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Integration of equitable resilience metrics into climate-informed electric utility planning processes: phase one

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ABSTRACT

Working together, Sandia National Laboratories, Southern California Edison (SCE) - an Investor-Owned Utility (IOU) - and the California Public Utilities Commission (CPUC) are studying how electric utilities can use equity and resilience metrics to help inform the prioritization and sequencing of resilience-driven infrastructure investments. To this end, this project evaluated "Social Burden," an equitable resilience metric which measures the potential impact of disruptions in access to non-electric critical services on people and estimates community resilience to these disruptions. The Social Burden was expanded to incorporate SCE's existing equity metric and applied to evaluate the potential impacts from a range of climate-informed hypothetical outage scenarios developed under SCE's 2022 Climate Adaptation Vulnerability Assessment. One baseline ("blue-sky") state and eight different outage scenarios were evaluated to measure the potential impacts of the outages on non-electric infrastructure, critical services, and people. Key findings include: 1) the Social Burden framework is flexible enough to adapt to and build upon existing utility equity and/or resilience metrics, 2) Social Burden results highlight the high degree of non-electric service redundancy within the SCE service area with most (6/8) hypothetical outage scenarios predicted to increase people's Social Burden by less than 10%; however, 3) access to critical services and people's ability to obtain them is unequal and spatially clustered, meaning that there are some hypothetical outage scenarios (2/8) that will exert a higher toll on communities directly experiencing the outage as well as some nearby communities with pre-existing vulnerabilities. The report concludes with recommendations for potential use cases of the expanded Social Burden metric and identifies priority follow-on work. Potential use cases may include incorporating equity into IOU's prioritization of climate resilience investments. Additionally, Social Burden analysis may provide additional data and insights to augment grid planning, potentially by identifying additional needs and/or prioritizing previously identified needs.

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EXECUTIVE SUMMARY

Working together, Sandia National Laboratories (Sandia), Southern California Edison (SCE) - an Investor-Owned Utility (IOU), and the California Public Utilities Commission (CPUC) are studying how electric utilities can use equity and resilience metrics to help inform the prioritization and sequencing of resilience-driven infrastructure investments.

Currently, there are no frameworks within the grid planning process that readily enable utilities to justify the cost of investments focused on improving resilience. Existing "value of service" estimates are quite low and generally focused on traditional reliability, making it challenging to justify investments based on this value alone. There is a known gap: traditional value of service estimates use average values applied across all customers within a class, and do not consider important impacts such as long-duration or widespread outages (the typical indicators of a "Resilience" event) or more customer-specific impacts related to income or social burden. A Social Burden metric may help solve this gap by eventually becoming a component of a new framework used by utilities to justify new or prioritized investments to address customer resilience needs.

Climate change is projected to bring more extreme temperatures, increased precipitation and flooding events, rising seas, and a longer wildfire season to Southern California. Planning for these changes will require a better understanding of the potential impacts on SCE's electric assets, grid operations, and services, as well as the potential impacts of electric outages on the communities that SCE serves. This work is motivated by the desire to plan for more equitable climate resilience outcomes, which we define as the extent to which communities experiencing grid power outages driven by climate events can withstand the loss of power with limited impact to their well-being. To do this, we consider how the impacts of the same outage may be experienced differently by different people.

In the recently completed first phase of the project partnership, described in this report, Sandia, SCE, and CPUC investigated the potential use of the Social Burden metric and the Resilient Node Cluster Analysis Tool (ReNCAT) for equity-informed resilience planning in the context of climate adaptation in California. This work focused specifically on understanding the challenges associated with data collection, methodology, and computational tool validation; working through how these frameworks could inform utility and PUC climate adaptation investment planning; obtaining utility and stakeholder feedback on use cases and integration; and identifying next steps and further research and development needs for metric refinement and validation.

Social Burden is a quantitative, spatially explicit, equitable resilience metric that is calculated as the ratio between people's ability to procure critical non-electric services (such as food, water, shelter, medical care, etc.) and the effort required to do so. Ability is based on the availability of critical services within the study area, their quality, and people's differing socioeconomic capacities to spend time, effort, and money to obtain them. Effort scales with the distance that different people need to travel to acquire critical services provided outside of their homes. Thus, Social Burden can represent inequities in the experiences of people based on differences in both the physical environment (e.g., the distribution of infrastructure that provides critical services) as well as the social environment (e.g. the distribution of communities' abilities to spend additional time, effort, and money).

For this study, SCE's Community Resilience Metric (CRM) – developed as part of the utility's 2022 Climate Adaptation and Vulnerability Assessment (CAVA) – was incorporated into Sandia's Social Burden metric. CRM is a 37-factor composite of adaptive capacity and vulnerability indicators that approximate people's differing levels of ability to experience hardships associated with climate

events and power outages. The CRM was incorporated into Social Burden as an equity criterion that could capture differences in people's "attainment ability" to obtain critical services. The updated Social Burden framework was used to evaluate the social impacts of eight different hypothetical climate change driven grid power outage scenarios identified in SCE's 2022 CAVA. Due to its novelty, the metric integration was evaluated using several statistical analysis and modeling approaches.

In this project, we define a community's resilience to a particular outage scenario in the context of Social Burden by its calculated "black-sky" burden values. Communities rely on critical services to meet their needs, but services that are included in the "blue-sky" or normal operation conditions calculation may become non-operational during a power outage or "black-sky" conditions. The total number of operating facilities therefore decreases, and the services they provide are proportionally reduced. All else being equal, the greater the number of facilities (and their corresponding services) that lose power, the greater the increase (differential) in Social Burden will be. Adopting this framework, electric grid interventions improve community resilience outcomes by reducing the differential between "blue-sky" and "black-sky" conditions and thereby reducing the increase (differential) in Social Burden. The extent to which the underlying social and physical infrastructure conditions intersect with one another was explored by evaluating Social Burden as an equity metric under "blue-sky" (baseline), and hypothetical outage conditions. The differential between the "blue-sky" Social Burden and the "black-sky" Social Burden represents the incremental burden due to the grid outage. This delta provides a potential indication of where additional grid resilience may be a prudent investment (whether achieved through conventional wires solutions or other alternatives.) Communities that experience a large differential resulting in a high "black-sky" Social Burden may be strong candidates for resilience investments (see Figure 1). Conversely, communities that have a high "black-sky" Social Burden but experience a low delta would not likely be strong candidates for grid resilience investments, but may need other, non-grid, investment in services for the community. These investments would typically be beyond the scope of utility activities, but would be worthy of identification. This metric provides a basis to understand the inequities in critical service access throughout SCE's service area, and how power outages can potentially further exacerbate those inequities.

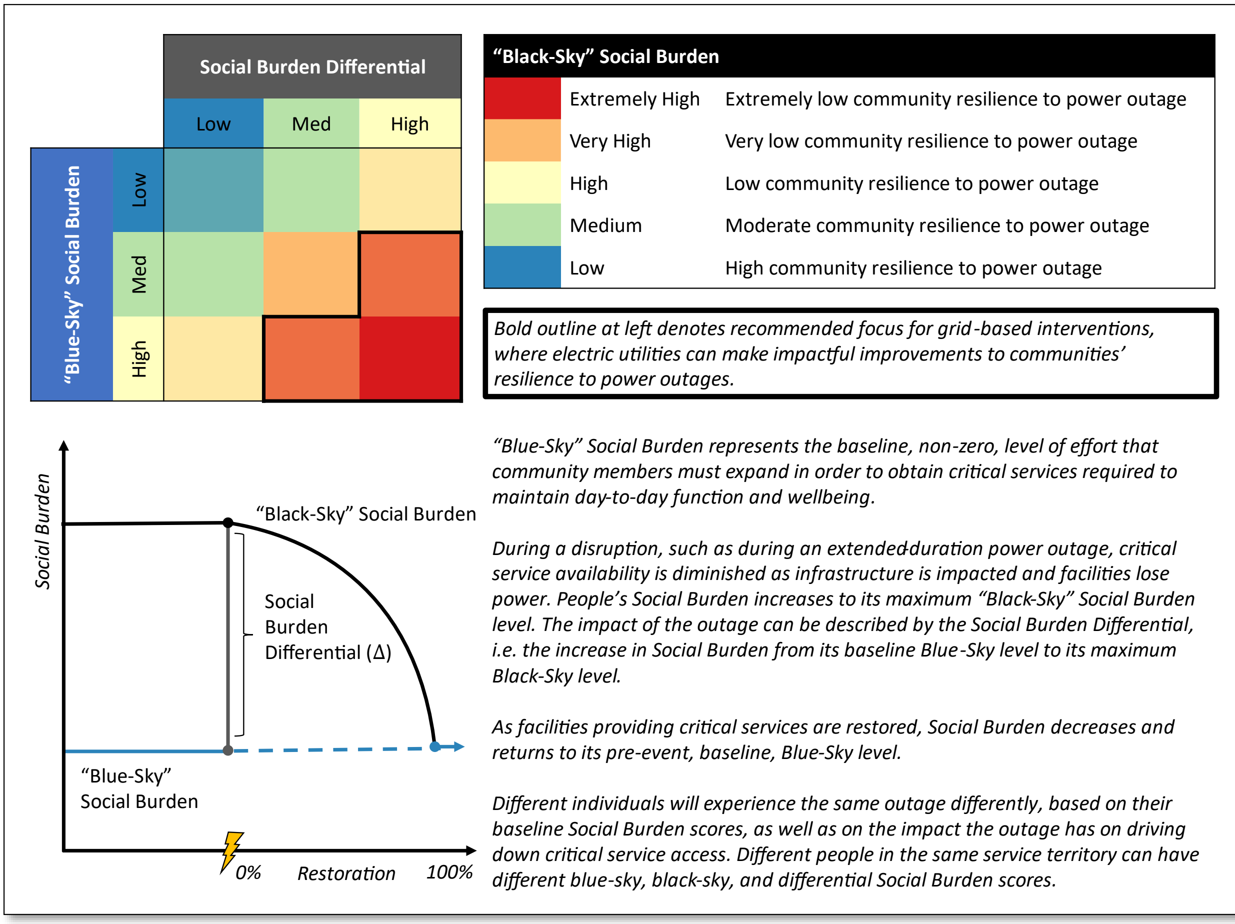

Figure 1. Relationship between "blue-sky" Social Burden, "black- sky" Social Burden, and community resilience to power outages.

This study established a "blue-sky" (baseline) distribution of Social Burden across SCE's 15-million customer, 50-thousand square mile service area at a census block group level and compared it with predicted "black-sky" Social Burden in response to eight hypothetical partial climate change driven electric grid outages.

In this case study, as in most real-world applications, neither the physical infrastructure landscape nor the social one was perfectly homogenous. This was further exacerbated in this case study by the size of the IOU service area and its geographic and socioeconomic diversity. Large gains in "blue-sky" Social Burden improvement can be made by prioritizing relatively few census block groups (CBGs). Although reduction of "blue-sky" Social Burden is outside the direct purview of the electric utility (as the grid is fully powered and is introducing no additional burden to the population), these findings can be leveraged by organizations like the CPUC that regulate non-electric utility services and infrastructure. Improvements to baseline service availability and/or people's underlying resilience would improve "black-sky" Social Burden outcomes as well, thus alleviating some of the hardship associated with power outages.

The Social Burden results also highlighted the high degree of service redundancy within the SCE service area, which means that when partial power outages render some critical services unavailable, many alternatives remain. The SCE service area overall is generally well-resourced, although population and services are clustered and there are large tracts of land with low population and low service density. Social Burden, as it was applied in this study, measured the availability of critical services (where people *can* go, not where people *do* go). In each one of the eight scenarios analyzed in this study, less than 1 percent of all locations that provide critical services throughout the SCE service area would lose power. Although the outages do impact critical services, many alternatives exist to serve the population. If all four heat and all four flood scenarios were to hypothetically occur at once, the resulting power loss would still result in only 2.2% of all critical service-providing locations in the SCE service area going offline. Thus, with >97-99% of critical services continuing to be available, the increase in Social Burden would be expected to be controllable. Six out of the eight hypothetical power outages explored in this study increased each individual census block group's Social Burden by 10% or less, with a median increase of just under 2.5%. The Baldwin flooding outage scenario and the Laguna heat outage scenarios were predicted to raise Social Burden by up to 49% (Baldwin) and 17% (Laguna) in some CBGs within the outage footprint, with a median increase of approximately 5%. However, when averaged across all SCE customers, the Social Burden differential of each outage was calculated to be 0.5% or less, indicating that the higher outage impacts remained localized, even for the Baldwin and Laguna scenarios.

Overall, while results from the first phase of this study suggest the SCE service area is relatively resilient to the eight specific hypothetical climate change driven outages explored in this report, there are important caveats. This analysis did not consider time-varying impacts, or cascading impacts on infrastructure (e.g., power outages disrupting service provided by non-electric infrastructure, such as impacts to transportation by traffic signal outages). Supply chain interruptions were not considered, which might extend the duration of an outage or decrease the service level at powered facilities over time, even if the grid continues providing electric power. Furthermore, the scope and redundancy of services within a 50,000 square mile and 15-million customer service area merits further investigation. Facilities which individually (e.g., a single hospital, a single retail superstore) provide high levels of service in small communities cannot unilaterally serve a population of 15 million within SCE service area as it was modeled in this study. Further analysis and stakeholder validation is required to develop guidance by which these Social Burden results can be used for decision making and investment in an absolute sense (i.e. identifying critical levels of Social Burden requiring immediate intervention), rather than a relative one (i.e., ranking and prioritizing CBGs from higher to lower Social Burden scores).

Follow-on work and research and development areas to be explored in potential subsequent phases of this partnership and by each organization individually are described in detail in the concluding sections of this report. In summary, these include the development of 1) a time-variable Social Burden formulation that accounts for outage duration and can better inform utilities of the social impacts of power outages to help align reliability and resilience investment portfolios; 2) tools to help utilities make more reliable outage predictions including duration and spatial extent; 3) refinement of geographic representation in Social Burden, including critical service boundaries and travel distances; 4) additional user-support for tools such as ReNCAT and the Social Burden metric that would simplify their adoption by utilities, and 5) fundamental research to support the development of a framework that could help guide and justify grid investment decisions based on both social and economic impacts of outages.

This report marks the completion of the first phase of an anticipated multi-phase effort. In this initial phase, a Social Burden assessment was performed for the Southern California Edison service area – a case study capturing roughly 40% of California's population. In addition to the development of a critical facilities and services database, the activities completed included the baselining of "blue-sky" Social Burden, the evaluation and integration of SCE's Community Resilience Metric into the Social Burden formulation, and the evaluation of hypothetical climate-driven impacts on the power system in relation to their expected social impact on people during an extended-duration outage. The project identified high-value next steps that can be explored in subsequent phases of this work. This phase represents an important incremental step towards the consideration of equity by utilities in infrastructure decision-making processes focused on climate resilience investments.

GLOSSARY

Term	Definition
Critical Services	Critical Services are those non-electric services that people need on a recurring basis in their day-to-day life for their health, safety, and well-being. Critical services most frequently used in past and ongoing Social Burden studies overlap in part with FEMA's lifeline services. Fifteen different kinds of critical services were considered in this study (Table 2). Note: the critical services described in this report are broader than CPUC's definition of critical infrastructure and critical facilities[1].
Facilities	Facilities considered for Social Burden analysis are those that provide critical services to people within the study area. A facility can represent a building (e.g., a hospital), an asset (e.g., a cell tower), or another infrastructure component (e.g., a traffic signal power supply) that provides one or more services and requires power to do so.
Social Burden	Social Burden is a metric used to represent the hardship different people in the same study area will experience in the process of acquiring the critical services they require to meet basic day-to-day needs and sustain their physical and mental well-being. Social Burden compares people's ability to obtain services with the effort required to do so and is a function of both the availability and quality of physical infrastructure as well as communities' socioeconomic characteristics.
"Blue-Sky" Social Burden	"Blue-sky" Social Burden is the hardship different people experience in the process of acquiring critical services during so-called "blue-sky" conditions, when the power grid is operating as normal and when all facilities and critical services that exist in a particular area are powered, operational, and providing critical services at their maximum available capacity. A high "blue-sky" Social Burden in an area indicates that investment in community non-electric services may need to be prioritized.
"Black-Sky" Social Burden	The (higher) Social Burden experienced during an outage when certain facilities are non-operational, therefore reducing availability of critical services. The "black-sky" Social Burden represents the challenge faced by communities during events, and may provide an indicator that additional investment in the community is warranted. The needed investment may or may not include investments related to electric grid resilience, depending on the Social Burden differential – see below
Social Burden Differential	The differential is the difference between "blue-sky" and "black-sky" Social Burden values, i.e., the incremental increase in Social Burden caused by grid outages. A high Social Burden differential may indicate a need for additional grid resilience, with priority given to those scenarios and locations where the resulting "black-sky" Social Burden values are also high.
Community Resilience Metric	The Community Resilience Metric is a metric intended to represent people's innate sensitivities that make them more vulnerable to climate-related threats, compared to their different levels of adaptive capacity to withstand those threats.

[1] https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M296/K598/296598822.PDF

ACRONYMS AND TERMS

Acronym/Term	Definition
CalEnviroScreen	California Communities Environmental Health Screening Tool
CalOES	California Governor's Office of Emergency Services
CalTrans	California Department of Transportation
CAVA	Climate Adaptation and Vulnerability Assessment
CBG	Census block group
CIM	Community Impact Metric
CPUC	California Public Utilities Commission
CRM	Community Resilience Metric
DBT	Design Basis Threat
DOE	U.S. Department of Energy
DVC	Disadvantaged and Vulnerable Community
EEEJ	Energy Equity and Environmental Justice
GIS	Geographic Information System
HFILD	Homeland Infrastructure Foundation-Level Data
IOU	Investor-Owned Utility
IWMS	Integrated Wildfire Mitigation Strategy
MHI	Median Household Income
OSM	OpenStreetMap; a free, open geographic database updated and maintained by a community of volunteers via open collaboration
PSAP	Public Safety Answering Point
QGIS	QGIS (Quantum GIS), is a free and open-source geographic information system software
QuickOSM	QQIS plugin to download and query OpenStreetMap data
ReNCAT	Resilient Node Cluster Analysis Tool
ROI	Return on Investment
SCE	Southern California Edison
VoS	Value of Service

1. INTRODUCTION

This report summarizes the motivation, methodology, results, and conclusions from the first, recently completed phase of an anticipated multi-phase collaboration between Sandia National Laboratories (Sandia), the California Public Utilities Commission (CPUC), and Southern California Edison (SCE). Working together, Sandia and SCE, a California Investor-Owned Utility (IOU), are studying how utilities can consider equity within climate resilience-driven infrastructure investment planning by evaluating "Social Burden." Social Burden is defined as the burden to a population for attaining needed services such as food, water, healthcare, financial services, and other services required for people's health, safety, and well-being [1] across SCE's service area. The objective of this project was to test the use of Sandia's Social Burden calculation in California and to provide a pilot metric that can reflect equity considerations. The intended outcomes of this work included identifying use cases for the metric and documenting benefits, drawbacks, and analysis of how it might apply to each use case. Potential use cases may include incorporating equity into IOUs' prioritization of climate resilience investments. Additionally, Social Burden analysis may provide additional data and insights to augment grid planning, potentially by identifying additional needs and/or prioritizing previously identified needs.

1.1. Integration of equity into resilience planning

Although there is widespread awareness of the need for equity and resilience planning and investments, in practice, operators and planners seeking to secure funding for these investments face multiple hurdles. One of these is the challenge of demonstrating confidence in the return on investment (ROI) financial or otherwise, of such investments, especially when they are being proposed as preemptive measures that seek to offset potential future harm.

Electric outages, particularly long-term outages, can take a toll on health and safety, daily life, and productivity. Most outages are short in duration. Since 2013, the average duration of electricity interruptions each year has remained consistently around two hours after excluding major events [3]. In 2022, the average US customer experienced 5.6 hours of outages and 1.4 outages per customer [3]. While it may still be challenging to predict the exact onset, extent, cause, and duration of any specific short-duration outage, in some cases probabilistic inferences can be drawn from historical data. Events that trigger long-term outages are more difficult to predict because a much smaller pool of analogous events exists in the historical record to inform probabilities and recurrence intervals [4], although active research and development to predict outage durations from the moment of impact has been ongoing [5]. The root causes of events that trigger long-duration outages may also be less stationary (e.g., climate change/natural hazards; Internet of Things (IoT)/cyberattacks [6]), thus further constraining the period of record that utilities may meaningfully draw on to inform their long-term outage planning efforts. Finally, the impacts of long-duration outages are also challenging to predict. In addition to the limited availability of representative past examples, the differences in how different people will experience the same long-duration outage are caused by diverse factors (socioeconomic and otherwise) that electric utilities traditionally are not responsible for and do not collect information about. This project undertook a demonstrable advance in the field with respect to considering how utilities could integrate information about communities into their resilience planning efforts.

The present work is motivated by the desire to better understand resilience outcomes, which we define as the extent to which communities experiencing grid power outages can weather the loss of power with limited impact to their well-being, considering how the impacts of the same outage may be experienced differently by different people. Planning for better resilience outcomes has been a challenge for grid planners and operators. Resilience and equity are part of, but not the only, considerations that utilities must make when planning and prioritizing funding and system upgrades. The work envisioned by this partnership and enabled by the completion of its first phase advances a metric that may be extended to allow for various primary objectives (e.g., resilience, reliability, affordability, decarbonization) to “crosstalk” such that different sets of project portfolios can be evaluated in tandem.

1.2. California’s efforts in equitable and resilient grid planning

The State of California has committed to reach a goal of economy-wide carbon neutrality by 2045 through a just and equitable transition from carbon-based fuels to renewable energy-powered technologies. Achieving this net-zero goal will require significant cross-sectoral investments and advancements across transportation, buildings, the electricity grid, and carbon management [7]. SCE estimates that these efforts will increase overall electricity demand in the state by approximately 82% from 2022 to 2045 [8] and require substantial investments in electric grid infrastructure. At the same time, California is facing significant challenges from climate change: rising temperatures, increasing extreme heat days, more severe precipitation and flooding events, sea level rise, and heightened wildfire and drought conditions will all impact the state's existing electricity infrastructure and the customers who rely on it [9]. To date, efforts to plan for an equitable and resilient grid in California have been framed and must be understood in the context of state climate policy and climate impacts.

