this is likely infeasible at a grid scale, as the economic cost of a perfectly reliable grid likely exceeds the cost of a few, short outages. That said, the way outages are currently addressed—determining targets for limiting outages and measuring whether those targets are met—relies on inequitable measurements like (1) overly-broad outage frequency and duration statistics that neglect geographic specificity and do not consider differential impacts on different households, or (2) VoLL, which values wealthier households higher than lower-income ones and is thus inequitable in its measurements and outcomes. This shortcoming could potentially be addressed by using an equity-focused VoLL calculation to determine which areas and outages are prioritized for funding.

Distributed energy, for instance solar and energy storage systems, can improve resilience by reducing customer-side outages. However, these systems are currently unaffordable for and/or unavailable to many households. Thus reducing outages with distributed energy resources or other customer-side interventions requires, in many cases, developing subsidies, policy, and programs that enable greater access. Ideally, these measures are equitably distributed—installed on households that are, or would be, the most severely impacted by outages. As discussed above, determining which households are most impacted requires access to household-level outage frequency and duration, as well as underlying demographic factors like income.

Potential Strategies and Areas of Future Research

Reduce Household Energy Burdens

Simply reducing a household's energy burden can make it easier for that household to withstand and recover from outages. The less a household has to spend on energy each month, the more they can afford to spend on resilience and the less impacted they will feel from outage damages. This lessening in outage impact is because households with lower energy burdens are likely to have more disposable income available to deal with unexpected events like outages or to put towards investments in resilience. But the closer a household is to being energy burdened—e.g., spending more than six percent of their gross or 8.5 percent of their net income on energy—the more resilience and/or outage damage costs are likely to squeeze their budgets and push them into the energy burdened category.

Programs like the California Alternate Rates for Energy (CARE) can and do help. The eligibility criteria that, for example, a three person household can get CARE assistance if their income is less than $51,640 per year is consistent with our results. (CPUC, n.d.-b) Our energy burden analysis shows that households with income less than $50,000 would need help keeping their energy affordability ratio below the 8.5 percent threshold. But the assistance rates in CARE of a 30-35 percent reduction in energy costs is less consistent with our findings. Households below $20,000 in annual gross income would need a 100 percent bill reduction to not be energy burdened, as their net incomes are negative after essential expenses. And households with less than $35,000 in annual gross income would need a greater than 50 percent bill reduction to not be considered highly energy burdened.

Energy efficiency measures, weatherization, and distributed energy resources like solar can all help reduce energy bills. This can lower energy burdens, freeing up money that can be spent mitigating outage damages or investing in resilience.

Improving energy affordability is also cost effective. A 2022 analysis showed that grants for efficiency and weatherization, investments in home energy upgrades, and expansion of efficiency, community solar, and demand response programs could improve energy affordability for the most burdened households (Lukanov et al., 2022). A 2024 study also demonstrated that rooftop solar could reduce a household's energy burden, particularly for low- and moderate-income households with high energy burdens (Forrester et al., 2024). Equity-focused efficiency and weatherization measures can also make resilience systems like paired solar and storage less expensive by lowering the amount of energy required to heat, cool, and power a home.

Reduce Energy Resilience Burdens

Some households may not be considered energy burdened under day-to-day circumstances, but may become energy burdened when resilience or outage damage costs are considered. Reducing these costs to consistently bring these households below the energy burdened threshold can be done through a combination of energy affordability measures and lowering the impact of outages on these households. This can be done by (1) reducing outages through grid infrastructure improvements; (2) installing solar and storage systems so they do not lose power during inevitable grid outages; (3) determining least-cost grid-vs-distributed investments by accounting for outage impacts.

Resiliency measures do not necessarily have to provide 100 percent of normal energy needs. Further research into community and household critical energy needs could allow for efficient deployment of smaller scale resiliency investments. These could include resilience hubs to support medical needs, clean air, cooling, and refrigeration for vulnerable populations. Reducing income losses by investing in critical support services to enable work even during outages goes beyond powering workplaces. It may need to include resilient power for communications and internet as well as resilient power for schools and daycare centers to allow people to leave their homes without worrying about children left home without electricity.