In the remainder of this section, we describe two key initiatives at the CPUC focused on improving resilience and grid planning: The Climate Adaptation and Vulnerability (CAVA) proceeding and the Microgrids and Resiliency Proceeding.

1.2.1. The CAVA Proceeding: from assessing climate impacts to deploying climate-focused investments

In August 2020 the California Public Utilities Commission (CPUC) issued Decision (D.) 20-08-046 directing California's Investor-Owned Utilities (IOUs) to develop 1) a Community Engagement Plan focused on Disadvantaged and Vulnerable Communities (DVCs[2]), and 2) a Vulnerability Assessment [10].

The CPUC acknowledged in D.20-08-046 that DVCs have heightened vulnerability to impacts from climate stressors and reduced capability to adapt to potential risks and emphasized the importance of including DVC voices in utility climate adaptation efforts. Prior to developing their Vulnerability Assessments, the CPUC directed the utilities to develop Community Engagement Plans describing utility efforts to engage with and consult DVCs to determine communities' levels of adaptive capacity and strategies to best promote equity within utility climate adaptation solutions. SCE filed its first Community Engagement Plan pursuant to the Decision in May 2021. In addition, with deliberate focus on equity impacts to DVCs, the Decision directed the IOUs to develop Climate Adaptation Vulnerability Assessments (CAVAs) that would identify, analyze, and address a range of climate impacts to utility resources and develop adaptive solutions to manage vulnerabilities. The CAVAs aimed to address climate risks to utility operations, services, and assets, assess possible solutions for managing or reducing vulnerabilities, and identify adaptation solutions for vulnerable infrastructure [11]. SCE filed its first CAVA in May 2022.

Through its community engagement process, SCE developed two metrics within its 2022 CAVA designed to link equity to climate impacts and adaptation investments: the Community Resilience Metric (CRM) and the Community Impact Metric (CIM). The CRM consists of a set of scores that measure the sensitivity and adaptive capacity of a given community to a potential climate-driven loss of utility service. The CIM is a set of qualitative indicators derived from survey results and community feedback that measure the positive, negative, or neutral effect of a deployed adaptation measure on a community.

The CRM utilizes a diverse set of nearly 40 indicators that, when combined, can collectively portray a wide spectrum of socio-economic conditions which capture many different dimensions of inequities relevant to resilience. Extensive community engagement was conducted to develop these

[2] For the purpose of SCE's CAVA work, CPUC defined DVCs in the climate adaptation context as: 25% highest scoring census tracts according to the California Communities Environmental Health Screening Tool (CalEnviroScreen); all California tribal lands; census tracts with median household incomes less than 60% of state median income; and census tracts that score in the highest 5% of Pollution Burden within CalEnviroScreen but do not receive an overall CalEnviroScreen score due to unreliable public health and socioeconomic data. Refer to: https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/climate-change

indicators and the final CRM scores and results were validated through additional community feedback and adjusted accordingly.

Because of its ability to create a composite view of community adaptive capacity and sensitivity, the CRM was incorporated into Sandia's Social Burden metric for this study. See Section 2.1.2 ("The Southern California Edison Community Resilience Metric (CRM)") for more discussion on the CRM and its development process.

The CRM is also being used by SCE to help prioritize climate-driven resilience investments proposed in its 2025 General Rate Case (GRC) filing. As details of specific proposed projects are further developed and associated costs finalized, the CRM will be used among other factors to help prioritize resilience-driven projects for implementation, up to the amount approved by the Commission for each program being proposed. Specifically, CRM will be used to elevate in priority projects located in census blocks with limited adaptive capacity (low CRM scores). Similarly, locations of proposed proactive asset replacements will be selected taking into consideration low CRM scores as part of the overall selection criteria.

1.2.2. The Microgrids Proceeding: Supporting resilience at the local level

The CPUC has also conducted substantial efforts to develop and implement strategies to support local energy resiliency within the Microgrid proceeding. Initiated in October 2019, the Microgrids proceeding aimed to develop a policy framework surrounding the commercialization of microgrids and related resiliency strategies pursuant to implementation of Senate Bill 1339.The Microgrid proceeding consists of five Tracks each focusing on different resiliency priorities and how they can be achieved through microgrids and microgrid-related efforts. Track 1 of this proceeding (D.2006017, June 2020) adopted solutions to accelerate interconnection of resiliency projects in advance of the then upcoming fire season and also adopted solutions to modernize tariffs to maximize social resiliency benefits. The Track 2 Decision (January 2021) directed the IOUs to develop a statewide Microgrid Incentive Program aimed to reduce financial barriers for disadvantaged and vulnerable communities to access the energy resilience benefits possible from microgrid systems. The Decision also directed the CPUC to create a Resiliency and Microgrids Working Group to host informal workshops exploring policy issues and challenges with implementing microgrids and other related resiliency strategies. Track 4 was divided into two phases, with Phase 1 adopting near-term resiliency solutions to mitigate the risk of short-term capacity shortfall for Summers 2022 and 2023, and Phase 2 approved implementation of the IOUs' Microgrid Incentive Programs. These resiliency efforts are further detailed below.

The CPUC recognized that while microgrid systems have potentially significant energy resiliency benefits, they are novel technologies and disadvantaged and vulnerable communities would likely face substantial financial barriers to accessing the benefits microgrid systems could provide.
In the Track 2 Decision the CPUC, among other directives, ordered the IOUs to develop a Microgrid Incentive Program (MIP) specifically targeted to reducing financial barriers for equity communities to access clean community microgrids that support critical community facilities (Figure 1). The Decision directed a budget of $200 million of incentive funding for the IOUs to implement the MIP. SCE was allotted ~$83 million to implement the MIP within its service area. The eligibility requirements for community participation in the MIP are shown below. To be eligible for the MIP, a community must meet one of the parameters of A, one of the parameters of B, and the project must meet all the parameters of C.

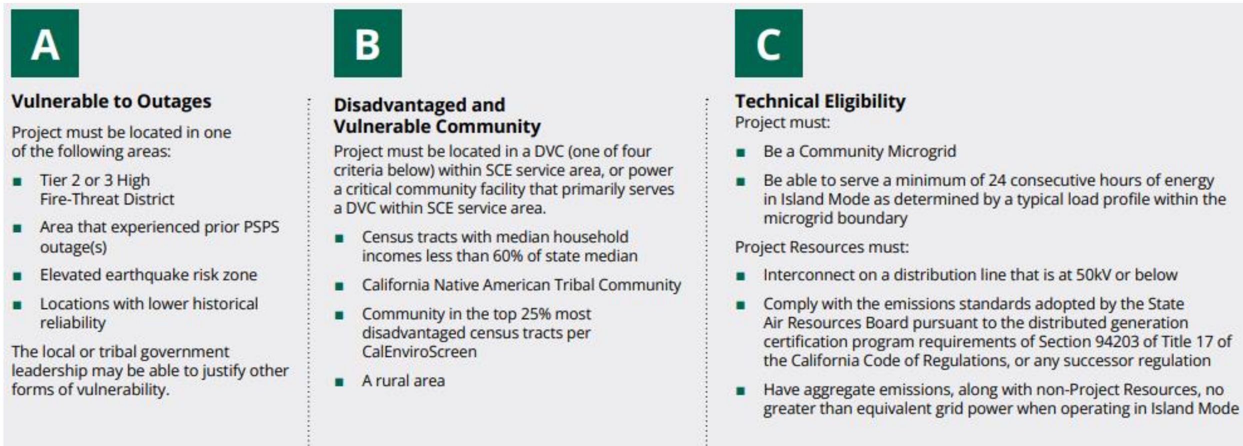

Figure 2. The Microgrid Incentive Program

As shown above, equity considerations are the crux of the MIP as the energy resilience benefits that microgrid systems could provide may be most acutely felt by the populations most vulnerable to climate impacts.

To share information about the MIP with DVCs, SCE conducted a combination of targeted social media reaching upwards of 81,000 impressions, newsletter promotion to 5000 community stakeholders in its service area, and workshops reaching more than 90 attendees from local government, tribal, or other partners. SCE is currently conducting initial consultations and technical consultations for microgrid project proposals with interested DVC applicants. Successful projects awarded incentive funding by the MIP will help enable historically disadvantaged communities to attain equitable access to energy resiliency technologies that can provide critical support to vital community resources.

On August 17, 2021, the CPUC issued an amended Scoping Memo and Ruling for Track 4 Phase 1 pursuant to Governor Newsom's Emergency Proclamation, which declared that extreme climate conditions including extensive drought and record-breaking extreme heat events had significantly strained California's energy grid. Among other directives, the Proclamation directed the CPUC to work with other regulatory entities and energy load-serving entities (LSEs) to accelerate plans for new clean energy and storage projects to mitigate the risk of capacity shortages and increase the availability of carbon-free energy. In response to the Proclamation, the CPUC issued an amended scoping memo directing parties to submit microgrid and resiliency proposals for projects that could result in increased grid reliability benefits by Summer 2023 and/or 2023[3]. Two project proposals, submitted by San Diego Gas & Electric (SDG&E) and Pacific Gas & Electric (PG&E), were approved. PG&E's proposal included expansion of its temporary generation program to contribute additional capacity to the CAISO controlled system during shortfall events, and SDG&E's proposal involved two circuit-level energy storage microgrid projects, and two additional projects, that could contribute up to a total of 40 megawatts to be available for least-cost dispatch during normal conditions in the CAISO market with revenue received from market participation partially offsetting ratepayer costs.

[3] Decision 21-12-004. Decision Adopting Microgrid and Resiliency Solutions to Enhance Summer 2022 and Summer 2023 Reliability. p.8

From October 2020 to March 2024, the CPUC hosted a series of Resiliency and Microgrids Working Group (RMWG) meetings to present and discuss with proceeding stakeholders the policy priorities for implementing microgrid systems and related resiliency projects. During workshops held May through August of 2021, CPUC staff presented the "4-Pillar Methodology" (4-PM) as a guiding framework and problem-solving approach for examining how to increase equitable electric resiliency, as it is currently understood, in a sequential, scalable, and iterative manner. The 4-PM is intended to help decision makers evaluate solutions to resiliency challenges ranging from the individual project-level up to the grid-planning level. With this methodology, staff is building on current processes with operating tools that aid in identifying what regulatory actions would be necessary to advance such equitable resiliency planning.

An important aspect of the 4-PM is to identify metrics that provide meaningful comparative analysis of effective mitigations to equitably improve resilience. Across several of the June 2021 RMWG workshops, Sandia National Laboratories (Sandia) presented their work to develop optimization models which find the "optimal investments, preemptive action, and restoration decisions to improve reliability [and] resilience." Included in these models was their Resilient Node Cluster Analysis Tool (ReNCAT) that could be used to 1) assess local community Social Burden and 2) identify optimal locations for resiliency investments to reduce impacts in areas of high social burden. The pilot partnership project between SCE and Sandia was initiated to explore the practical application of ReNCAT and the resultant Social Burden as one of those metrics.

1.2.3. Next Steps Towards Improving Resilience Planning

Currently, there are no frameworks in the grid planning process that readily enable utilities to justify the cost of investments focused on improving resiliency. Existing "value of service" estimates are quite small and generally focused on traditional reliability, making it challenging to justify costs based on this value alone. There is a known gap: traditional value of service estimates use average values applied across all customers within a class, and do not consider important impacts such as long-duration or widespread outages (the typical indicators of a "Resilience" event) or more customer-specific impacts related to income or social burden. Social Burden analysis may help solve this gap, by eventually becoming a component of a new framework used by utilities to justify new or prioritized investments to address resiliency needs.

1.3. Project Overview

The motivation for this project was to investigate the potential use of Social Burden and ReNCAT for equity-informed resilience planning in California. In this first phase of the partnership, Sandia partnered with one California IOU (SCE), to test drive the application of Social Burden in climate resilience planning to support the objective in CPUC Decision 20-08-046 for IOUs to "promote equity relative to climate adaptation of their infrastructure"[4]. The objectives of this phase were to focus on understanding the challenges associated with data collection, methodology, and computational tool validation, working through the process of integrating these frameworks with utility and PUC planning processes, and obtaining utility feedback on use cases and integration.

[4]California Public Utilities Commission. (n.d.) *Climate Adaption*. Retrieved September 11, 2024 from https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/climate-change.

SCE is one of the largest electric utilities in the United States, providing electricity service to more than 15 million people through 5 million customer accounts. SCE's service area includes portions of 15 counties with hundreds of cities and communities in a 50,000 square mile service area within Central, Coastal, and Southern California, representing approximately one third of the state's landmass (Figure 2). Thirteen federally recognized tribes reside within SCE's service area [12].

Figure 3. Study area

2. METHODOLOGY

This project explored the integration of equitable resilience metrics into electric utility climate adaptation planning processes. Southern California Edison filed California's first Climate Adaptation and Vulnerability Assessment (CAVA) in May 2022. The CAVA analyzed the impacts of changing climate patterns, including temperature, precipitation, sea level, wildfire, and cascading events on SCE's assets, operations, and service; discussed adaptation strategies for addressing these risks and presented metrics for equity-based prioritization of interventions [13]. Using the SCE CAVA as an exemplar, this project developed a methodology which allows utilities to extend, rather than replace or duplicate, their ongoing climate resilience planning efforts. This involved both technical and stakeholder outreach activities, as described below.

2.1. Technical Approach

This study incorporated SCE's CRM – developed as part of the 2022 CAVA – into Sandia's Social Burden metric. The updated Social Burden framework was used to evaluate the social impacts of eight different hypothetical grid power outage scenarios identified in SCE's 2022 CAVA. The Social Burden analysis described in this report was performed in the open-source geographic information system QGIS [14] using the QGIS Social Burden Calculator plugin that has been developed by Sandia [15] as a supplement to its Resilient Node Cluster Analysis Tool (ReNCAT) toolkit [16]. The metric integration was evaluated using several statistical analysis and modeling approaches. All metrics, methodologies, and tools are described in greater detail in the subsequent sections. Additional information regarding the statistical analysis is also provided in Appendix B.

2.1.1. The Sandia Social Burden Metric

The Social Burden metric is intended to represent the relative hardship people experience in the process of acquiring the critical services they require to meet basic day-to-day needs and sustain their physical and mental well-being [1]. For the purposes of Social Burden analysis, the term "critical services" is used in this report as a blanket term to include (1) people's *immediate needs* such as food, water, shelter, medications, and medical care, (2) *enabling (or supporting) services*, such as communications, finance, and fuel, that sustain the provision of immediate needs, and (3) other functions that sustain normal social function in communities, such as safety, security, or waste disposal. In many communities, these services are enabled by a combination of publicly and privately-owned facilities (such as grocery stores or hospitals) and infrastructure assets (such as water treatment plants or cellular towers).

Accessing critical services frequently requires physical effort, time, and expenditure of money, and other hardships and tradeoffs. The scale of these efforts depends on the *proximity* of critical service-providing locations and the *availability* of services relative to the demand for them. Other factors, like the *affordability* of the service(s) may also factor in. This combination of efforts is captured in the Social Burden metric through a spatially explicit representation of the locations of people and critical services, and further modulated by several effort parameters that approximate other variables like wait times and travel times. Some critical services, such as water treatment plants, do not require direct access or travel, but rather serve defined geographic areas in which people may benefit from their services.

Just as critical services and the physical infrastructures which provide them are not distributed in perfect uniformity, so too the social infrastructures of communities form a heterogenous landscape.

Even barring disparities in proximity and availability, not all people are equally equipped to undertake the expenditures of time, effort, and not least of all – money – that are required to successfully obtain critical services [17]. While this is true even during "blue-sky" conditions when nothing is adversely impacting the grid or the provision of critical services by infrastructure, power outages may further exacerbate these inequities. For example, in response to Hurricane Irma in Florida, higher-income individuals were able to evacuate to destinations with lower power outage rates (and higher critical service availability) than lower-income individuals [18]. For this reason, another component of Social Burden metric is the *ability* of individuals to acquire or *attain* these resources once they have arrived at the location where the critical services are available. Prior to this project, most Social Burden analyses had represented the difference in people's abilities via a single socio-economic indicator, most commonly median household income [19] or in special situations, median residential land value [20], which was meant to rank the *attainment factor* of each population group relative to others in the study area. However, in this project, in collaboration with Southern California Edison, the definition of the Social Burden ability criterion (the *attainment factor*) has been expanded to consider a 37-factor composite criterion [see Section 2.1.2 *The Southern California Edison Community Resilience Metric* for more details].

Defining Social Burden as people's access to critical services enables a spatially explicit calculation that can produce a unique Social Burden score for each population sub-group within a study area. The available granularity of the input data defines unique sub-group attainment factors and population counts. Each population sub-group represents the average of all individuals living within the sub-group's geographic boundary. For privacy and public data availability reasons, Social Burden analysis does not represent each individual person in a sub-group separately. As a result, acute medical needs of individual members of a sub-group are not included in this analysis. Social Burden scores can be aggregated and disaggregated by population subset and by service category. Social Burden scores can be represented on a per-capita basis, or multiplied by population counts for the respective population sub-group polygons to obtain population-weighted Social Burden scores. Social Burden can be calculated and represented on a per-service basis, individually for each critical service category, or aggregated with any number of per-service Social Burden scores added together. The total sum of all per-service Social Burden scores – the burden associated with acquiring the full portfolio of necessary services – represents the overall Social Burden.

2.1.1.1. Rationale

Sandia's Social Burden metric has been used to study equity and the resilience of communities to power system disruptions in 18 communities ranging in size and composition. As a resilience metric, Social Burden can quantify the potential human impact resulting from the loss of critical services following some major disruptive event that results in electric grid outages and other infrastructure damages [1]. As an equity metric, Social Burden can identify the disparities in hardship experienced by people in a study area as a function of their social and physical infrastructures: i.e., the differences in people's baseline capacity to undertake the time, effort, and cost requirements necessary for obtaining all critical services (social infrastructure) and the availability and proximity of critical services to where people are located (physical infrastructure). As an equitable resilience metric, Social Burden can measure disparities in the impact of power outages and benchmark progress towards and evaluate efforts to enhance energy justice. Energy justice refers to the concepts of equity, affordability, accessibility, and participation in the energy system and energy transition regardless of race, nationality, income, or geographic location [21]. Energy justice can be achieved by reducing energy costs and burdens on low-income customers; avoiding disproportionate impacts; and ensuring equitable benefits, access to reliable and clean energy, and inviting community participation in energy sector decision-making and development [21]. Access to services is a primary measure of energy justice [22]. Social Burden directly measures this access and identifies disproportionate impacts of energy provision (or the lack thereof). Social Burden also provides a framework for direct, measurable participation of stakeholders in the energy system by encouraging community-sourced, or community-vetted, identification and prioritization of critical services.

2.1.1.2. Formulation

Conceptually, Social Burden may be described as:

$$Social\ Burden = \frac{Effort}{Ability} \cong \frac{Distances\ to\ Services_{people,services}}{Service\ Levels_{facilities,services} \times Attainmnet\ Factor_{people}}$$

Mathematically, the conceptual formulation is defined as:

$SB_{n,m} = \frac{E_{n,m}}{A_n}$, where $SB_{n,m}$ is the Social Burden, a matrix over discrete space composed of population sub-groups (*n*) and infrastructure services (*m*); $E_{n,m}$ is the Attainment Effort, or how hard people work to attain their infrastructure needs, also an *n x m* matrix; and A_n is the Attainment Ability, or the resources people have at their disposal for attaining their infrastructure service needs, not dependent on the type of service, a vector of length *n*. Effort (E) is a function of the individual "pairwise efforts" between each spatial element (*n*) and each point that provides an infrastructure service (*l*), as follows:

$E_{n,m} = \frac{1}{\sum_l S_{l,m}/I_{n,l}}$, where $S_{l,m}$ is the Infrastructure to Service relationship, a matrix of infrastructure locations (l) and infrastructure services (m); and $I_{n,l}$ are the individual pairwise efforts between spatial elements (*n*) and infrastructure points.

Refer to [1] and [16] for more information on the Social Burden metric formulation and its implementation.

2.1.1.3. Inputs

As described in the Formulation section above, the calculation of Social Burden requires information about how facilities (*l*) are providing critical services (*m*) to people (*n*). This includes information cataloging the facilities (i.e., their location and the service levels per service), services (i.e., the service to facility mapping), and people (i.e., location, population counts, and attainment factors for each population group evaluated in the study) contained within the study area.

2.1.1.3.1. Facilities

The definition of facilities in the context of Social Burden analysis is locations that provide critical services to people within the study area. A facility can represent a building (e.g., a hospital), an asset (e.g., a cell tower), or another infrastructure component (e.g., a traffic signal power supply) that provides one or more services and requires power to do so [16]. Sandia and SCE identified 54 unique categories of facilities that were to be considered in this study (Table 1). Data on the distribution of these facilities throughout the SCE service area were obtained from a collection of open-source databases, including ones maintained by federal agencies such as the U.S. Department of Homeland Security [23] and state agencies such as the California Department of Transportation [24] and the California Governor's Office of Emergency Services [25]. Select datasets were provided to Sandia directly by SCE. Sandia filled any remaining data gaps using OpenStreetMap (OSM), which is a free, open geographic database updated and maintained by a community of volunteers via open collaboration. Contributors to OSM collect data from surveys, trace from aerial imagery and import from other freely licensed geodata sources [26]. See Table A-1 in Appendix A for complete list of facilities and corresponding data sources. The spatial distribution of facilities relative to the SCE service area (the project study area) is shown in Figure 3. Each facility has a unique XY coordinate placing it in space.