Consider Cross-Cutting Interventions

Resilience-boosting interventions can also be cross cutting, as measures that improve energy affordability can also reduce energy resilience burdens. While further research is needed to understand all of the various potential policy levers and model cost-optimal community-level solutions, a few key areas for consideration are outlined here. Potential cross-cutting policy levers include:

- **Energy Efficiency.** Improving a home’s energy efficiency, including through weatherization, can lower household energy bills and is particularly effective for older housing stock.
- **Equitably Distributed Energy Resilience.** Distributed energy resources like solar and battery storage can help lower energy bills and make homes resilient to outages.

- **Electrified Heating Using High-Efficiency Heat Pumps.** Efficient heat pumps are less expensive to operate than other heating systems such as fuel oil, propane, and electric baseboard heating. Heat pumps can also be used for both heating and cooling, lowering summer energy usage in households that typically use wall AC units.
- **Reduced Housing Burden.** Beyond energy policy, the high cost of living, driven by high housing costs, drives down net income, and thus increases energy and resilient energy burdens and gaps. Lowering housing costs, especially for the lowest-income households, would help reduce energy and resilient energy burdens. More than 5.7 million households (44 percent of California households) face housing burdens greater than 30 percent of household gross income, with a total housing affordability gap of more than $34 billion dollars annually. Housing assistance programs like the Homeless Housing, Assistance and Prevention Program, State Low-Income Housing Tax Credits, and others help. But these total only $3.3 billion in assistance—less than 10 percent of the $34 billion housing affordability gap (Legislative Analyst's Office, 2023).

Policy measures should target both homeowners and landlords, as roughly 35 percent of households in the U.S.—which grows to 44 percent in California—are renters (PPIC, 2024). Policy to target both groups will help ensure affordability and resilience benefits are not confined to homeowners alone.

Additionally, policies to promote community-level solutions may significantly reduce costs, as some resilience-boosting technologies—for instance, backup solar and energy storage systems—are significantly less expensive as they are scaled up to become community-level solutions. Updating policy that currently acts as a barrier to community-level solutions, for instance around microgrids, can help lower the cost of resilience for communities.

Examine the Challenges of Decarbonization

Policymakers are pursuing widespread electrification to meet economy-wide decarbonization goals. This effort has clear implications for resilience. It mitigates climate change, and in the long term can reduce exposure to outages. But as more services begin to depend on electricity, the transition from fuel combustion to electrical heating, water heating, and cooking in homes and other buildings puts additional importance on resilient electricity systems to ensure these services are available. Additional research exploring the challenges and opportunities of electrification on resilience is warranted.