Table 1. List of facilities evaluated in the study, categorized by facility category, primary service, and facility type

Category	Primary Service	Facility Type
Emergency Services	Evacuation	Emergency Operations Center
	Emergency Logistics	Point of Distribution, Public Safety Answering Point (PSAP), Public Safety Communication Site
	Medical Services	Hospital, Urgent Care, VA Medical Facility, EMS, Air Ambulance, Clinic
	Security	Local Law Enforcement
	Safety	Fire Station
Basic Needs	Shelter	Shelter, Cooling Center, Hotel, Motel
	Food	Food Bank, Convenience Store, Greengrocer, Grocery Store, Supermarket, Retail Superstore (e.g., Walmart), Fast Food
	Water	Water Storage Tank, Water Purification Main Office, Water Tower, Drinking Water Access Point
	Medications	Pharmacy
	Finance	Bank Branch, ATM, Money Transfer
Critical Infrastructure	Communications	AM/FM Transmission Tower, Cellular Tower, Microwave Tower
	Electricity	Service Center
	Waste Management	Landfill, Sewer Pump, Wastewater Treatment Plant
Mobility	Transportation	Port, Public Airport, Military Airport, Metro Station, Bus Station, Car Rental, Cruiseline Terminal, EV Charging Point, Ferry Terminal, Rail Station, CalTrans Maintenance Facilities, Rail Yard
	Fuel	Oil Refinery, Gas Station, Natural Gas Facility

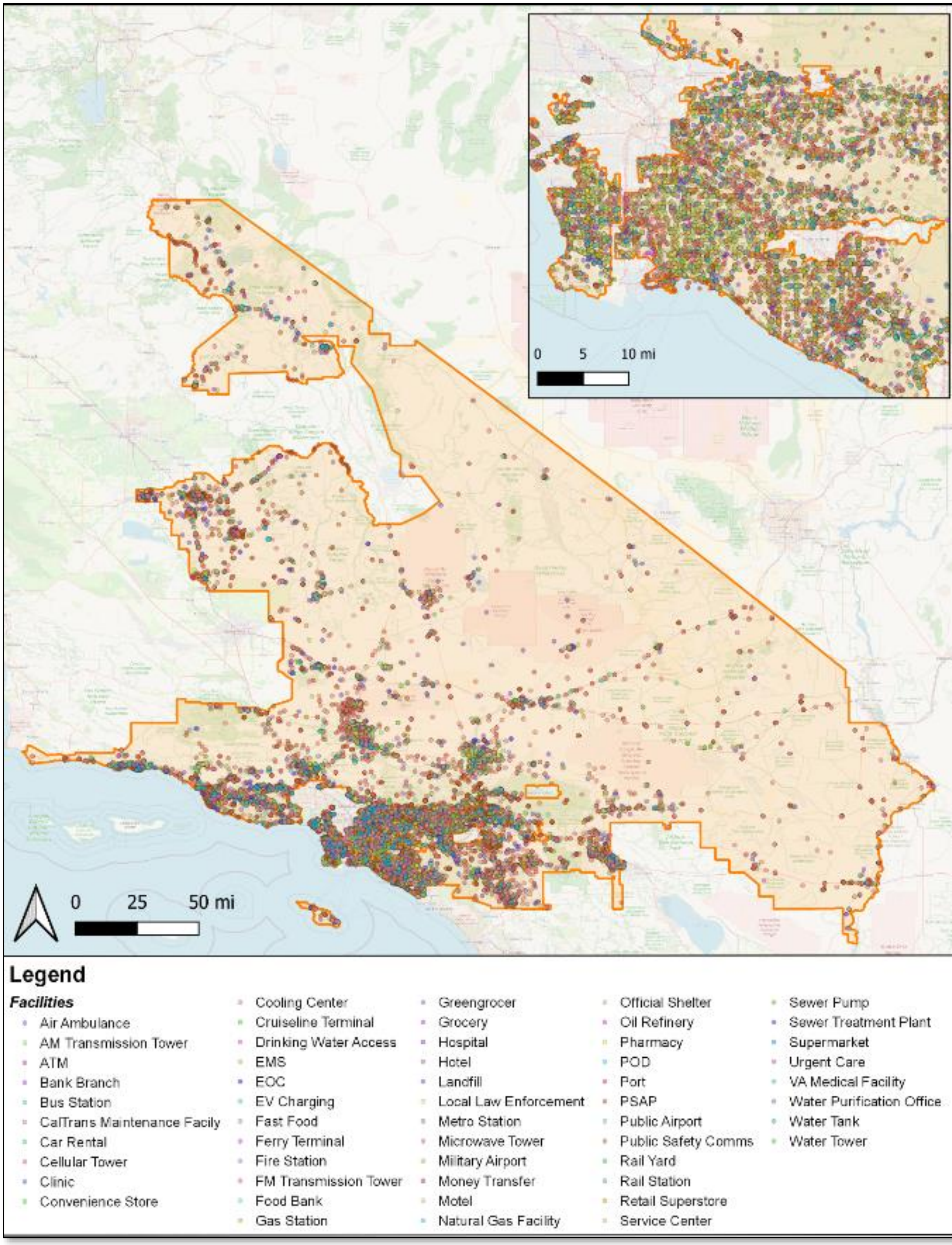

Figure 4. Map showing the distribution of facilities across the study area

2.1.1.3.2. Services

Critical Services are those services that people need on a recurring basis in their day-to-day life for their health, safety, and well-being. Critical services most frequently used in past and ongoing Social Burden studies overlap in part with FEMA's lifeline services [27]. Fifteen different kinds of critical services were considered in this study (Table 2). Each facility (see discussion above) provides one or more types of critical services, thus matrixing the services to specific points in space (X-Y location of facilities) within the study area. The same service can be provided at multiple facility types (e.g., water and food may be available at both grocery stores and gas stations). Among different facility categories that supply the same type of service, the level of service can vary. Some of the considerations for determining the level of service include how many people the facility could serve, and if applicable, how much supply the facility has and how long it would last. Service levels are assessed from the viewpoint of how much service they provide to the community at large. A fire station may have ample shelter, food, and water for the firefighters who the facility is designed for and stocked to house during normal operating conditions. However, that same supply of shelter, food, and water can fulfill only a fraction of the entire community's needs. Therefore, the service levels assigned to the fire station would be ranked low [16].

Table 2. Critical services and their descriptions.

Critical Service	Short Description
Communications	Infrastructure contributing to communication services such as cell phone towers, cable systems, TV and radio, satellite, and internet.
Emergency Logistics	Infrastructure and personnel enabling and carrying out logistics during emergency situations, including emergency systems such as alerts, warnings, 911 and dispatch, responder networks, enabling government organizations, and the responders themselves.
Evacuation	Services helping residents leave areas posing a threat to their wellbeing.
Finance	Banking services, including money transfer and cash withdrawals.
Food	Emergency food distribution and places where food is available for purchase.
Fuel	Processing, storage, and distribution of fuels (gas stations, refuel points)
Medical Service	Facilities providing medical care outside the home such as hospitals, long-term health facilities, dialysis, etc.
Medications	Over-the-counter and prescription pharmaceuticals.
Restoration	Services that help with the coordination, supply, and/or execution of restoration activities.
Safety	Primarily fire departments and search and rescue; services that enable them to operate, and services that help prevent threat-related impacts within the community.
Security	Primarily police stations and the services that enable them to operate.
Shelter	Official and unofficial shelters that can be used to shelter residents who have evacuated their homes.
Transportation	Services that enable transportation, including taxis, rental cars, public transportation networks (such as buses, trains, metros), electric vehicle charging locations, airports, and ports.
Waste Management	Solid waste and wastewater systems that serve the community.

Critical Service	Short Description
Water	Drinking water utilities (intake, treatment, storage, distribution), emergency drinking water distribution, bottled water available for purchase, and drinking water access points.

2.1.1.3.3. People

Attaining critical services may require certain members of the community to travel further than others in search of available facilities. Furthermore, some subsets of the population may be better able to absorb disruptions than others.

A Social Burden analysis requires three pieces of information about the people within the study area:

- Where they are, relative to where facilities and services are located;
- How the population is distributed across the study area; and
- How some relevant equity criterion, describing the resources that different people have at their disposal to enable them to obtain critical services, is distributed across the study area.

The equity criterion is represented in a Social Burden analysis by an attainment factor. The attainment factor is a quantitative measure of some proxy variable that accounts for the key aspects of vulnerability and/or capacity, that make obtaining critical services more difficult for some members of the community than others. In this study, Sandia integrated the SCE CRM as the Social Burden "attainment factor" (equity criterion) and relied on the U.S. Census for population count data. The study area is divided into population blocks, which set the spatial granularity of the Social Burden analysis. Each population block is anchored in space by its centroid and represents people living in that region within the study area as a single unit. Each population block is assigned a population count and a single representative value of the attainment factor. In this, and most previous studies, Sandia relies on the Census Block Group (CBG) (statistical divisions of census tracts generally defined to contained between 600 and 3,000 people – see [28]) to define the population block geometry. As noted previously, CBGs represent the most granular level at which extensive socioeconomic datasets are made available by the US Census Bureau. Refer to Figure 4 for a spatial representation of the distribution of population across the study area, and to Figure 5 for the distribution of SCE's CRM scores (percentile rank transformed). Table 3 summarizes population statistics.

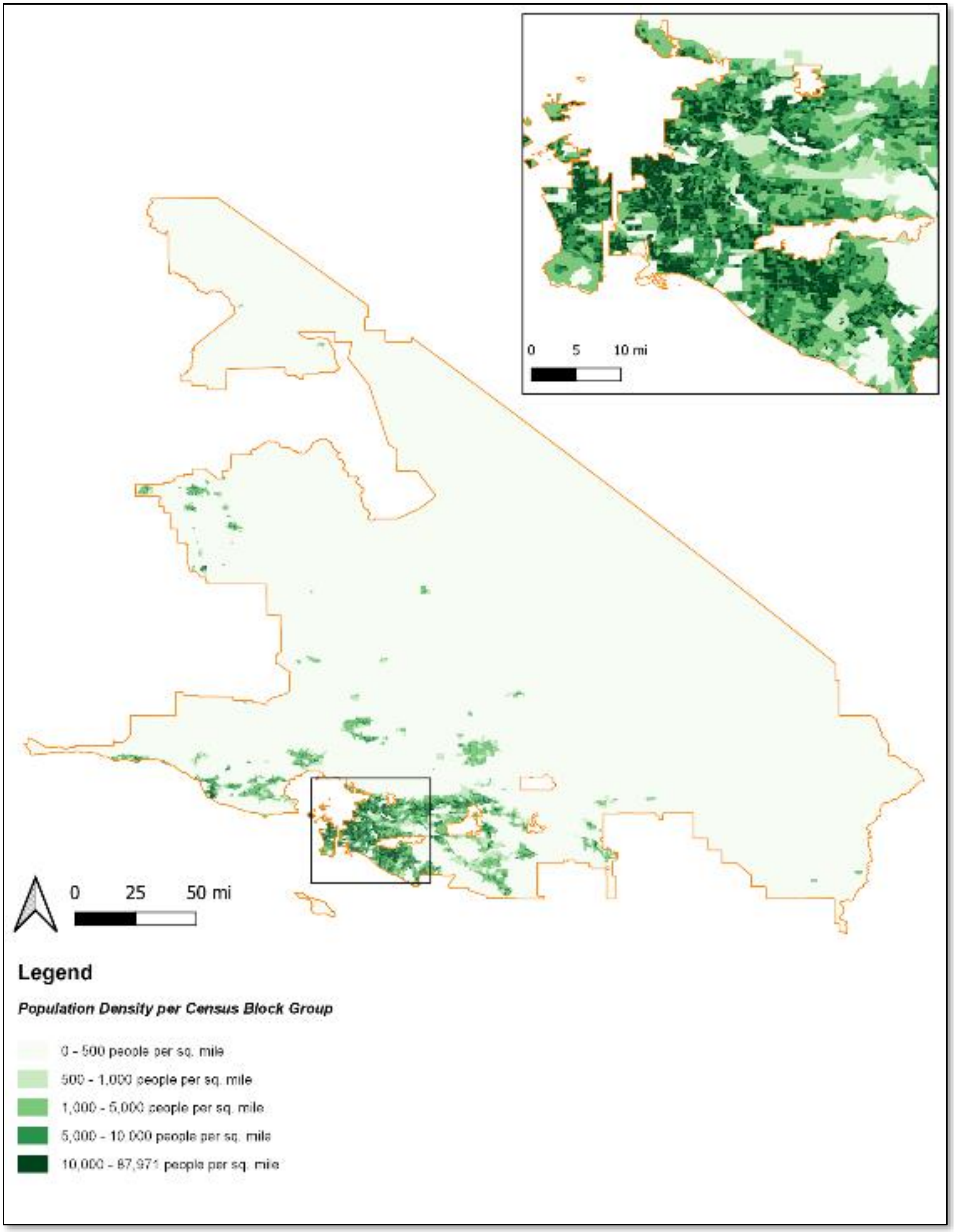

Figure 5. Spatial distribution of population counts per census block group across the study area

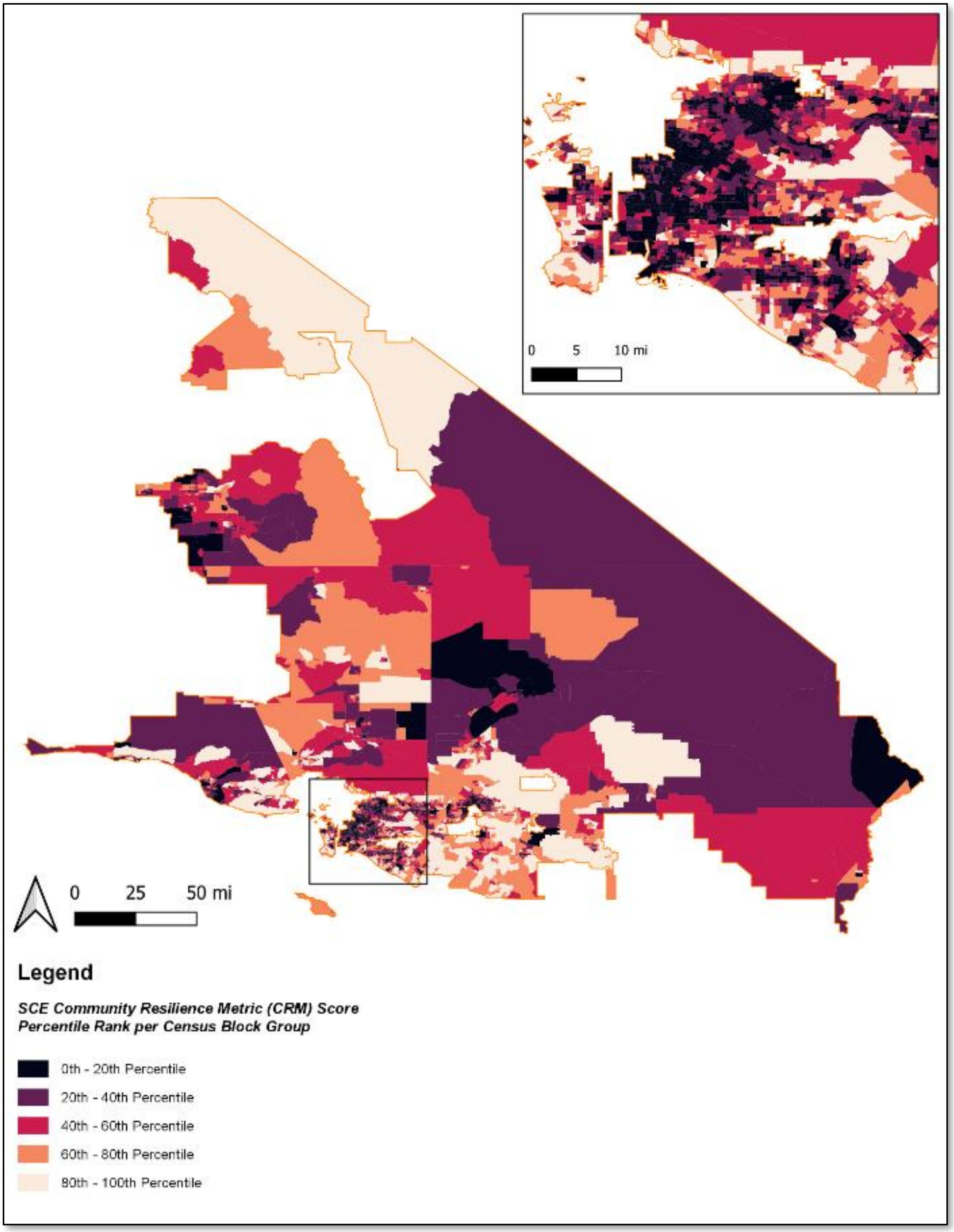

Figure 6. Spatial distribution of Community Resilience Metric percentile ranked scores per census block group across the study area

Table 3. Summary statistics describing people included in the project analysis

Count	Attribute
9,094	Census block groups
14,613,508	Sum population

2.1.1.3.4. Threats

Social Burden is a threat-informed analysis framework, meaning that it can be used to calculate the Social Burden implications of a threat that could disrupt power or other infrastructure if the analyst performs a series of pre-processing steps to identify the area of impact. Analyst-identified severity of damage to a facility providing critical services and the resulting reduction in level of service can likewise be considered. Specifically, the framework would calculate the updated Social Burden for a population once any facilities providing critical services are no longer available following the disruptive event. Typically, threats that should be considered for inclusion in a ReNCAT model are those that impact resilience and are low probability but high consequence. These might include natural hazards like flooding, wildfires, or hurricanes, or threats by malicious actors, like a cyberattack [16]. However, any threat (singular or compounded) can be considered for "what-if" scenario-based Social Burden evaluation, provided the user can estimate the outage area of impact and any additional damage to facilities (e.g., flooding) which would reduce their ability to provide critical services even if power remains available. In this study, climate-related threats to the SCE service area were evaluated. The threats were represented by a set of alternative hypothetical flooding and heat events that impacted specific equipment throughout the SCE system and resulted in (hypothetical) power outages.

2.1.2. The Southern California Edison Community Resilience Metric (CRM)

As part of the CAVA process, the CPUC directed SCE to determine methods for identifying and prioritizing utility climate adaptation investments in Disadvantaged and Vulnerable Communities (DVCs). In response, SCE conducted extensive engagement with CBO leaders operating in DVCs. This work was conducted by convening SCE's first Climate Resilience Leadership Group (CRLG) cohort in September 2021, with the intention of improving engagement with DVCs on utility climate adaptation efforts. SCE's approach of developing and engaging a CRLG was informed by prior outreach efforts across its service area, which inform the engagement objectives and subsequent approaches adopted by SCE in forming its Community Engagement Plan to develop its CAVA. The CRLG consisted of a competitively solicited, paid, six-month opportunity for community leaders operating in DVCs to work with SCE on climate adaptation in the electricity sector.

The CRLG cohort consists of 11 community leaders:

- American Indian Chamber of Commerce of California
- Breathe Southern California (Breathe So Cal)
- Building Resilient Communities (BRC)
- Day One
- East San Gabriel Japanese Community Center (ESGVJCC)
- East Yard Communities for Environmental Justice (East Yard)
- Fierce Courage

- Happy Fifty Plus (Happy 50+)
- High Sierra Energy Foundation (HSEF)
- Inland Empire Concerned African American Churches (IECAAC)
- Village Solutions Foundation (Village Solutions).

SCE convened the CRLG thirteen times from October 2021 through March 2022. The first three months of convening the CRLG were primarily dedicated to educating members about climate change and SCE's climate adaptation work; learning together on the best strategies for DVC engagement; and co-developing adaptation materials and surveys for DVC engagement, including translations into different target languages. During the second three months, CRLG members further refined their communication and outreach strategies and directly engaged with DVCs to gather feedback on SCE's potential climate adaptation strategies and the perceived climate resilience of DVCs.

In total, the CRLG engaged 75 DVCs, reaching communities representing 60.3% of SCE's DVC population[5], along with 11 tribes[6]. At total of 792 surveys were collected to inform SCE's CRM and CIM. CRLG's efforts enabled SCE to benefit from both quantitative and qualitative data to design its metrics tied to community resilience and adaptation investment.

The CRLG helped shape the development of two metrics within the 2022 CAVA that could link equity to adaptation investments. The first metric, the Community Resilience Metric (CRM), is a set of scores measuring the sensitivity and adaptive capacity of a given community to a potential climate-driven loss of utility service. The second metric, the Community Impact Metric (CIM), is a set of indicators that measure the positive, negative, or neutral effect on a community of an adaptation being deployed in that community. The CRLG also helped verify CRM scoring via a ground-truthing process in which they administered surveys in DVCs.

The CRM was meant to help SCE answer the question of where to build adaptations first. The CRM can be used to help prioritize the timing or order of adaptations based on socioeconomic indicators that approximate a community's resilience to the impacts of climate threats, including potential power outages. It was adapted to and used in the Social Burden evaluation performed in this project.

[5] On October 21, 2021 -- after the CRLG process had begun, CalEnviroscreen v. 4.0 was officially released, resulting in about 70 new census tracts and seven new cities in SCE's service territory that are now considered DVCs. The new DVC cities are: Azuza, Exeter, Hinkley, Littlerock, Midway City, Tustin, and Santa Barbara. These additional cities will be included as SCE continues DVC engagement in the implementation of the CAVA and development of future CEPs.

[6] Tribal feedback consisted of one response per tribe voted on by its leadership. In contrast, the feedback from non-tribal DVC members was collected on a person-by-person basis. As a result of these differing methodologies, SCE analyzed tribal data separately from the remainder of the DVC data collected.

2.1.2.1.1. Rationale for the CRM as a measure of baseline community wellbeing

The CRM was originally developed to represent a community's resilience to electrical outages caused by climate events. To do this, it draws upon a diverse set of nearly 40 indicators that represent broader community wellbeing. These indicators collectively portray a wide spectrum of socio-economic conditions which capture many different dimensions of inequities relevant to resilience. The CRM defines resilience as a range, rather than a binary designation, and thereby avoids applying stringent or arbitrary thresholds to equity data.

In the eyes of the communities within SCE's service area, the CRM indicators and their groupings, or domains, characterize the primary equity dimensions that should be considered when prioritizing adaptations. This is because each indicator and domain, and its respective data source and weighting, was selected for use in the CRM based on feedback received through community workshops and surveys involving the 11 CRLG cohort participants and 12 social science data and equity experts. This group consisted of leaders with lived experience operating in underserved communities and experts in social science data techniques for accommodating equity. Most importantly, the final CRM scores and results were validated through additional community feedback and adjusted accordingly. One key adjustment that was implemented following survey results from tribal representatives was a 16% score decrease to all census block groups that included any federally recognized tribal land.

2.1.2.1.2. Formulation

The CRM consists of two components: sensitivity and adaptive capacity. Each of these components is comprised of four equally weighted domains, with each domain score being the average of its normalized indicator values. The sum of a census block group's sensitivity domains (a negative value) is added to the sum of the same census block group's adaptive capacity domains (a positive value), to result in the community's resilience score (CRM).

$$\sum Sensitivity + \sum Adaptive\ Capacity = Community\ Resilience\ Score\ (CRM)$$

Where:

$$\sum Sensitivity = \sum Sensitivity\ Domains$$

$$\sum Adaptive\ Capacity = \sum Adaptive\ Capacity\ Domains$$

$$Domain_{\mathrm{x}} = \overline{Normalized\ Indicators_{\mathrm{x}}}$$

$$Normalized\ Indicator_{\mathrm{x}} = \frac{(Indicator_{\mathrm{x}} - Indicator_{min})}{(Indicator_{max} - Indicator_{min})}$$

$$Indicator_{min} = Minimum\ value\ over\ SCE\ service\ area\ Indicator_{max} = Maximum\ value\ over\ SCE\ service\ area$$

A community's sensitivity refers to the degree to which a community is affected by power outages. A community's adaptive capacity refers to the ability of the community to adjust, moderate damages, and cope with the consequences of power outages.

To better understand how the CRM represents sensitivity and adaptive capacity, consider this example:

- Climate event: There is a heat wave in my neighborhood.
- Sensitivity: I am elderly.
- Adaptive capacity: My community has organized a program to transport residents to Cooling Centers.

2.1.2.1.3. Inputs

The CRM used in this study is calculated at the CBG level and is based on 12 indicators under 4 domains of Adaptive Capacity and 25 indicators under 4 domains of Sensitivity. The original CRM developed in the 2022 CAVA was calculated by census tract. For this project, the CRM data sources were updated, and the metric was recalculated at the more granular census block group level. Indicator data come from the American Community Survey (ACS), Healthy Places Index (HPI), CalEnviroScreen (CES), Centers for Disease Control and Prevention (CDC) PLACES, National Land Cover Database (NLCD), and more. Indicators are equally weighted within each domain with the exception of the Built Environment domain under Sensitivity. Within this domain, the CalEnviroScreen Pollution Burden indicator is weighted as 12/13 while the Noise Pollution indicator is weighted as 1/13, because the CalEnviroScreen indicator represents 12 unique pollutants. The Sensitivity and Adaptive Capacity Indicators are displayed in Tables 4 and 5 below.

Table 4. Sensitivity Indicators and their corresponding domain groupings

Domain	Sensitivity Indicators
Built Environment	CalEnviroScreen pollution burden; Noise pollution
Health	Asthma; Cardiovascular disease; Children; Diabetes; Disability; Health insurance; Medical baseline
Housing	Group quarters; Housing burden; Housing quality; Mobile homes; Renters
Socio-Economic	Educational attainment; Elderly living alone; Foreign born; Linguistic isolation; Outdoor workers; Poverty; Race/ethnicity; Rural communities; Single female head of household; Tribal and indigenous; Unemployment

Table 5. Domain groupings of 12 Adaptive Capacity Indicators

Domain	Adaptive Capacity Indicators
Community Built Environment	Permeable surface cover; Tree canopy/green space
Governance and Services	Cooling centers; Medical facilities; Planning level; Supermarket access; Urgent Care facilities; Voters
Individual Built Environment	Air conditioning; Telecommunications access
Transportation	Transit access; Vehicle access

2.1.3. *Integration of the Community Resilience Metric and Social Burden*

2.1.3.1. Rationale

The definition of CRM as a composite of community adaptive capacity and sensitivity paints a multi-faceted picture of the baseline capacity of communities within the SCE service area and the project's area of interest. The CRM is quantitative, and its inputs and outputs are available at spatial scales that are appropriate for the level of granularity of a Social Burden analysis. Social Burden extends the CRM as a measure of community-level resilience because the Social Burden metric can be used to measure the impact of disruption in power supply as well predict the impact of mitigations or adaptation measures (e.g., the addition of cooling centers, investment in backup power systems, etc.). It can also measure the impact of changing socio-economic and other population sensitivity or adaptive capacity factors on people's Social Burden during "blue-sky" or "black-sky" conditions (i.e., when the grid is operating at full capacity versus when a grid outage causes infrastructure to lose power and critical service provision to be reduced). By contrast, CRM is a static measure of community wellbeing. It can be updated when new data on its component indicators is made available, but it is not structured to assimilate or represent the impact from a power outage or other infrastructure failure. Thus, the CRM lends itself to representing the baseline state of different populations as they approach an outage scenario. It is complementary but not redundant to a Social Burden analysis.

2.1.3.2. Transformation

Computationally, the Social Burden formula requires attainment factors (proxy of ability criterion) be non-zero inputs, so the calculation does not result in division by zero. Conceptually, the Social Burden formula also assumes that attainment factors will be positive numbers. Consequently, in order to integrate CRM into Social Burden, it was necessary to transform CRM from [-infinity, +infinity] to a (0, +infinity] space. This was accomplished using the percentile rank function in python (scipy.stats.percentileofscore) [29] to transform the raw CRM scores into transformed CRM scores that were used in the subsequent Social Burden calculation.

2.1.3.3. Formulation

The CRM-adjusted Social Burden formulation is defined as follows:

$$SB = \frac{Distances\ to\ Services_{people,services}}{Service\ Levels_{facilities,services} \times CRM\_percentRank_{people}}$$

NOTE: This is a specific formulation of Social Burden developed in collaboration with SCE for this collaborative project; previous applications of Social Burden in other communities utilized other socioeconomic indicators as proxies for the population sub-groups relative attainment factors and did not rely on SCE's CRM.

2.1.4. Software Tools

In this project, Sandia relied on the tools it has developed as part of its ReNCAT toolkit. ReNCAT (Resilient Node Cluster Analysis Tool) is a software application that suggests distribution system resilience upgrade portfolios that are co-optimized using a genetic algorithm to reduce the impact of bulk grid power outages, as measured by the Social Burden metric, at least cost [16]. ReNCAT is a desktop application that runs on Windows operating systems. It is available to be used by government, educational, and commercial organizations. ReNCAT contains two capabilities: Social Burden evaluation and investment optimization, that can be applied to three applications: Social Burden evaluation, resilience investment optimization, and "what if" scenario evaluation which can explore other modifications to the built (physical) and social landscapes [16]. The work described here evaluated Social Burden in response to alternative outage scenarios but did not utilize the optimization capability of the ReNCAT tool to explore mitigation options.

The analysis performed under this project was performed in QGIS Desktop 3.28.1 [9] using a custom open-source plugin created by Sandia called the "Social Burden Calculator". The Social Burden Calculator installation is available for download as a zip file containing source code and all ancillary files through the developer platform GitHub [15], or it can be added to a user's QGIS environment directly by loading the Social Burden Calculator from the official QGIS Python Plugins Repository [30]. The QGIS Social Burden Calculator Plugin calculates total, per-service, and per-population group Social Burden scores and provides the outputs in shapefile and tabular formats for visualizing, mapping, analyzing, and post-processing.

2.2. Stakeholder Engagement

One way that energy justice can be advanced is by inviting community participation in energy sector decision-making and development. Therefore, although the CRM and Social Burden had been separately reviewed with stakeholders and communities prior to this project, stakeholder engagement and public awareness were considered a cornerstone of a successful project.

Over the course of this partnership project, Sandia, CPUC, and SCE hosted three public webinars. These webinars were open to the public and CPUC stakeholders. Participants were encouraged to engage with the project team and share how the proposed study or its particulars (e.g., the Social Burden framework; the integration of CRM and Social Burden; etc.) mapped to their priorities and objectives for equitable and resilient climate-informed grid planning.

Copies of the agendas, presentation materials, and recordings are archived by CPUC and made publicly available on the Resiliency and Microgrids Events and Materials webpage [31]. On July 7, 2022, the webinar series kicked off with a workshop on the Value of Resiliency: Economic & Equity Impacts of Large Disruptions. Sandia presented an introduction to ReNCAT and the Social Burden metric and fielded stakeholder questions about the metric, software, and process [32]. On July 26, 2023, SCE and Sandia delivered a presentation as part of the CPUC Energy Division's Workshop Series on Resiliency that covered the SCE CRM, the Sandia Social Burden Metric, and the planned integration of the two metrices in this project [33]. On November 28, 2023, Sandia and SCE presented final results and discussed next steps for the collaboration [34].

3. SCENARIO DEVELOPMENT

Sandia and SCE collaborated to develop a series of scenarios that were used as the foundation for Social Burden evaluations within SCE's service area under normal grid operation and climate change driven outage conditions. These scenarios intentionally depict climate-driven events, e.g., extreme heat or flooding, that can impact normal grid operations and lead to equipment failure and customer outages. The focus on climate-driven resilience scenarios in this study is consistent with the broader context of equitable and resilient grid planning in California: specifically, the need to better understand how climate change may affect SCE's service area and pose resilience impacts for diverse communities, and how utilities can better prepare for such impacts. These scenarios consisted of a "blue-sky" baseline Social Burden scenario and eight outage scenarios that spanned different climate impacts, locations, customer classes and counts, and other key parameters. The baseline scenario evaluated Social Burden in the SCE service area on a "blue-sky" day when the grid was fully powered, and the state of the power system introduced no additional burden. The outage scenarios evaluated how Social Burden in the SCE service area may be impacted in the event of various climate vulnerabilities and associated hypothetical equipment failures.

3.1. The "Blue-Sky" Baseline Scenario

The "blue-sky" scenario was evaluated to establish a baseline distribution of Social Burden in the SCE service area. "Blue-sky" refers to the state of operation of the power grid, as well as all other infrastructure providing critical services in the study area, when there is no disruption, and all infrastructures are operating at normal capacity. Social Burden during the "blue-sky", or baseline, state reflects the inherent differences in the availability and accessibility of critical services in the study area and underlying social capacity (i.e., people's differing abilities to obtain those services). Because the grid is fully up and running in this scenario, power outages do not introduce any additional burden by reducing access to services. During the baseline state, Social Burden is going to be at its lowest – for all people and across all service categories, although notably, never zero, since people will still expend effort to travel to locations where critical services are provided and spend resources (time and money) to acquire those services.

3.1.1. Rationale

The "blue-sky" Social Burden can be used as an equity metric on its own. Additionally, Social Burden results from a "blue-sky" scenario can be compared to Social Burden results from an outage scenario to capture the impact of a power outage on social burden. The difference, or the differential between the Social Burden under "blue-sky" conditions and that calculated under outage conditions, can be used to describe the resilience or lack thereof of the study area and its population to a particular outage scenario.

3.1.2. Assumptions, Inputs, and Limitations

During the "blue-sky" scenario, the grid is assumed to be completely powered, with all available facilities online. All existing facilities are assumed to provide full service to people. The analysis is subject to limitations related to 1) the imperfect nature of the input datasets (for more information about the origin of facility and critical service datasets, refer to Appendix A), 2) structural sources of error related to the simplification of complex social phenomena to a deterministic framework, as well as 3) random error, which is likely to exist when attempting to encapsulate unpredictable human behavior, especially under duress. Refer to the Discussion and Conclusion chapters for further explanation on uncertainty quantification and future work.

3.2. The Climate Change Driven Hypothetical Outage Scenarios

A "black-sky" scenario in Social Burden analysis can represent any partial or total outage on the grid. The outages can be hypothetical or based on real (historic or projected) events. In this study, the outage scenarios are hypothetical and based on SCE's prior analysis of potential climate impacts in its service area as documented in the 2022 CAVA. SCE chose outage scenarios driven by extreme heat and flooding because these variables have reasonably well-defined geographic boundaries, lending themselves well to a pilot geospatial analysis. Extreme heat outage scenarios were chosen by identifying areas with a high number of projected heatwaves in 2030 and substation transformers with low health indices. Flood outage scenarios were chosen by identifying 100-year FEMA floodplains near each other with the potential to be joined by flowlines under an extreme flood event. In this project, a subset of the CAVA heat and flood scenarios were used to explore the Social Burden response to potential outages in these locations. Four of the 13 heat outage scenarios, and four of the 14 flood outage scenarios were evaluated (Table 6, Figure 6). These scenarios should be considered to depict illustrative rather than likely outages (see Assumptions, Inputs, and Limitations, below).

Table 6. Summary of the climate threat scenarios explored through Social Burden analysis

Hazard	Scenario Name	County	CRM	Rural	Customer Count	IWMS Risk[7]
Temperature	Hemet	Riverside	High	Low	Medium	Medium
Temperature	Chino	San Bernardino	High	Low	Medium	Medium
Temperature	Baldwin	Los Angeles	Low	Low	High	Low
Temperature	Jurupa	San Bernardino	Low	Low	Low	Low
Flood	Laguna	Orange	High	Low	Medium	High
Flood	Oxnard	Ventura	Low	Low	High	Low
Flood	Fillmore	Ventura	Medium	Medium	Low	High
Flood	Westminster	Orange	Medium	Low	Medium	Low

[7] IWMS (Integrated Wildfire Mitigation Strategy) is SCE's holistic approach to developing portfolios of effective and complementary mitigations and deploying them in a manner that focuses on the areas of greatest risk. IWMS defines 3 risk tranches based on wildfire burn, consequence, and road availability. IWMS is included here for its measure of road availability used as a proxy for egress and evacuation ability.

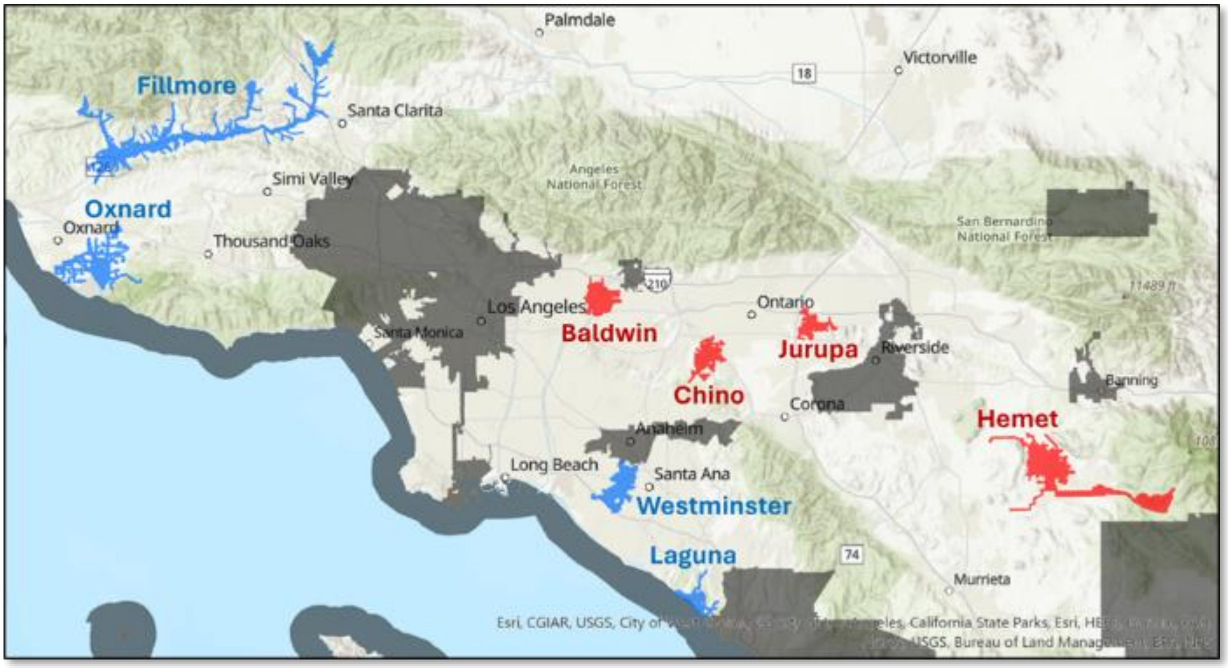

Figure 7. Hypothetical outage scenarios

3.2.1. Motivation

The purpose of studying these specific climate change driven scenarios was to explore the potential implications of different outage characteristics (e.g., geographic extent, customer composition, location, threat type) on Social Burden outcomes. The subset of original heat- and flood-driven scenarios selected for analysis from the original set of CAVA scenarios was therefore chosen to capture a range of customer and location characteristics (see Table 6 for a summary of characteristics considered). Specifically, these include a range of CRM scores of affected census block groups (CBGs), customer diversity (urban versus rural), number of customers without power, and evacuation difficulty.

3.2.2. Assumptions, Inputs, and Limitations

These hypothetical outage scenarios represent the possible geographic extent of outages resulting from the failure of key equipment due to climate hazards. These scenarios assume that failures of key equipment interrupt the flow of electricity to downstream equipment and customers. These scenarios are designed to be liberal in their extent: i.e., they do not account for existing system redundancies that would preserve electric service for portions of the geographic areas marked as affected. Therefore, SCE does not consider these to be *likely* outage scenarios, and they have not been and should not be used on their own to guide resilience decision-making or investments. However, they do provide illustrative geographic extents of potential climate-informed outages and can therefore serve as useful test cases to evaluate the response of the Social Burden tool.

To apply the outage polygons to a Social Burden analysis, additional assumptions were made. The hypothetical outage (or "Black-Sky") scenarios represent a situation in which certain parts of the study area lose grid power. All facilities within the outage boundary are no longer powered and are assumed to stop providing services. No backup generation resources are simulated, although this is a simplification that can likely be refined for some categories of facilities (e.g., hospitals, official FEMA shelters, etc.) with limited additional data in subsequent work (see Discussion and Conclusions for more information). All facilities outside the outage boundary are assumed to continue to be powered and to provide services at their baseline, unaltered, levels.

4. RESULTS

4.1. “Blue-Sky” Baseline Social Burden Results

The baseline (“blue-sky”) scenario represents a state in which the electric grid is fully up and running, all customers and existing facilities have power, and the power system is not introducing any additional burden to the hardship people normally experience in their day-to-day sourcing of critical services. All burden during a “blue-sky” state exists outside of the control of the IOU or electric regulator.

Figure 8 shows the baseline, or “blue-sky” values of Social Burden. The histogram counts denote the number of SCE customers who fall within a given range of Social Burden scores.

“Blue-sky” Social Burden is highest in two distinct categories of communities: urban, low-CRM communities in southeastern Los Angeles County (see insets in Figure 8), and rural, low-CRM communities in San Bernardino, Inyo, Mono, and east Riverside counties (see complete service area maps in Figure 8).

In a “blue-sky” scenario, actions which would improve people’s Social Burden include the addition of new critical service locations or actions that would enhance people’s adaptive capacity (Table 4) or reduce their vulnerabilities (Table 5). If such investments are based on per-capita results (Figure 8), in the SCE service area those investments would tend to prioritize low-density rural populations. Population-weighted results would shift the priority more to urban, low-CRM populations, where the same investment could benefit significantly more people.

Understanding the cause of high “blue-sky” Social Burden scores can help inform impactful investment. In denser urban CBGs, high Social Burden is driven by low CRM (high vulnerability/low adaptive capacity) that cancels out high service availability. Investment in additional critical service locations would not be meaningful in reducing Social Burden because the area is already relatively well-covered (see Figure 3). In dispersed rural CBGs, high Social Burden is driven by a combination of low service availability, and where applicable, also low CRM scores. Investments targeting Social Burden reductions in these communities could include both the addition of new critical services as well as efforts to improve adaptive capacity and reduce vulnerabilities.

The cumulative Social Burden scores are not evenly distributed across all individual services (Table 7). Note that values in Table 7 are not weights assigned a-priori: all critical services were weighted equally in the Social Burden analyses described in this report. Rather, the values in Table 7 are part of the Social Burden analysis results. Differences shown in Table 7 represent differences in the availability and accessibility of different types of critical services across the study area. Critical service categories with higher contributions to cumulative Social Burden represent critical services that are more difficult to access and/or have fewer alternative access points. Critical service categories with lower contributions to cumulative Social Burden represent service types that are readily available and for the provision of which many alternative facilities exist, providing a high degree of accessibility and redundancy. Across all CBGs, restoration, shelter, finance, medical service, and emergency logistics contributed the highest amounts towards the total burden experienced by the average resident of a CBG – that is to say, accessing these services is expected to take more effort than accessing all other critical services. Communication, safety, and security contributed the least – that is to say, accessing these services is expected to take less effort (on average) than accessing all other critical services.

Note that this analysis was performed with a time-agnostic definition of Social Burden, in which all critical services are considered equally important without considering potentially worsening impacts over time and are weighted equally. Recommended next steps – including the evolution of the Social Burden metric to consider weighting services and establishing baselines to define maximum acceptable levels of burden (or minimum acceptable levels of service availability) for a community – are described in Section 6.4 Future Work.