References

1. Baik, S., Morgan, M.G., and Davis, A. L. (2018). "Providing Limited Local Electric Service During a Major Grid Outage: A First Assessment Based on Customer Willingness to Pay." *Risk Analysis*, 38(2), 272–282. DOI: 10.1111/risa.12838
2. Belloso, N.T., Gucho, C., McFarland, S., Heltzel, E., DeWit, T. (2024). "Power Outage Survey Final Report." Prepared by Teach Earth Action for PSE Healthy Energy. https://www.teachearthaction.org/power-outages
3. Billington, R., Allan, R.N. (2013). "Reliability Evaluation of Power Systems (Reprint)." Springer Science Business Media.
4. Brelsford, C., Tennille, S., Myers, A., Chinthavali, S., Tansakul, V., Denman, M., Coletti, M., Grant, J., Lee, S., Allen, K., Johnson, E., Huihui, J., Hamaker, A., Newby, S., Medlen, K., Maguire, D., #Dunivan Stahl, C., Moehl, J., Redmond, D.P., … Bhaduri, B. (2023). "The Environment for Analysis of Geo-Located Energy Information's Recorded Electricity Outages 2014-2023 (Version 2)." figshare. DOI: 10.6084/m9.figshare.24237376.v2
5. Brockway, A.M., Conde, J., Callaway, D. (2021). "Inequitable access to distributed energy resources due to grid infrastructure limits in California." *Nature Energy*, 6, 892-903. DOI: 10.1038/s41560-021-00887-6
6. Brown, D P. (2022). "Socioeconomic and demographic disparities in residential battery storage adoption: Evidence from California." *Energy Policy*, 164, 112877. https://doi.org/10.1016/j.enpol.2022.112877
7. Bureau of Labor Statistics. (2019). "Consumer Expenditure Surveys. California: Quintiles of income before taxes, 2017-2018. State-Level Expenditure Income Tables: U.S. Bureau of Labor Statistics." Bureau of Labor Statistics. https://www.bls.gov/cex/tables/geographic/mean/cu-state-ca-income-quintiles-before-taxes-2-year-average-2018.html
8. Bureau of Labor Statistics. (2020). "Consumer Expenditure Surveys. California: Quintiles of income before taxes, 2018-2019. California: Quintiles of income before taxes, 2018-2019. State-Level Expenditure Income Tables: U.S. Bureau of Labor Statistics." Bureau of Labor Statistics. https://www.bls.gov/cex/tables/geographic/mean/cu-state-ca-income-quintiles-before-taxes-2-year-average-2019.html
9. Bureau of Labor Statistics. (2021). "Consumer Expenditure Surveys. California: Quintiles of income before taxes, 2019-2020: U.S. Bureau of Labor Statistics." Bureau of Labor Statistics. https://www.bls.gov/cex/tables/geographic/mean/cu-state-ca-income-quintiles-before-taxes-2-year-average-2020.html

10. Bureau of Labor Statistics. (2022). “Consumer Expenditure Surveys. California: Quintiles of income before taxes, 2020-2021: U.S. Bureau of Labor Statistics: U.S. Bureau of Labor Statistics.” Bureau of Labor Statistics. https://www.bls.gov/cex/tables/geographic/mean/cu-state-ca-income-quintiles-before-taxes-2-year-average-2021.htm
11. Bureau of Labor Statistics. (2023). “Consumer Expenditure Surveys. California: Quintiles of income before taxes, 2021–2022: U.S. Bureau of Labor Statistics.” Bureau of Labor Statistics. https://www.bls.gov/cex/tables/geographic/mean/2022/cu-state-ca-income-quintiles-before-taxes-2-year-average-2022.htm
12. Bureau of Labor Statistics. (2024). “CPI Inflation Calculator.” CPI Inflation Calculator. https://data.bls.gov/cgi-bin/cpicalc.pl?cost1=1.00&year1=197801&year2=202301
13. Casey, J.A., Fukurai, M., Hernandez, D., Balsari, S., Kiang, M.V. (2020). Power outages and community health: a narrative review. *Current Environmental Health Reports*, 7, 371-383. DOI: 10.1007/s40572-020-00295-0
14. Clark, S., Peterson, S., Rivera-Gutiérrez, R., Zambrana-Rosario, A.C., & Shelly, M. (2022). “Impact of Infrastructure Disruptions on Puerto Rican Household Capabilities, Health, and Well-Being.” Natural Hazards Center Public Health Grant Report Series, 21. Natural Hazards Center, University of Colorado Boulder. Retrieved January 8, 2023 from https://hazards.colorado.edu/public-health-disaster-research/impact-of-infrastructure-disruptions-on-puerto-rican-household-capabilities-health-and-well-being
15. Clark, S.S., Peterson, S.K.E., Shelly, M.A., & Jeffers, R.F. (2023). “Developing an equity-focused metric for quantifying the social burden of infrastructure disruptions.” Sustainable and Resilient Infrastructure, 8(sup1), 356–369. DOI: 10.1080/23789689.2022.2157116
16. Colton, R.D. (2021). “Ratepayer-Funded Utility Bill Affordability: A Path forward to Serve Low-Income Connecticut Residents.” Fisher, Sheehan, and Colton. https://www.michigan.gov/documents/mpsc/Connecticut_affordability_Final_040821_721903_7.pdf
17. California Public Utilities Commission. (n.d.-b) “Affordability Ratio.”2019 Annual Affordability Report. Retrieved July 9, 2024 from https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/affordability/affordability-ratio
18. California Public Utilities Commission. (n.d.-b) “CARE/FERA Program.” Retrieved October 1, 2024 from https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/electric-costs/care-fera-program
19. Do, V., McBrien, H., Flores, N., Northrop, A.J., Schlegelmilch, J.,