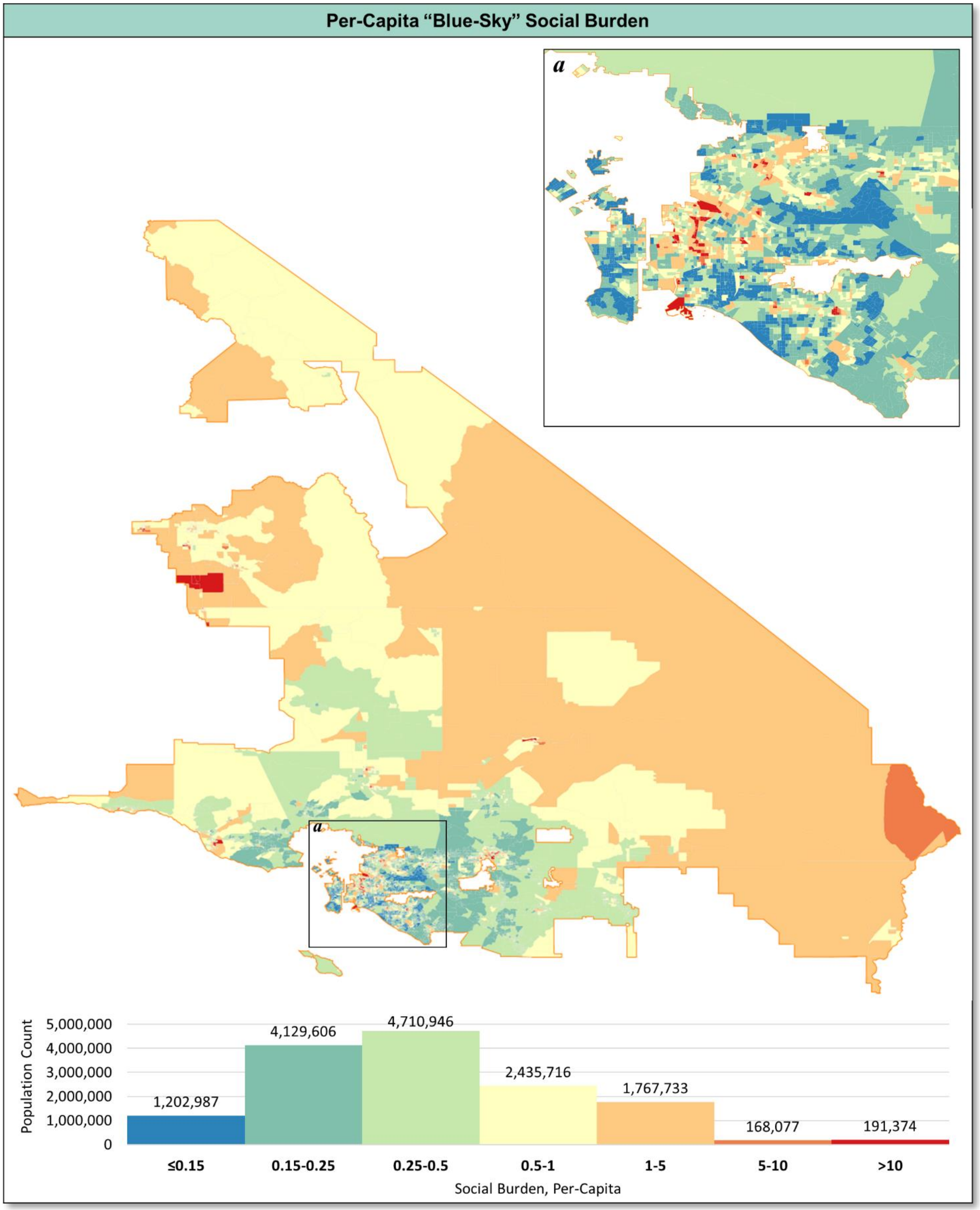

Figure 8. Baseline state ("blue-sky") per-capita Social Burden, summed across all critical service categories

Table 7. Critical services and their contribution to the total Social Burden when the grid is powered ("Blue-Sky" baseline scenario)

Critical Service	Average contribution to total burden	Standard Deviation of contribution to total burden
Communications	1.5%	0.2%
Emergency Logistics	7.4%	2.1%
Evacuation	5.2%	0.8%
Finance	11.8%	1.5%
Food	4.2%	0.3%
Fuel	4.1%	0.4%
Medical Service	9.9%	0.7%
Medications	5.7%	0.4%
Restoration	21.0%	2.7%
Safety	1.8%	0.4%
Security	2.3%	0.5%
Shelter	12.6%	1.7%
Transportation	5.0%	0.8%
Waste Management	4.3%	0.5%
Water	3.2%	0.3%

4.2. Hypothetical Outage Scenarios Social Burden Results

Each of the eight hypothetical climate change driven outage scenarios represents a state in which most of the SCE electric grid is up and running and most existing facilities are powered. A partial outage impacts a subset of SCE customers and leaves grid-tied assets, including facilities that would normally provide critical services, without power. With some facilities offline and no longer able to provide critical services, the state of the power system (partially down) now introduces additional burden to the hardship people already experience in their day-to-day sourcing of critical services. Social Burden during an outage scenario is a combination of "blue-sky" burden plus the added burden imposed by a partial reduction in services as a direct result of the power outage. The differential between the "blue-sky" and the outage scenario's "black-sky" Social Burden is within the purview of the IOU or electric regulator to modulate through adaptation or mitigation measures. While there are additional aspects of hardship related to experiencing a power outage, including physical discomfort, emotional duress, economic costs, and others, this Social Burden analysis considered only the difference in the availability and proximity of critical service-providing locations outside the home.

4.2.1. What is lost (infrastructure × services)

During an outage, facilities that provide critical services (e.g., grocery stores that provide food, water, and over-the-counter medications, or gas stations that provide fuel) lose power and are assumed to no longer be able to provide such services. In each of the eight scenarios analyzed in this study, less than one percent of all locations that provide critical services throughout the SCE service area would lose power. Although the outages do impact critical services, many alternatives exist to serve the population. If all four heat and all four flood scenarios were aggregated, the resulting loss would still be only 2.2% of all critical service-providing locations in the SCE service area. The spatial distribution of these impacts is illustrated in Figures 10 (all heat scenarios) and 11 (all flooding scenarios).

Table 8 shows the count of facilities that are impacted by the various heat- and flooding-related outages that were explored in this analysis. Note that only facility categories that experience one or more outages under one or more of the hypothetical scenarios are listed. Facility categories which are not impacted by any of the hypothetical outages are excluded from Table 8 but remain (unaltered) in the analysis.

The impact on services is further attenuated by the fact that the facility-to-service relationship is usually not a simple 1:1, and multiple facility types can provide the same critical service, just as a single facility can provide multiple types of services. For instance, food service can be provided at (different levels) by a food bank, a grocery store, a convenience store, a supermarket, etc.; similarly, a convenience store can provide not only food, but also low levels of water and medications. Table 9 describes the loss in terms of critical services. The negative values in Table 9 indicate that facilities have hypothetically lost power and are not available to provide critical services.

The sum of "blue-sky" total service points presented in Table 9 is calculated by summing the product of all facilities and their corresponding service level scores in each of the 15 critical service categories. For example, if a clinic has a service level of 5 for medical service and a service level of 3 for medication, a single clinic will contribute 5 points towards the medical service category and 3 points towards the medication category. 10 clinics will contribute [5 x 10 = 15] points to medical service and [3 x 10 = 30] points to medication. Points are summed by service level across all contributing facility types. The sum of points lost per outage scenario is calculated similarly but includes only the subset of facilities that intersect the given outage polygon and are therefore considered to be "offline" and no longer providing service.

Note that Table 9 is presented for illustrative purposes only. The point system does not directly map to Social Burden scores, as Social Burden is also a function of the distance matrix between people (CBG centroids) and services (X-Y location of facilities) and the people's ability criterion, but it is being presented here to explain the relationship between facilities and services, and how the loss of power to facilities translates to service reduction.

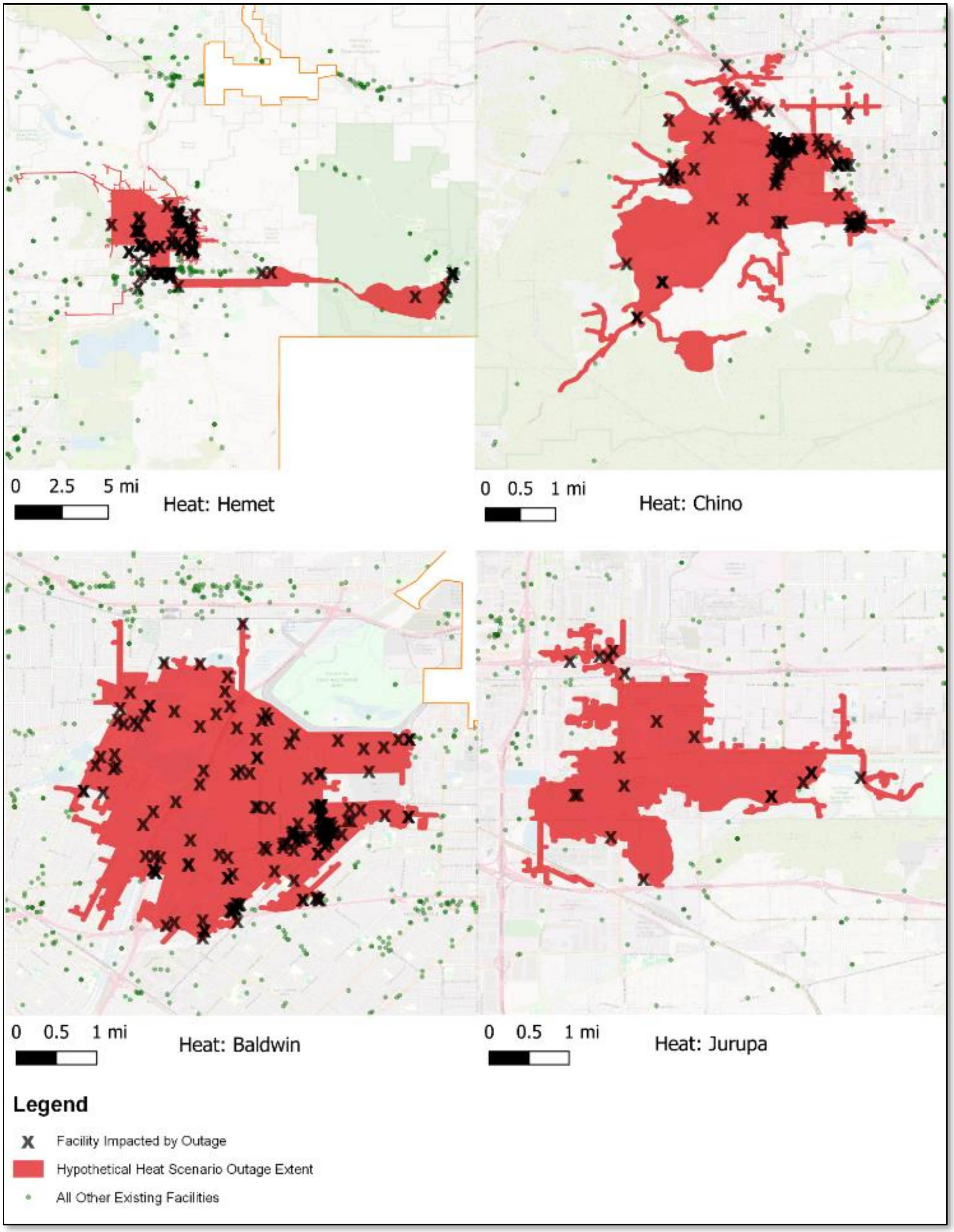

Figure 9. Spatial distribution of heat scenario infrastructure impacts

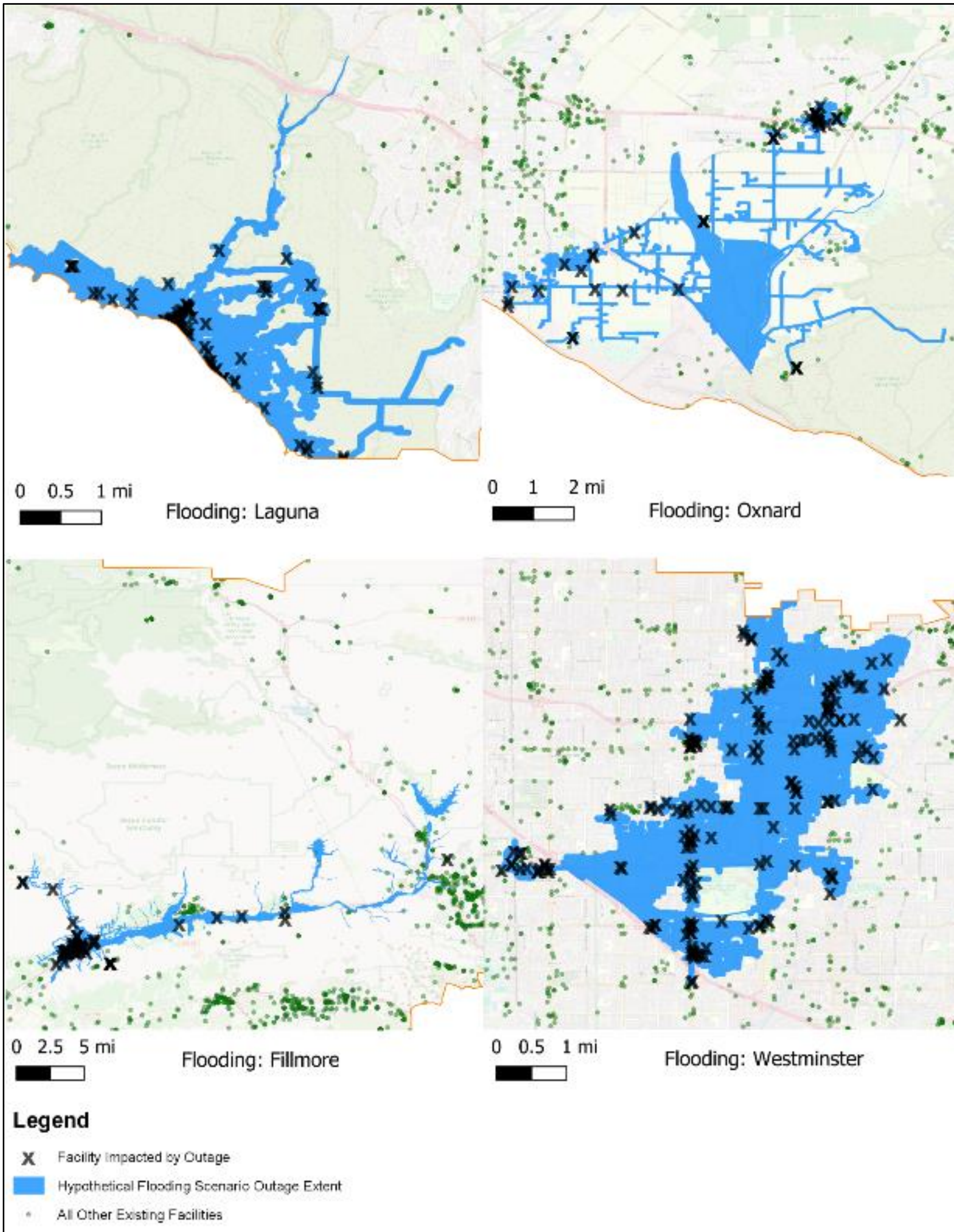

Figure 10. Spatial distribution of flooding scenario infrastructure impacts

Table 8. Count of facilities assumed to be offline under each hypothetical outage scenario versus total number of existing alternative facilities of the same class across SCE territory

Facility Type	Total Facilities	Count Offline per Outage Scenario							
		Heat Scenarios				Flooding Scenarios			
		Hemet	Chino	Baldwin	Jurupa	Laguna	Oxnard	Fillmore	Westminster
AM Radio Station Transmitter	71	1		2				1	
ATM	366	2	5	10		4	1		1
Bank Branch	2305	8	17	6		7	3	5	20
Bus Station	49								1
CalTrans Maintenance Facility	90	1						1	
Car Rental	84		1						
Cellular Tower	410						2		
Clinic	195					3			
Convenience Store	658	2	4	10			2		8
Cooling Center	238	3	2	1					1
Drinking Water Access Point	782	1		5		11			
Electric Vehicle Charging Point	4371	4	6	10		11	13	1	12
Emergency Medical Service	847	5	3	3	1	2	1	3	4
Fast Food	2862	6	13	24	2	6			15
Fire Station	828	3	2	3	1	4	1	3	3
FM Radio Station Transmitter	352	1				1	3		
Gas Station	3074	15	8	11	1	5	5	7	36
Grocery Store	11					1			
Hospital	205			1				1	1
Hotel	195					3			
Landfill	920	1		18		1	3	3	2
Local Emergency Operations Center	87					1		2	2
Local Law Enforcement Location	277	1	1	2		1		1	2
Microwave Service Tower	7207	16	9	29	11	3	7	18	25
Money Transfer	15	2				2			1
Natural Gas Facility	13							1	
Official Shelter	2087	8	10	12	2	4	5	6	10
Pharmacy	1876	5	11	7	1	4		2	26

Facility Type	Total Facilities	Count Offline per Outage Scenario							
		Heat Scenarios				Flooding Scenarios			
		Hemet	Chino	Baldwin	Jurupa	Laguna	Oxnard	Fillmore	Westminster
Point of Distribution	170	4						1	
PSAP Facility	439			1				2	1
Public Safety Communication Site	871	2	1	2		2		1	
Public Use Airport	60							1	
Rail Station	69			1				1	
Retail Superstore	389	2	5	3					4
Sewer Treatment Plant	38						1		
Supermarket	561	1	4	2					5
Urgent Care Facility	232	2	3			1		2	1

Table 9. Loss of critical service points (service level x count) per outage scenario

Critical Service	Sum of "Blue-Sky" Total Points	Sum of Points Lost per Outage Scenario							
		Heat Scenarios				Flooding Scenarios			
		Hemet	Chino	Baldwin	Jurupa	Laguna	Oxnard	Fillmore	Westminster
Communications	8,847	-16	-9	-29	-11	-3	-15	-19	-25
Emergency Logistics	5,189	-25	-12	-19	-2	-12	-18	-21	-21
Evacuation	15,825	-16	-23	-37	0	-37	-43	-18	-47
Finance	7,944	-36	-66	-48	0	-33	-12	-15	-66
Food	23,419	-86	-110	-154	-12	-43	-21	-29	-173
Fuel	14,574	-70	-57	-59	-4	-20	-20	-35	-164
Medical Service	10,343	-41	-42	-30	-7	-40	-6	-35	-58
Medications	16,558	-62	-81	-59	-7	-37	-10	-34	-167
Restoration	1,063	-4	-10	-6	0	0	0	-5	-8
Safety	13,223	-37	-22	-36	-7	-32	-11	-36	-29
Security	7,445	-13	-9	-22	0	-13	-4	-17	-14
Shelter	8,075	-33	-36	-39	-6	-32	-15	-18	-33

Critical Service	Sum of "Blue-Sky" Total Points	Sum of Points Lost per Outage Scenario							
		Heat Scenarios				Flooding Scenarios			
		Hemet	Chino	Baldwin	Jurupa	Laguna	Oxnard	Fillmore	Westminster
Transportation	19,050	-19	-28	-44	0	-44	-52	-16	-52
Waste Management	7,187	-16	-12	-103	-2	-9	-25	-21	-21
Water	21,806	-80	-89	-133	-10	-69	-19	-27	-145
Total	180,548	-554	-606	-818	-68	-424	-271	-346	-1,023
Outage Extent (Miles^2)		33.6	8.4	10.9	6.2	4.9	15.2	38.7	12.9
Points Lost per Mile^2		-16	-72	-75	-11	-86	-18	-9	-79

4.2.2. Black Sky Social Burden

The magnitude of Social Burden impact an outage exerts on people in the utility's service area is a function of people's underlying vulnerability and adaptive capacity (Social Burden's "attainment factor") intersected with critical service availability (the location of infrastructure alternatives relative to where people live and those alternatives' capacity to provide critical services during a grid outage elsewhere in the utility's service area).

Figures 11 through 18 show the spatial distribution of "black-sky" per-capita Social Burden scores for CBGs across the SCE service area calculated for each of the eight hypothetical outage scenarios explored in this project. For each scenario, histograms showing population counts experiencing each category of "black-sky" Social Burden score are provided for the service area at large, as well as for people living in CBGs intersected by the outage polygon (inset *b*). Note that the binning of Social Burden scores depicted in Figures 11 through 18 was manually set to illustrate the distribution of scores. Differences at the lower end of the range were provided more resolution through narrower binning, with larger values binned into increasingly wider ranges. The color ramp is intended to illustrate, *in a relative sense*, how CBGs fall on the low / medium / high / very high / extremely high spectrum illustrated in Figure 1. In other words, CBGs shaded red in Figures 11 through 18 have calculated Social Burden scores that are extremely high as compared to CBGs shaded blue, which are low by comparison. Refer to Sections 5.5 and 6.4 for more in-depth discussion about the need for further conceptual framework development as well as validation with community stakeholders to establish formal definitions for Social Burden acceptability criteria that can be used to identify Social Burden as *actionably* high, medium, or low such that binning and cutoff criteria can be formalized. These follow-on activities were outside the scope of the pilot phase summarized in this report but can be investigated in subsequent phases of this work.

Overall, as may be expected, each outage has a marginal impact on the distribution of Social Burden scores when evaluating the entire SCE service area as a whole (refer to histograms at the bottom of Figures 11 through 18). Relative to the utility's total customer base, only minor movement of customers occurs from a lower Social Burden category to the next higher one. Overall, more than 70% of the SCE customer base continues to experience Social Burden scores that are within an order of magnitude of the lowest Blue-Sky values. However, for customers living in CBGs directly intersecting the outage polygons (see inset maps and histograms at the tops of Figures 11 through 18), the distributions of customers experiencing elevated levels of Social Burden are substantially different from the territory-wide distribution as well as differing from one outage to the next. The Laguna, Jurupa, and Chino outage scenarios result in the lowest levels of "black-sky" Social Burden, whereas the Oxnard, Fillmore, and Baldwin scenarios result in the highest levels. Refer to Section 5 for discussion of the drivers behind these differences, the implications of the results, and intervention pathways suggested by the analysis.

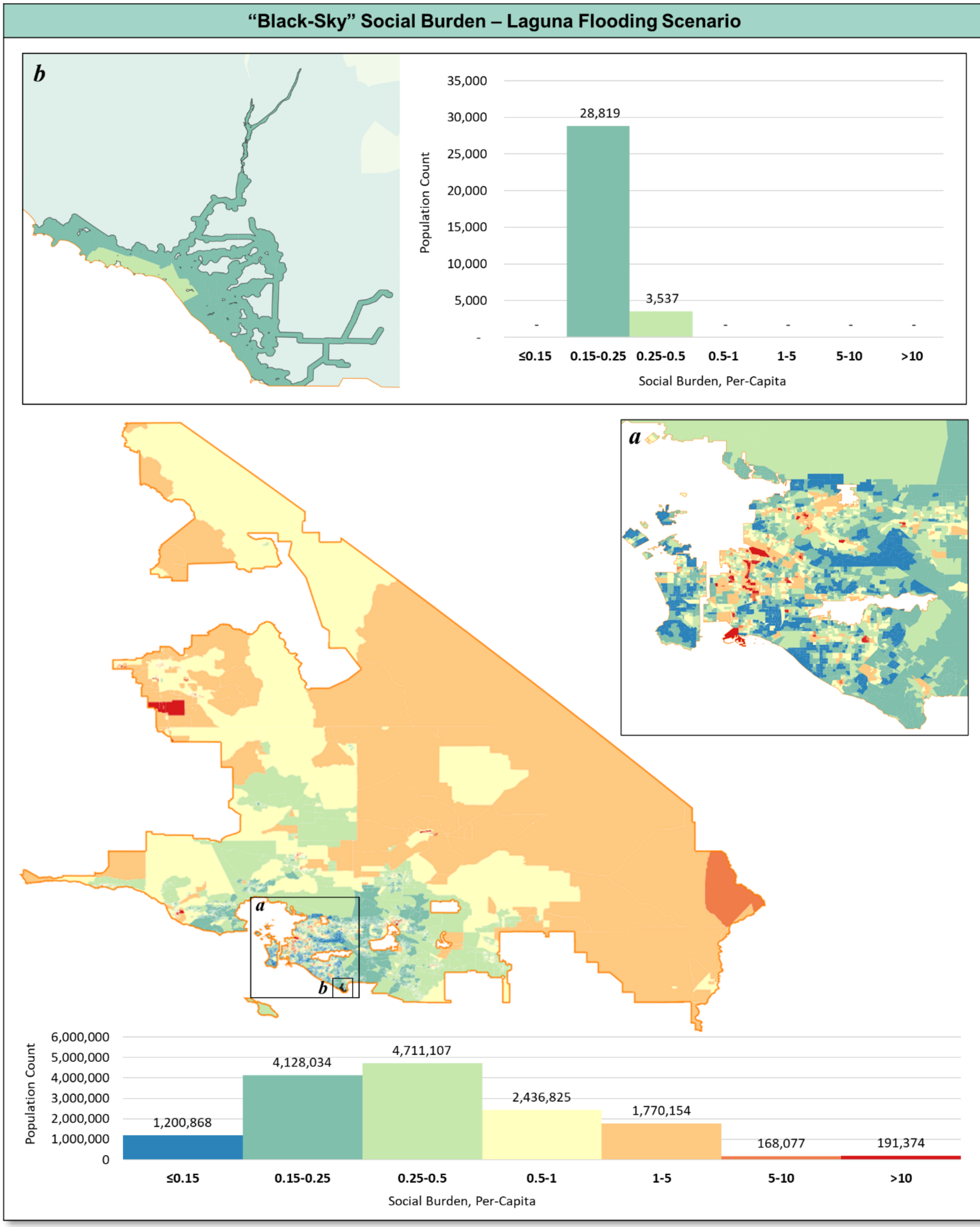

Figure 11. "Black-Sky" Social Burden in response to Laguna flooding power outage scenario

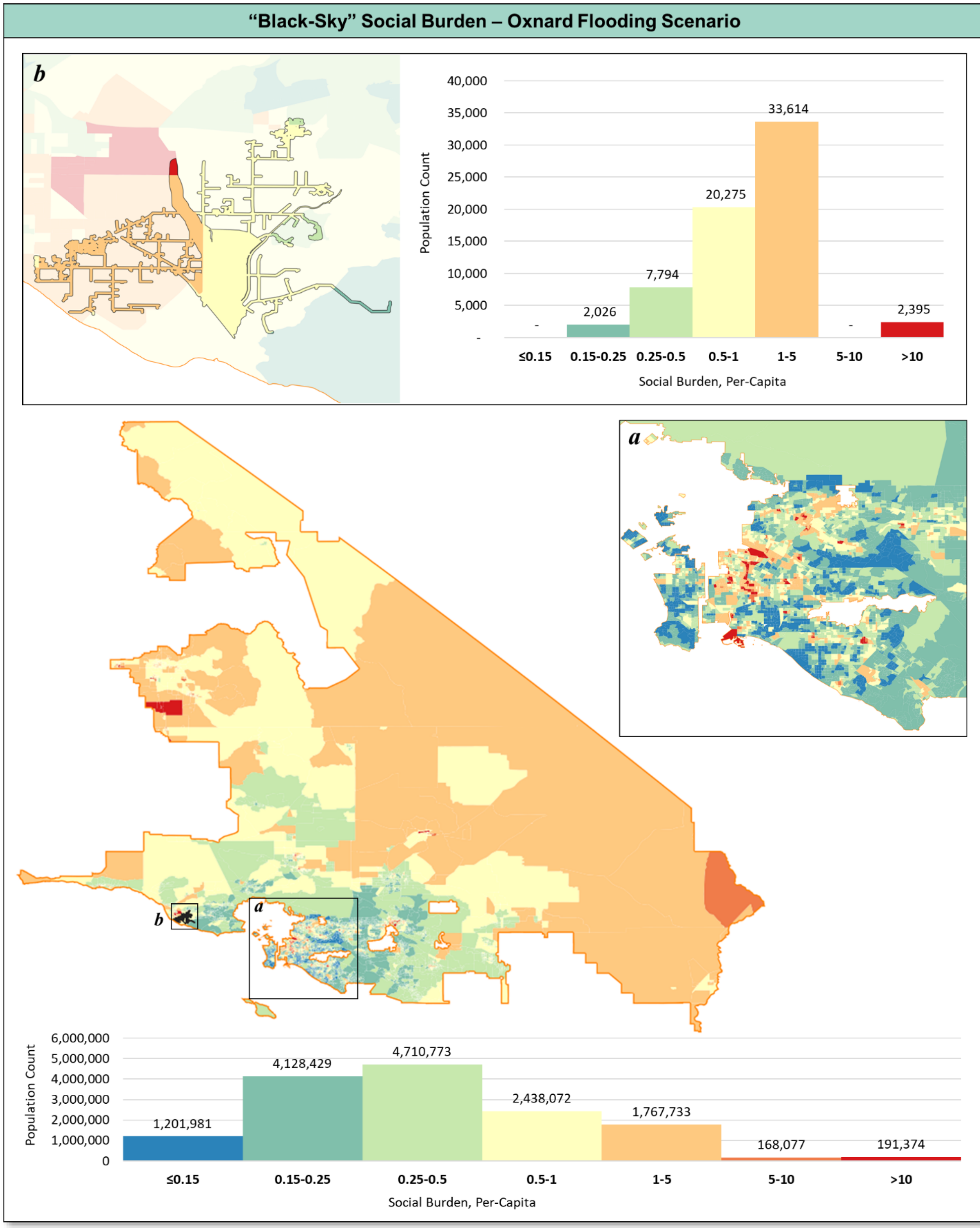

Figure 12. "Black-Sky" Social Burden in response to Oxnard flooding power outage scenario

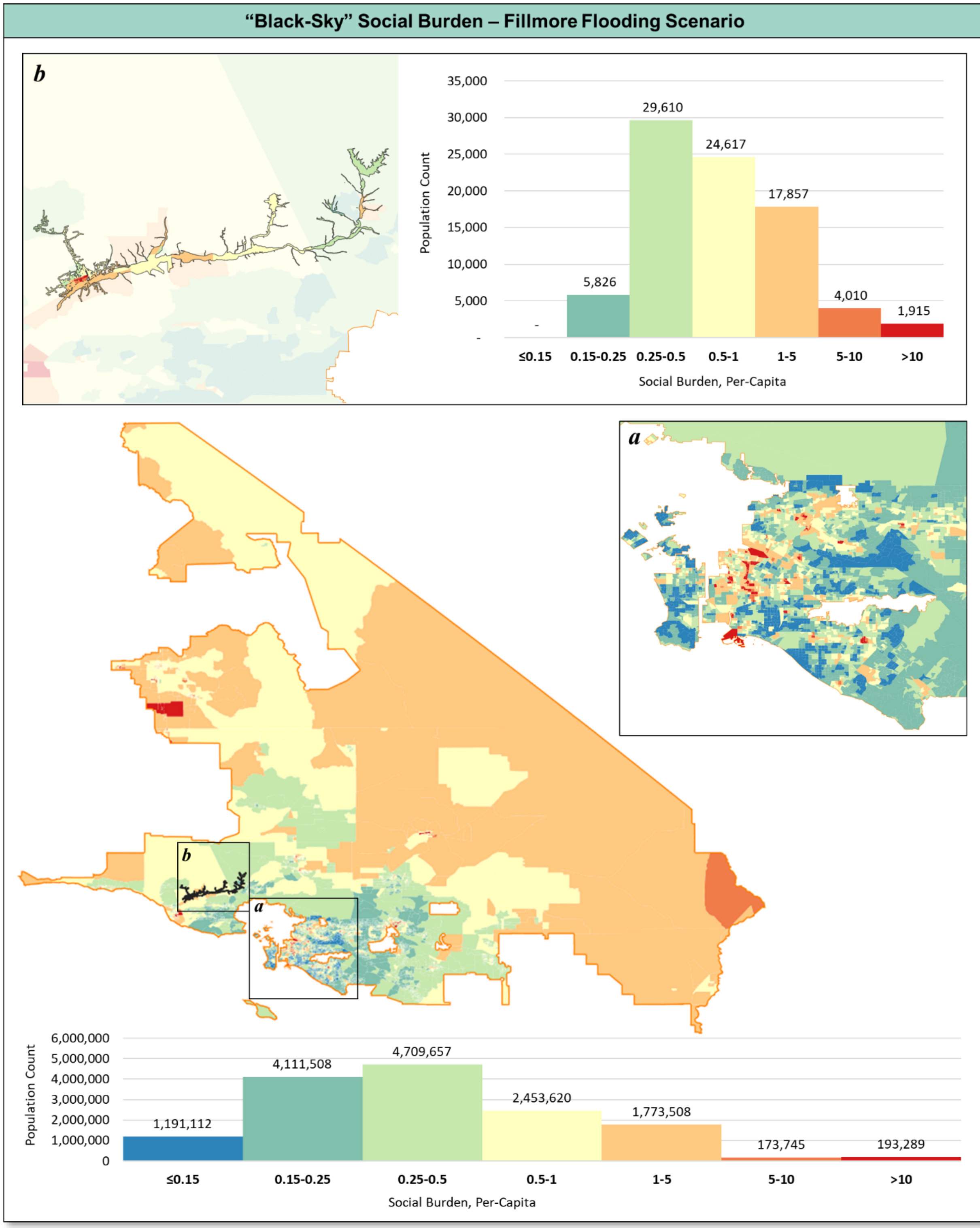

Figure 13. "Black-Sky" Social Burden in response to Fillmore flooding power outage scenario

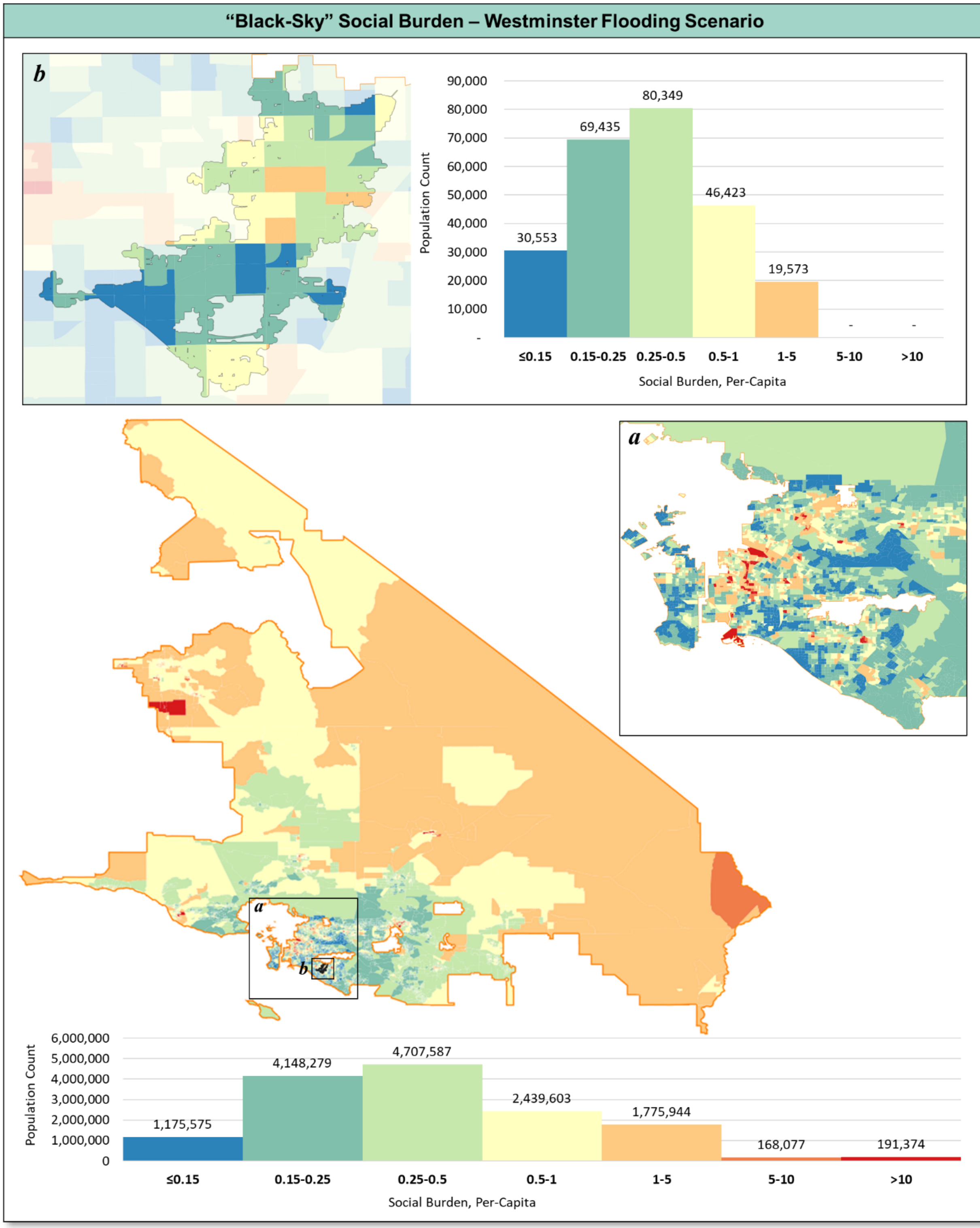

Figure 14. "Black-Sky" Social Burden in response to Westminster flooding power outage scenario

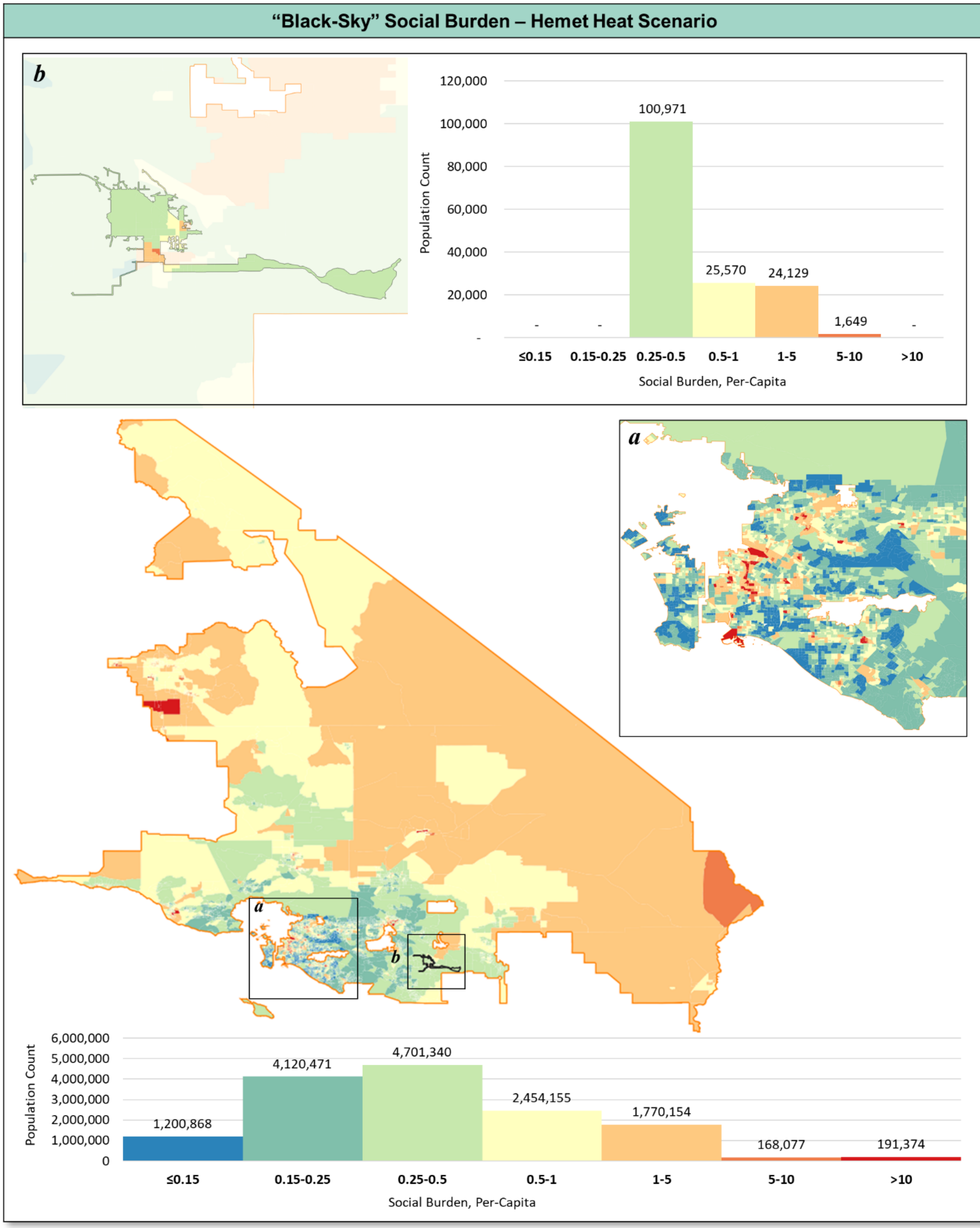

Figure 15. "Black-Sky" Social Burden in response to Hemet heat power outage scenario

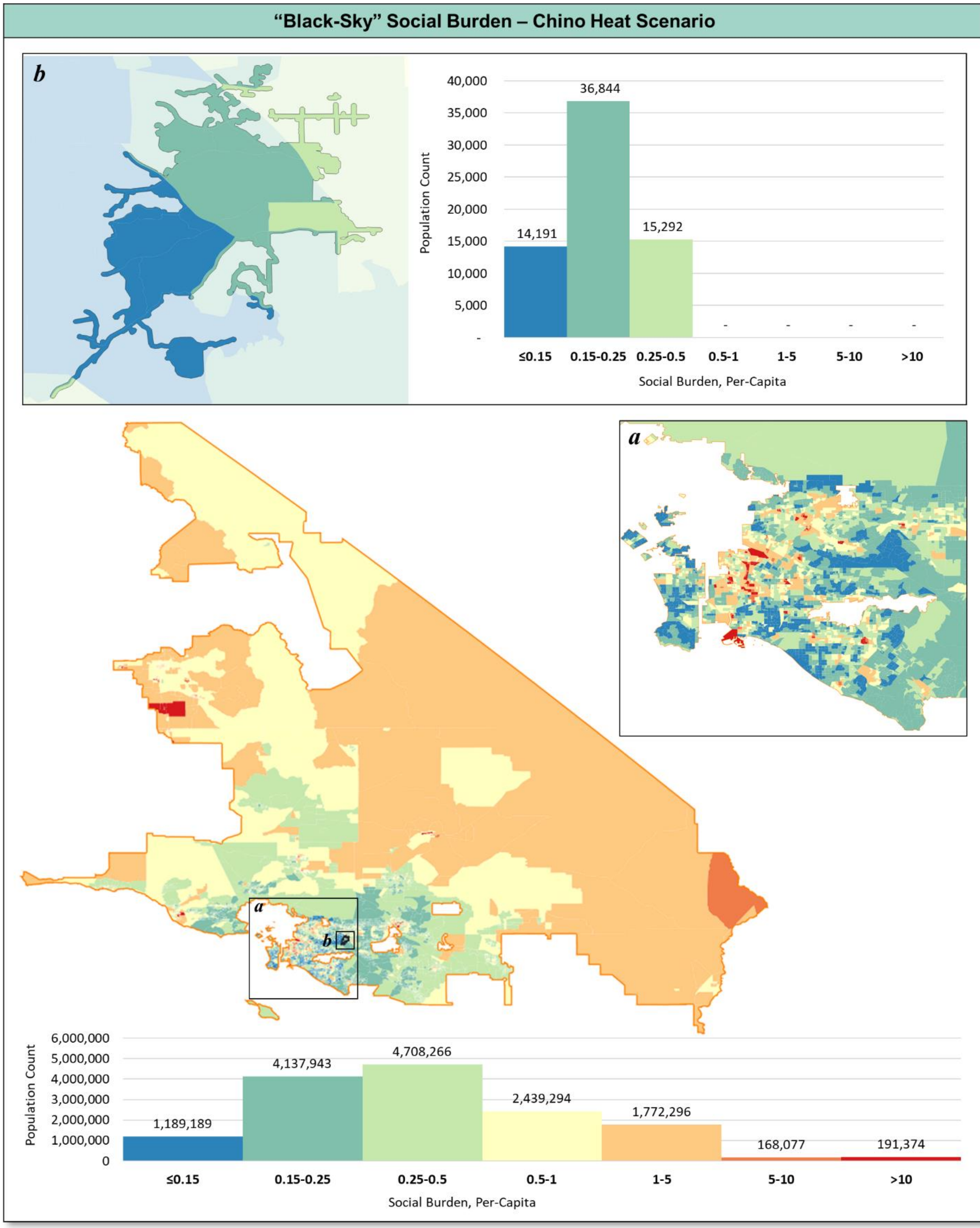

Figure 16. "Black-Sky" Social Burden in response to Chino heat power outage scenario