Kiang, M.V., Casey, J.A. (2023). “Spatiotemporal distribution of power outages with climate events and social vulnerability in the USA.” *Nature Communications*, 14, 2470. DOI: 10.1038/s41467-023-38084-6

20. Fankhauser, S., Tol, R.S.J., & Pearce, D.W. (1997). “The Aggregation of Climate Change Damages: A Welfare Theoretic Approach.” Environmental and Resource Economics, 10(3), 249–266. DOI: 10.1023/A:1026420425961
21. Forrester, S.P., Montañés, C.C., O’Shaughnessy, E., Barbose, G. (2024). “Modeling the potential effects of rooftop solar on household energy burden in the United States.” Nature Communications, 15, 4676. DOI: 10.1038/s41467-024-48967-x
22. Gorman, W. (2022). “The quest to quantify the value of lost load: A critical review of the economics of power outages.” *The Electricity Journal*, 35(8), 107187. DOI: 10.1016/j.tej.2022.107187
23. Jain, A., Sieren-Smith, B., Hancock, J., Ho, J., Lai, W. (2021) “2019 Annual Affordability Report.” California Public Utilities Commission. https://www.cpuc.ca.gov/-/media/cpuc-website/industries-and-topics/reports/2019-annual-affordability-report.pdf
24. Kallay, J., Napoleon, A., Havumaki, B., Hall, J., Odom, C., Hopkins, A., Whited, M., Woolf, T., Chang, M., Broderick, R., Jeffers, R., Garcia, B.M. (2021). “Performance Metrics to Evaluate Utility Resilience Investments.” Sandia National Laboratories. SAND2021-5919. https://www.synapse-energy.com/sites/default/files/Performance_Metrics_to_Evaluate_Utility_Resilience_Investments_SAND2021-5919_19-007.pdf
25. Krohm, G.C. (1978). “A Survey of Disruption and Consumer Costs Resulting From a Major Residential Power Outage.” Integrated Assessments and Policy Evaluations Technical Memo. Argonne National Laboratory. DOI: 10.2172/6492613
26. Legislative Analyst’s Office. (2023). “The 2023-2024 California Spending Plan Housing and Homelessness.” The California Legislature’s Nonpartisan Fiscal and Policy Advisor. https://lao.ca.gov/Publications/Report/4808
27. Lukanov, B.R., & Krieger, E.M. (2019). “Distributed solar and environmental justice: Exploring the demographic and socio-economic trends of residential PV adoption in California.” *Energy Policy,* 134, 110935. https://doi.org/10.1016/j.enpol.2019.110935
28. Lukanov, B., Makhijani, A. Shetty, K., Kinkhabwala, Y., Smith, A., Krieger, E. (2022). “Pathways to Energy Affordability in Colorado.” PSE & Institute for Energy and Environmental Research CO study. https://www.psehealthyenergy.org/wp-content/uploads/2022/02/Colorado-Energy-Affordability-Study_Full-Report.pdf