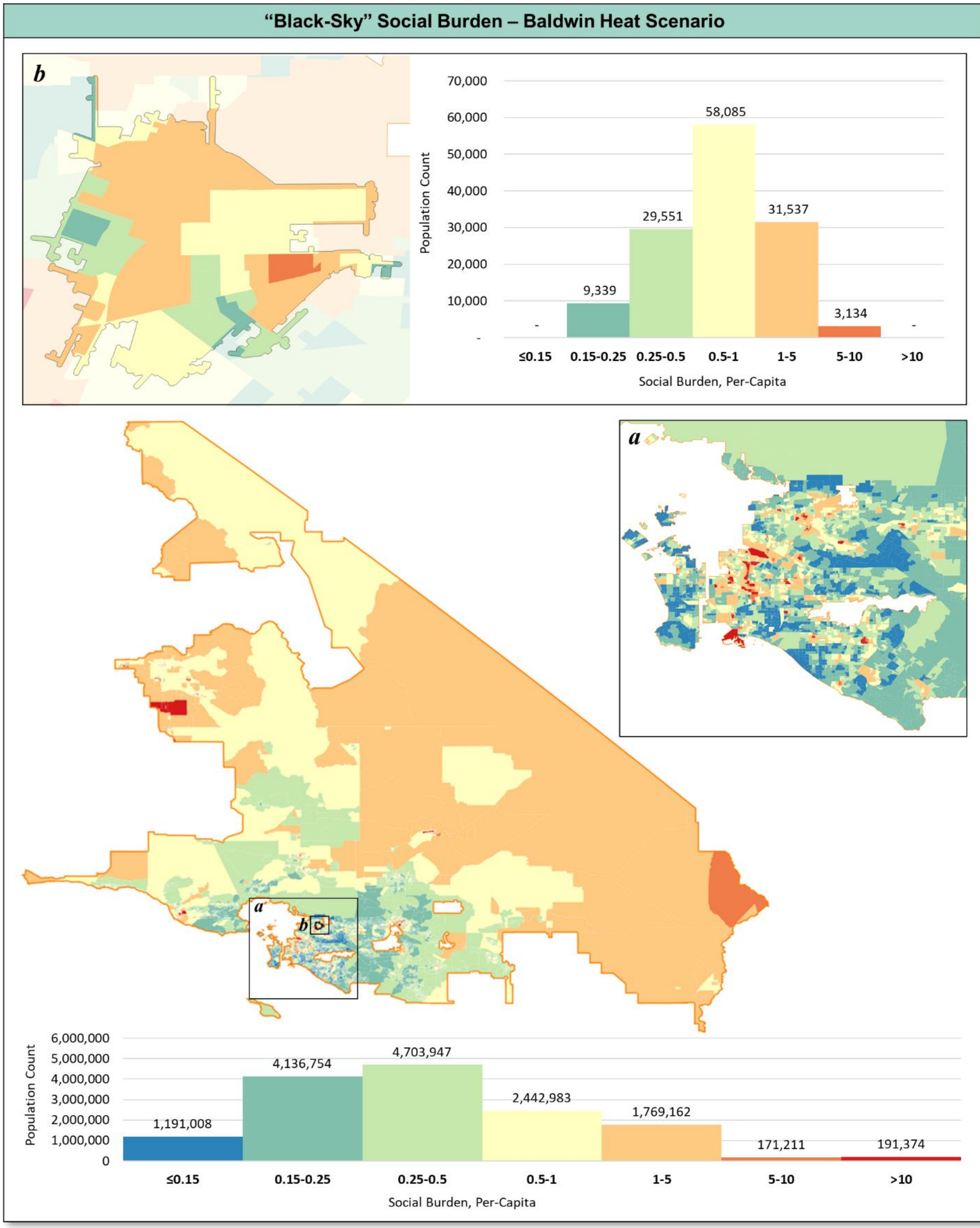

Figure 17. "Black-Sky" Social Burden in response to Baldwin heat power outage scenario

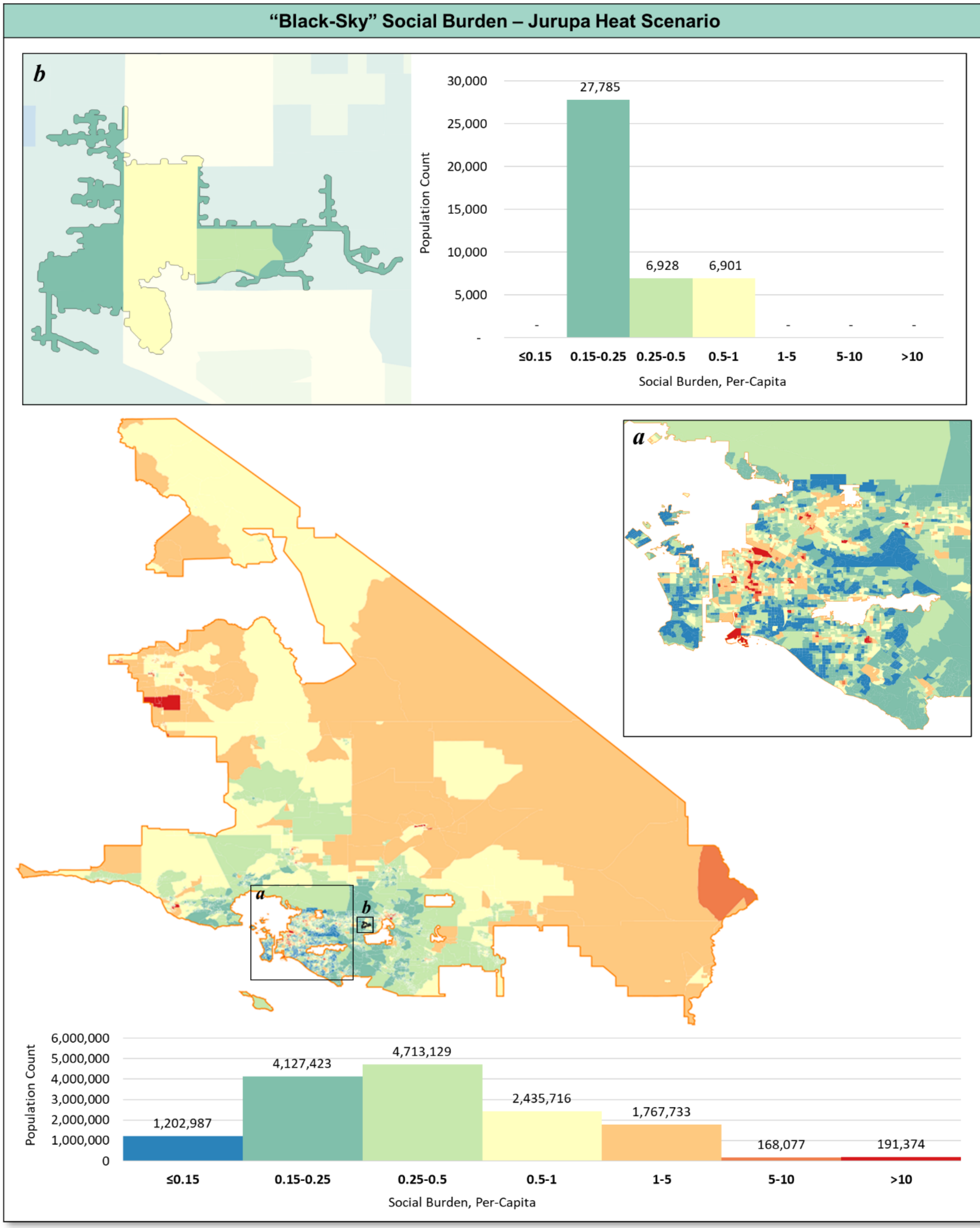

Figure 18. "Black-Sky" Social Burden in response to Jurupa heat power outage scenario

4.2.3. Social Burden Differential

The Social Burden differential is the difference between the "blue-sky" and the "black-sky" Social Burden. Whereas the "black-sky" Social Burden is partially a function of the innate distribution of critical services and people's ability to access them (i.e. "blue-sky" Social Burden), the differential is the direct result of the grid power outage and can be used by the electric utility to understand differences in how the same outage can be experienced by different customers, and/or how alternative mitigation measures can help alleviate outage impacts for different customers.

Figures 19 through 26 show the spatial distribution of the Social Burden differential, calculated for each CBG in the study area as the percent increase relative to its baseline state (i.e. its "blue-sky" Social Burden value). The differential is calculated separately for each of the eight hypothetical outage scenarios explored in this project. For each scenario, histograms showing population counts experiencing each category of Social Burden differential are provided for the service area at large, as well as for people living in CBGs intersected by the outage polygon (inset *b*).

Note, as before, that the binning of Social Burden scores depicted in Figures 19 through 26 was manually set to illustrate the distribution of scores. Differences at the lower end of the range were provided more resolution through narrower binning, with larger values binned into increasingly wider ranges. The color ramp is intended to illustrate, *in a relative sense*, how CBGs fall on the low / medium / high / very high / extremely high spectrum illustrated in Figure 1. In other words, CBGs shaded red in Figures 19 through 26 have calculated Social Burden differentials that are extremely high as compared to CBGs shaded blue, which are low by comparison. Refer to Sections 5.5 and 6.4 for more in-depth discussion about the need for further conceptual framework development as well as validation with community stakeholders to establish formal definitions for Social Burden acceptability criteria that can be used to identify Social Burden as *actionably* high, medium, or low such that binning and cutoff criteria can be formalized. These follow-on activities were outside the scope of the pilot phase summarized in this report but can be investigated in subsequent phases of this work.

Within CBGs directly intersecting the outage polygons, Social Burden differentials were highest for the Fillmore, Westminster, Hemet, Baldwin, and Chino outage scenarios, and lowest for the Oxnard, Jurupa outage scenarios. The impacts of the outage scenarios propagated outside of the outage polygons to various degrees. The greatest influence of an outage on differentials in CBGs outside its boundaries was calculated for the Fillmore outage scenario. The least influence of an outage on CBGs outside its extent was calculated for Jurupa. Refer to Section 5 for further discussion of the drivers behind these differences, the implications of the results, and intervention pathways suggested by the analysis.

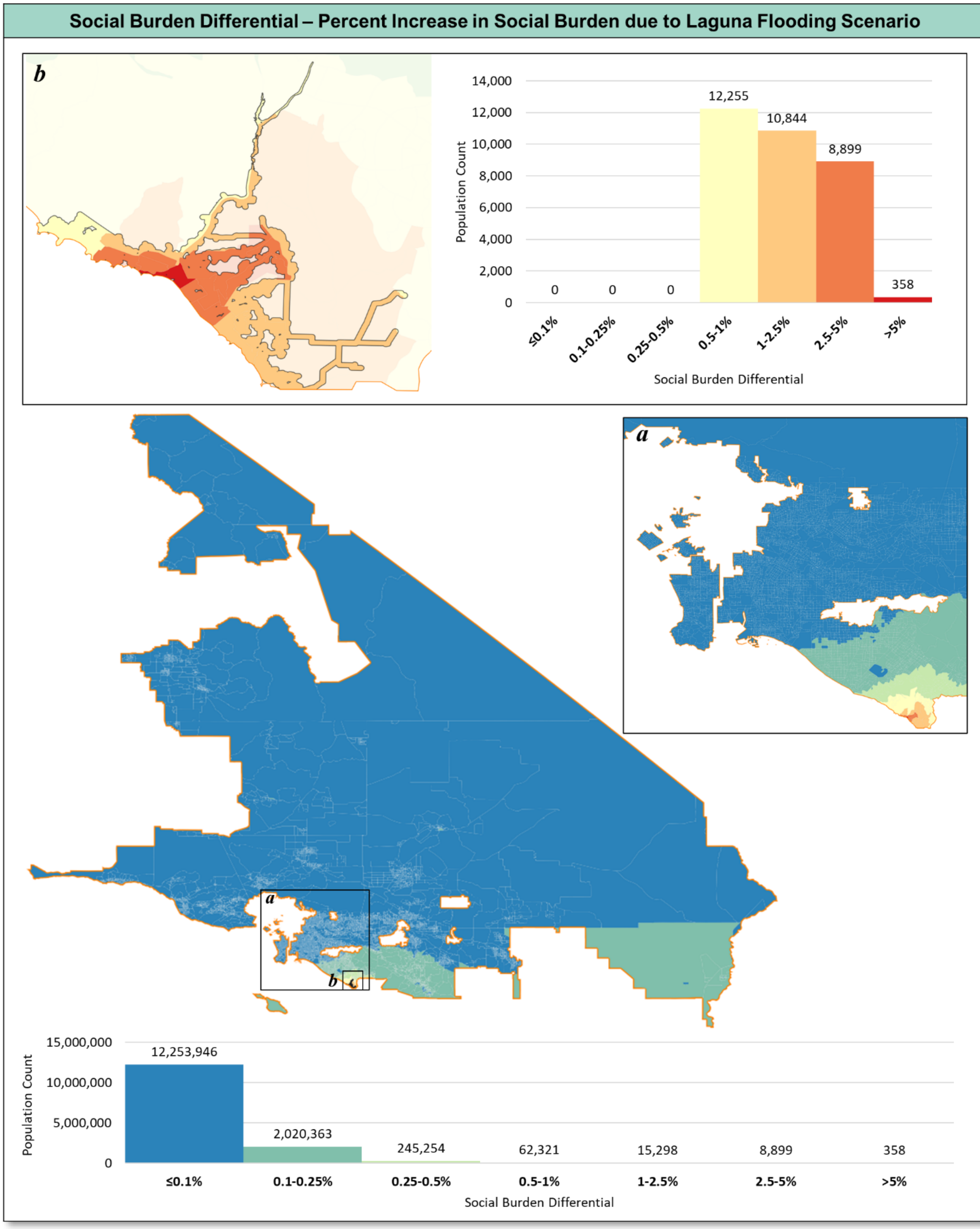

Figure 19. Impact of Laguna flooding power outage scenario: Social Burden differential

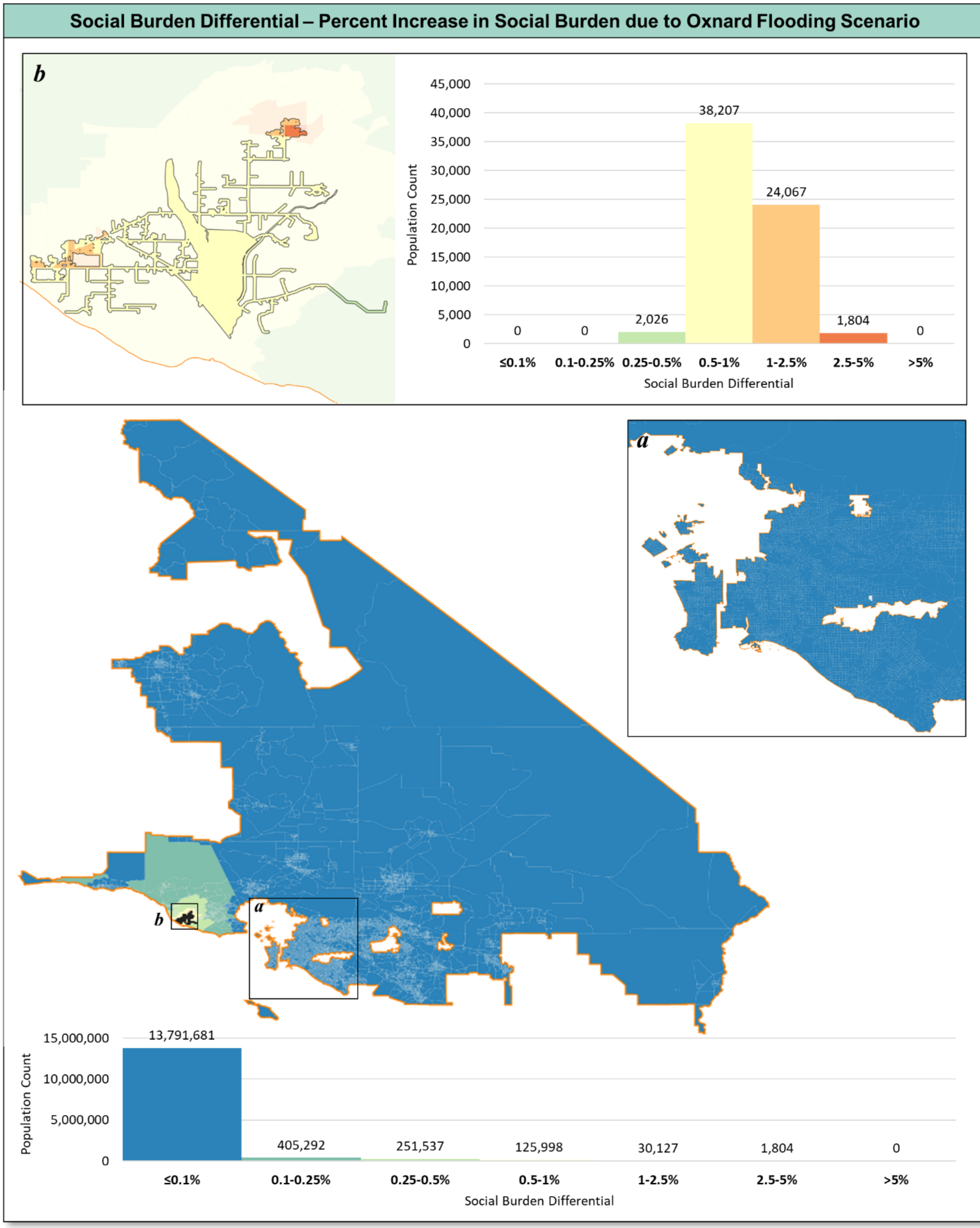

Figure 20. Impact of Oxnard flooding power outage scenario: Social Burden differential

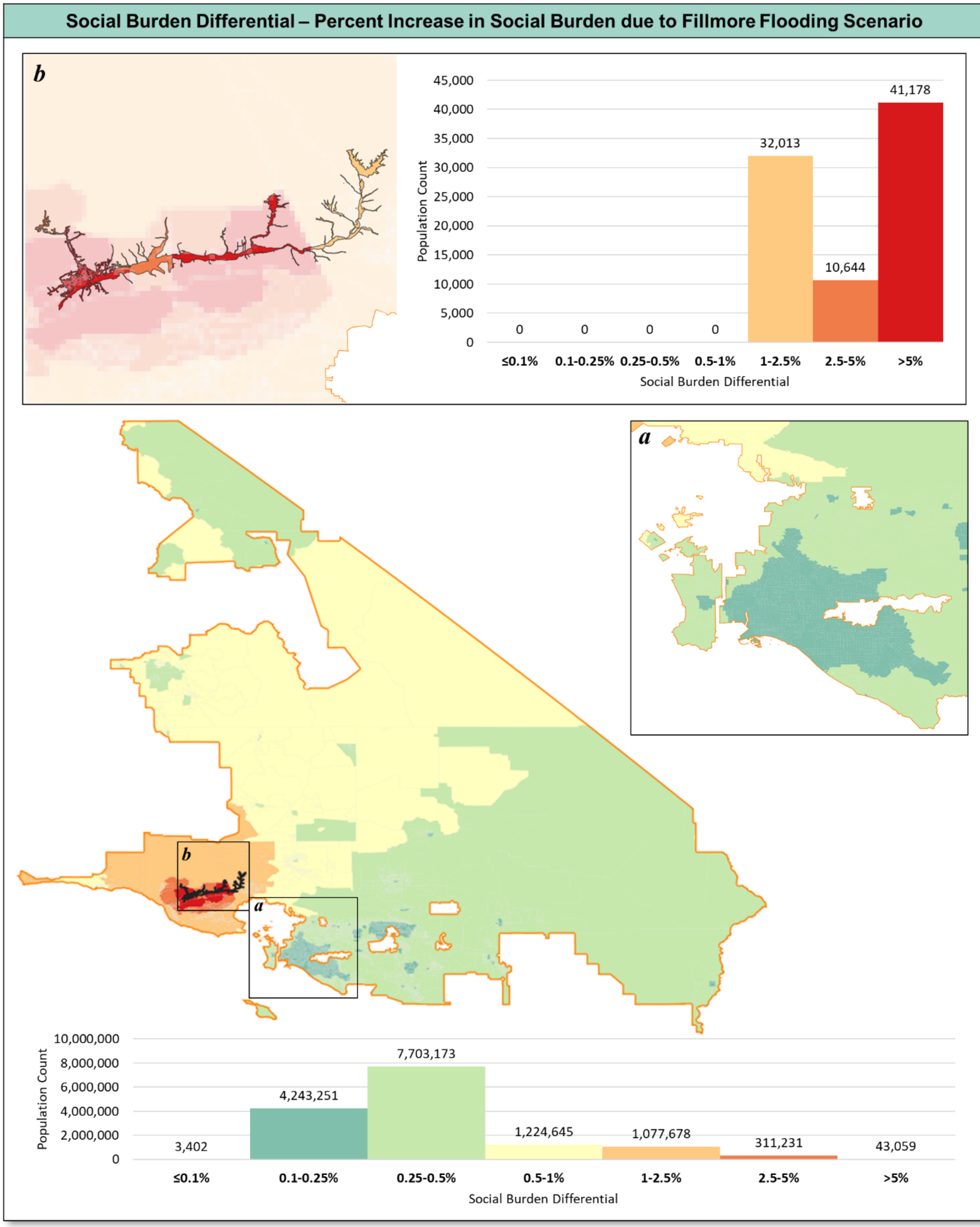

Figure 21. Impact of Fillmore flooding power outage scenario: Social Burden differential

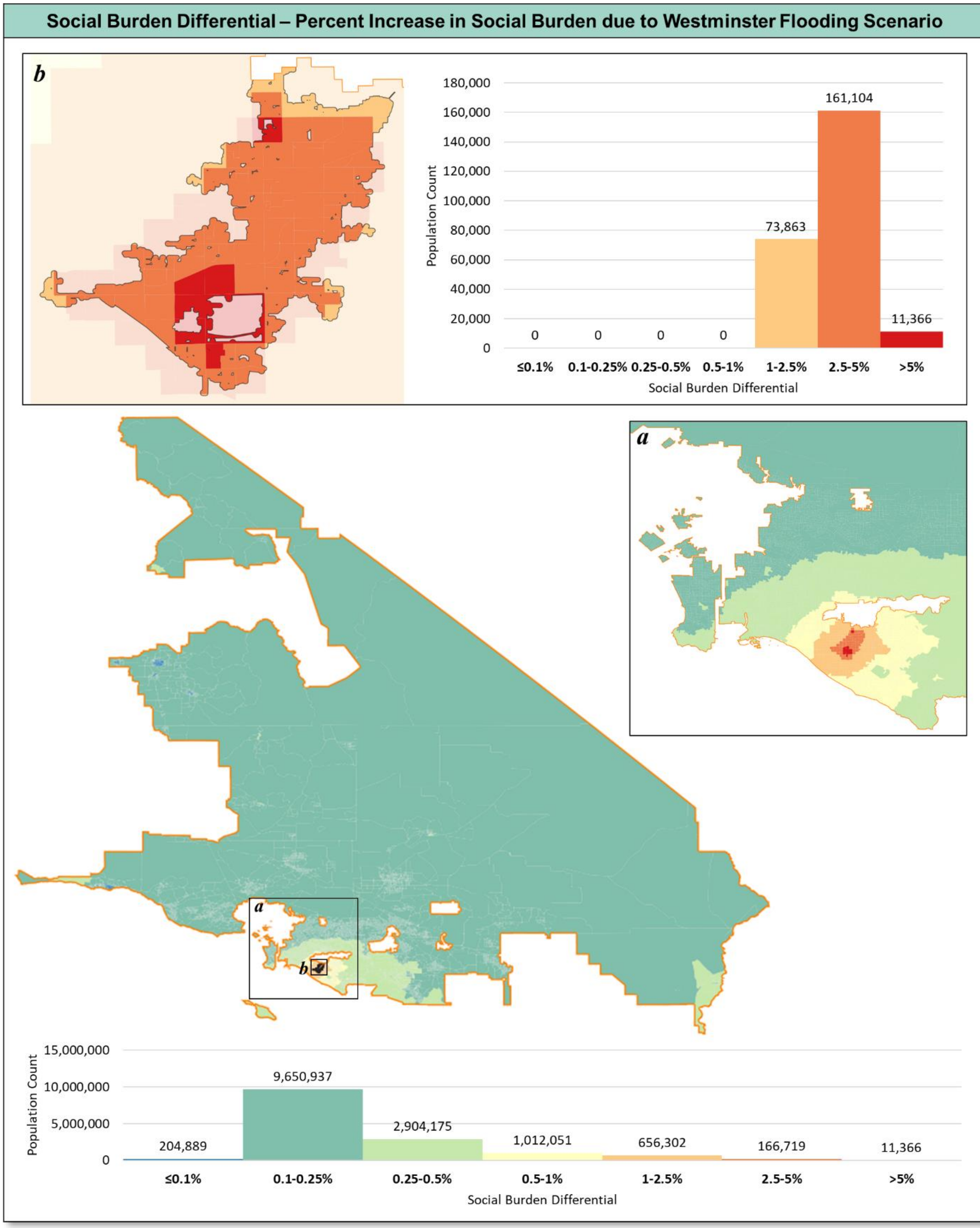

Figure 22. Impact of Westminster flooding power outage scenario: Social Burden differential