29. Makhijani, A. (2021) “Addressing Energy Burden: Estimate of funds for low- and moderate-income households during the transition to a clean, regenerative, and just energy system.” *Just Energy Papers*. https://ieer.org/wp/wp-content/uploads/2022/02/Addressing-Energy-Burden_Just-Solutions-Collective.pdf
30. Munasinghe, M., & Sanghvi, A. (1988). “Reliability of Electricity Supply, Outage Costs and Value of Service: An Overview.” *The Energy Journal*, 9(01). DOI: doi.org/10.5547/ISSN0195-6574-EJ-Vol9-NoSI2-1
31. National Renewable Energy Laboratory. (n.d.). “Customer Damage Function Calculator.” Retrieved August 12, 2024 from https://cdfc.nrel.gov
32. Office of Environmental Health Hazard Assessment. (2023). “CalEnviroScreen 4.0.” OEHHA. https://oehha.ca.gov/calenviroscreen/maps-data
33. Pearce, D.W. (1971). “The Valuation of Costs and Benefits.” In: Cost-Benefit Analysis. Macmillan Studies in Economics. Palgrave, London. DOI: 10.1007/978-1-349-01091-2_7
34. Public Policy Institute of California. (2024). “California’s Renters.” PPIC Blog. https://www.ppic.org/blog/californias-renters/
35. San Francisco Mayor’s Office of Housing and Community Development. (2019). “2019 AMI Income Limits HMFA.” https://sfmohcd.org/sites/default/files/Documents/MOH/Asset%20Management/2019%20AMI_IncomeLimits-HMFA.pdf
36. Shivakumar, A., Welsch, M., Taliotis, C., Jakšić, D., Baričević, T., Howells, M., Gupta, S., & Rogner, H. (2017). “Valuing blackouts and lost leisure: Estimating electricity interruption costs for households across the European Union.” Energy Research & Social Science, 34, 39–48. DOI: 10.1016/j.erss.2017.05.010
37. Sovacool, B.K., Carley, S., Kiesling, L., and Heleno, M. (2024). “Energy Justice and Equity: Applying a Critical Perspective to the Electrical Power Grid for a More Just Transition in the United States.” *IEEE Power and Energy Magazine*, 22(4), 18–25.DOI: 10.1109/MPE.2024.3393942
38. Su, J. (2020). “Losing Power in the Time of COVID19, Climate Change and Racism.” Rosa Luxemburg Stiftung. https://rosalux.nyc/utility-shut-offs/
39. Sullivan, M.J., Mercurio, M., Schellenberg, J. (2009). "Estimated Value of Service Reliability for Electric Utility Customers in the United States." Ernest Orlando Lawrence Berkeley National Laboratory. LBNL-2132E. https://eta-publications.lbl.gov/sites/default/files/lbnl-2132e.pdf
40. Sullivan, M.J., Schellenberg, J., Blundell, M. (2015). "Updated Value of Service Reliability Estimates for Electric Utility Customers in the United States." Ernest Orlando Lawrence Berkeley National

Laboratory. LBNL-6941E. https://eta-publications.lbl.gov/sites/default/files/lbnl-6941e.pdf

41. US Census Bureau. (2019) “2015-2019 American Community Survey 5-Year Estimates.” American Community Survey, ACS 5-Year Estimates Data Profiles. https://data.census.gov/table/ACSDP5Y2019.DP04?q=ACS&g=040XX00US06&d=ACS 5-Year Estimates Data Profiles
42. US Census Bureau. (2024). Public Use Microdata Areas (PUMAs). Census.Gov. https://www.census.gov/programs-surveys/geography/guidance/geo-areas/pumas.html
43. USDA. (2021) “Food spending as a share of income declines as income rises.” Retrieved January 5, 2023 from http://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=58372
44. US Energy Information Administration. (2018). “One in Three U.S. Households Faces a Challenge in Meeting Energy Needs.” Today in Energy. https://www.eia.gov/todayinenergy/detail.php?id=37072
45. Walker, K., & Herman, M. (2024). “tidycensus: Load US Census Boundary and Attribute Data as “tidyverse” and ’sf’-Ready Data Frames (R package version 1.6.3).” [dataset]. Retrieved October 4, 2024 via API from https://walker-data.com/tidycensus