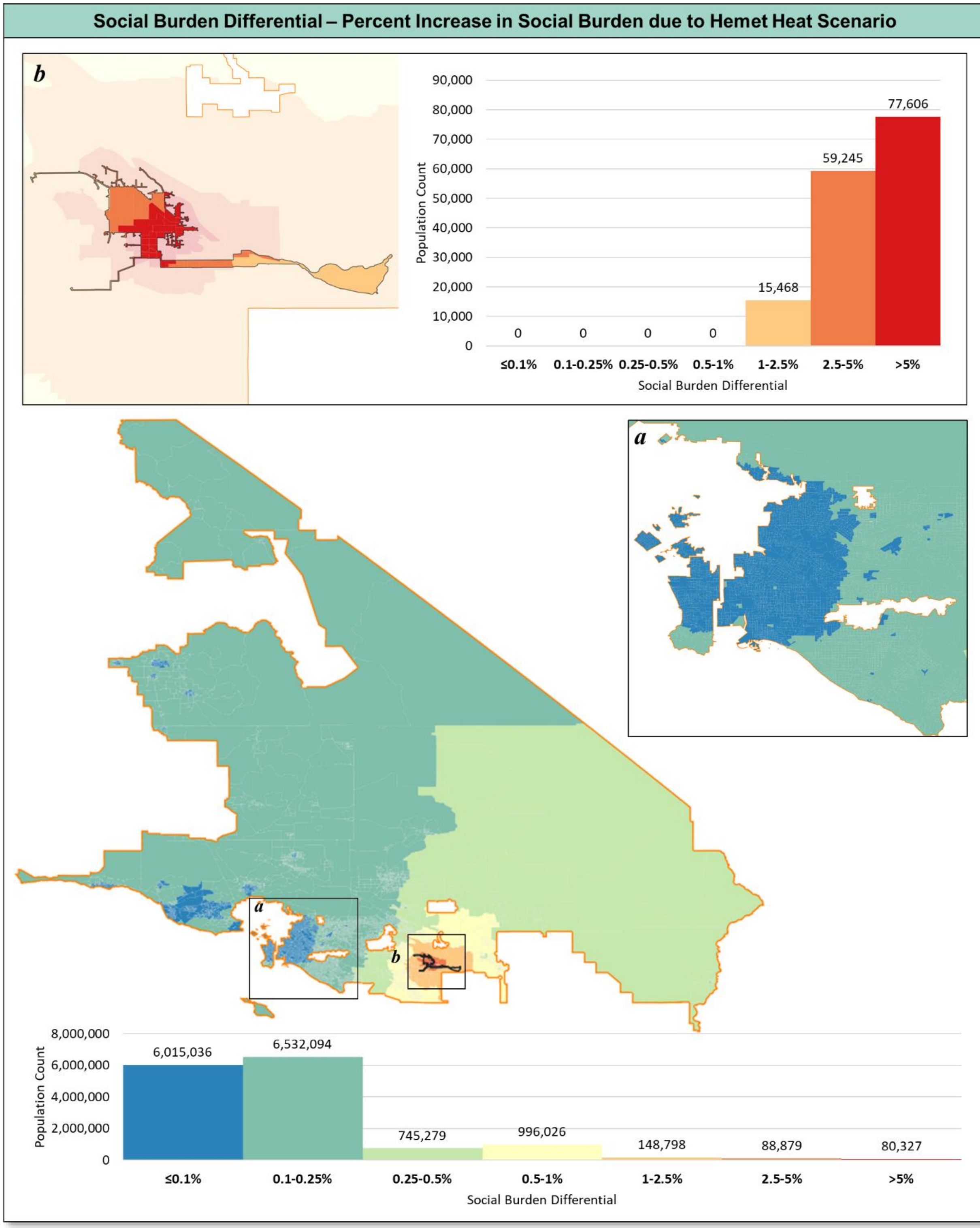

Figure 23. Impact of Hemet heat power outage scenario: Social Burden differential

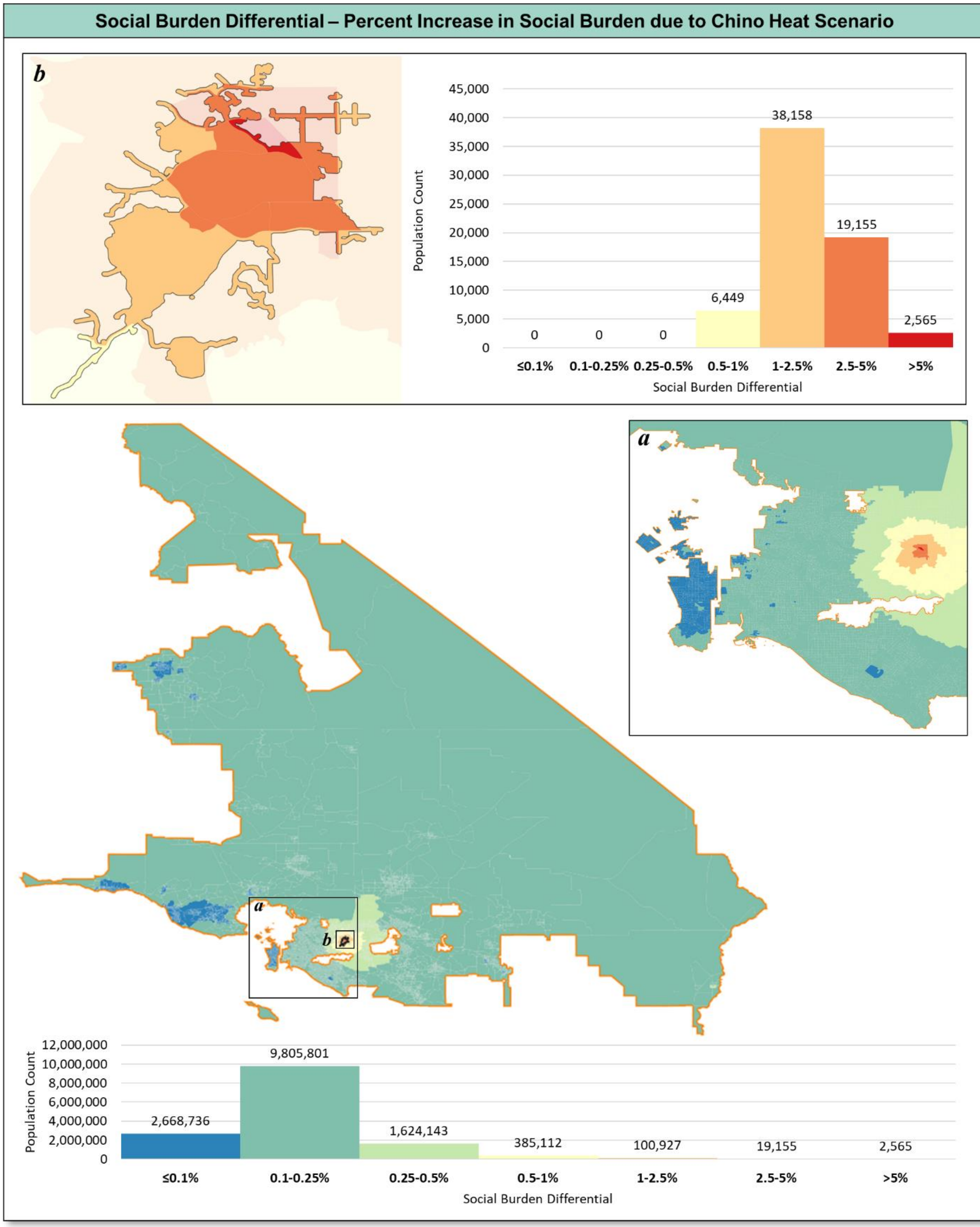

Figure 24. Impact of Chino heat power outage scenario: Social Burden differential

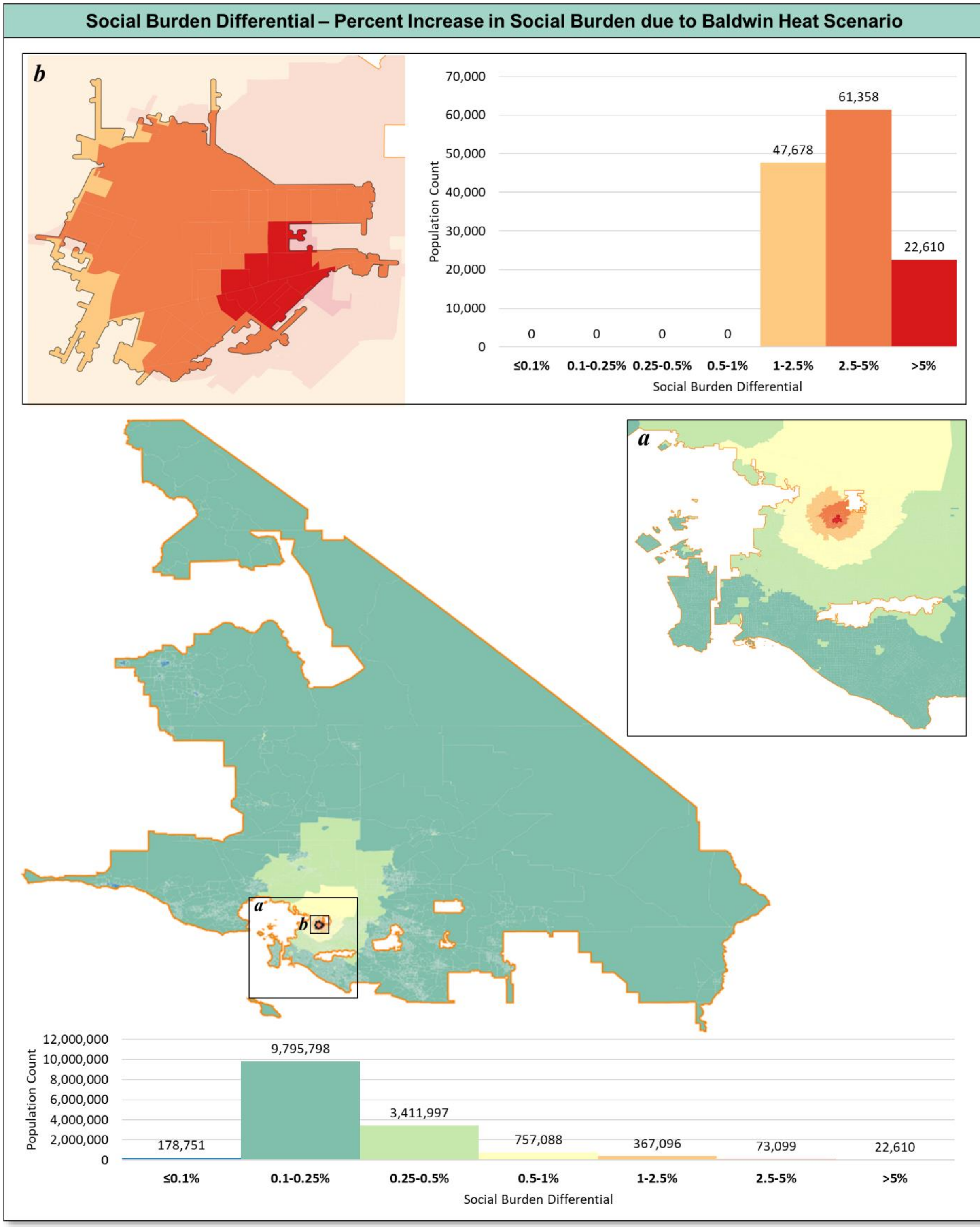

Figure 25. Impact of Baldwin heat power outage scenario: Social Burden differential

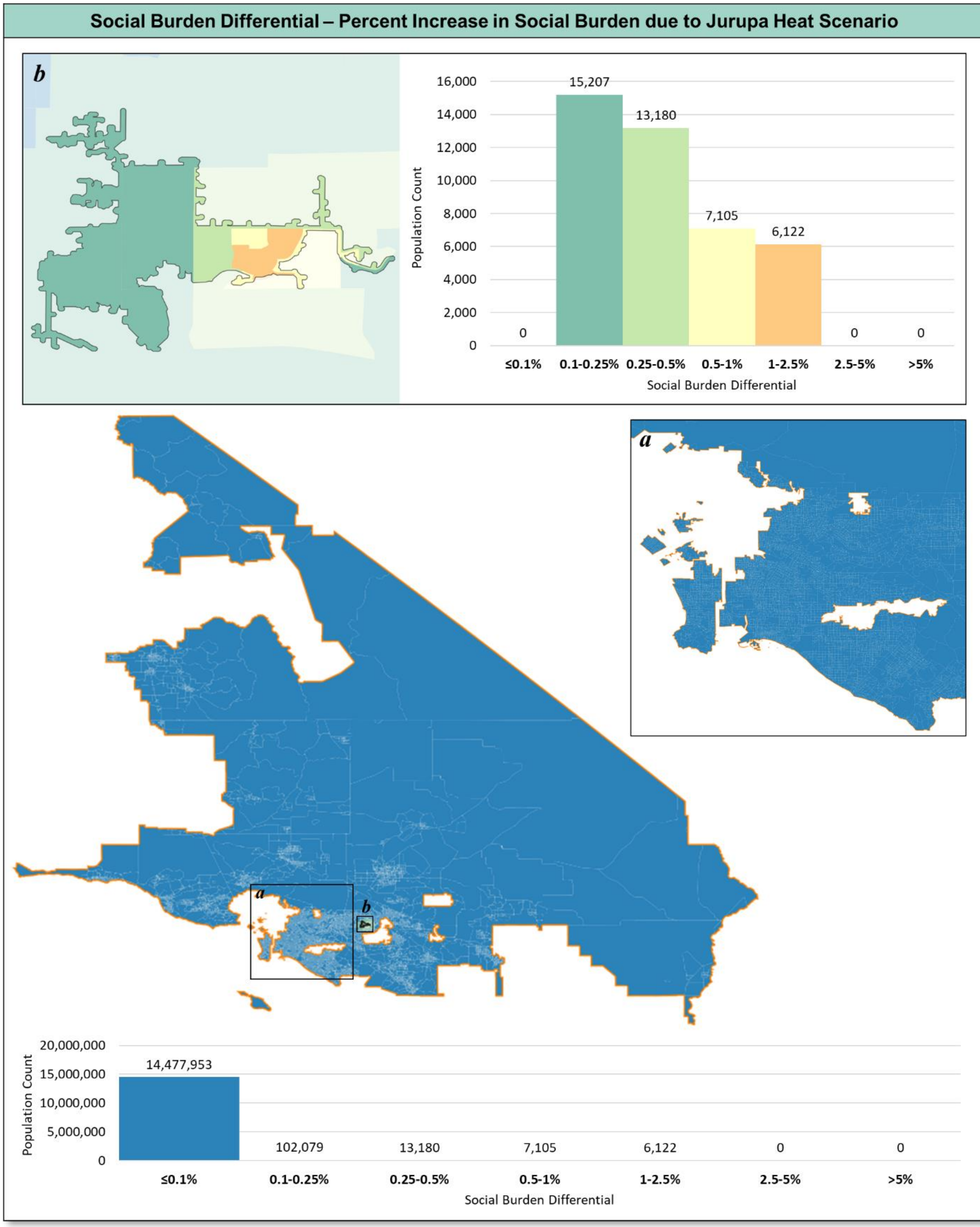

Figure 26. Impact of Jurupa heat power outage scenario: Social Burden differential

5. DISCUSSION

5.1. Metrics Integration

This study was the first of its kind to integrate a composite metric into the Social Burden formulation. Nearly every previous Social Burden analysis relied on an attainment factor composed exclusively or in large part of median household income (MHI). MHI captures economic disparities and thus is well-suited to represent the hardship that an expenditure of money to obtain critical services represents to households with different economic means. MHI has also been correlated with other factors that may act as determinants for increased hardship, such as lower car ownership [35] [36] [37] , adverse physical and mental health status [38], including mobility limitations [39], and greater caregiving responsibilities and subsequent reduction in free time [40].

However, the correlation between MHI and these and other relevant outcomes is in practice modulated by details such as age, gender, dependents, nationality, etc. Thus, additional socioeconomic indicators are relevant. The social landscape (the capacity of the community as a whole) also contributes to the way that individuals experience hardships. Tight-knit communities rely on mutual aid during and following disasters [41]. Physical infrastructure, including but not limited to that which provides critical services included in a Social Burden analysis, also plays a role in modulating hardship. Because Social Burden treats individuals as part of their population group (CBG or otherwise), the context becomes even more important for representing the attainment criterion of a group.

The CRM enhances the explicit representation of these nuances. It captures a greater dimension of socio-economic indicators (averaged as they are across population groups). It also characterizes some of the aspects of the social and built environment that modulate hardship. It contains MHI, thereby continuing to anchor the attainment factor in economic ability, but it goes beyond simply affordability.

Because this was the first study of its kind, the metrics integration was explored in detail, to understand the implications on the Social Burden results of the substitution of a new attainment factor. A statistical analysis was conducted on the log-log transformed data using a linear mixed model with random effects [42] dependent on service type using the CRM and MHI in turn as the attainment factors. The relative contributions of each variable were evaluated using a leave-one-covariate-out configuration [43] and a comparison metric of correlation between the predicted Social Burden scores from the model and the true calculated Social Burden scores.

From this evaluation it was determined that for the SCE service area, the Social Burden metric calculation is strongly dependent on the attainment factor, with 72% of the output of Social Burden attributed to the attainment factor when using CRM and 51% when using MHI. In the CRM model about 21% of the Social Burden score can be attributed to service type and in the MHI model about 35% can be attributed to service type. For the CRM model about 2% is explained by the distance information provided by the sum-over-facility term and 6% in the MHI model. This leaves 4% and 8% unexplained which can be attributed to non-linearity in the data. The high relative contribution of CRM may be due to the percentile rank transformation that the value underwent before being implemented in the Social Burden model. For more details on this see Appendix B.

These results indicate that, all else being equal, the Social Burden formulation as currently defined, attributes 72% of the social impact of outages to socioeconomic indicators (~CRM) and 21% to physical infrastructure-enabled critical service access. It also indicates, loosely, that approximately 30% of CRM information is not captured by MHI alone – although this is complicated by the percentile ranking of CRM and not of MHI and should be explored further.

The outage scenarios explored in this project were intentionally selected from a list of hypothetical outages. As such, they do not lend themselves to validation by direct comparison to lived experiences. Further validation is recommended to understand, based on actual historical outages, the respective roles that physical infrastructure access and people's innate capacities play in the impacts of extended-duration power outages. Doing so would require multiple comparative alternatives. The SCE service area is of sufficient size to support such a comparison. However, because long-duration outages are relatively unique, a variable-duration Social Burden formulation, that could be applied to outages of short or intermediate lengths, could support a more thorough validation exercise by providing a wider pool of historical outages to select from.

Finally, note that questions in the social sciences can be raised about the extent to which composite metrics are appropriate representations. These questions were not directly explored in this project, though they are noted. Discussion about the validation of the CRM with communities can be found in the SCE 2022 CAVA report. This study engaged in preliminary discussion with stakeholders about the metrics integration during the June 2023 webinar hosted by the CPUC. It is expected that additional stakeholder engagement and community validation activities would occur before a framework could be finalized and formally integrated into IOU planning.

Table 10. Summary of attribution results

Model	Attainment factor only	Service Type	Sum-over-Facility	Unexplained
CRM Model	0.72	0.21	0.02	0.04
MHI Model	0.51	0.35	0.06	0.08

Table 11. Statistical analysis models and formulas explored

Model	Formula
Attainment Factor Only Model	Log(SB) = Log(AF)
Attainment Factor and Sector	Log(SB) = B_1 Log(AF) + $B_{0,s}$
Full Model	Log(SB) = B_1 Log(AF) + B_2 facility sum + $B_{0,s}$

5.2. Drivers of Social Burden Disparities

Social Burden measures access to services relative to people's ability to obtain them. In this case study, as in most real-world applications, neither the physical infrastructure landscape nor the social one is perfectly homogenous. This is further exacerbated in this case study by the size of SCE's service area and its geographic and socioeconomic diversity. The extent to which the underlying social and physical infrastructure conditions intersect with one another was explored in the evaluation of Social Burden as an equity metric under "blue-sky" (baseline), and hypothetical outage conditions. This provides a basis to understand the inequities in critical service access throughout the service area, and how power outages can potentially further exacerbate those inequities.

Even during "blue-sky" conditions when the grid is fully operational and introducing no additional burden, there is a wide spread in the Social Burden experienced by people living in different CBGs across the SCE service area. There are three main clusters of these highly burdened areas. These include: 1) remote rural residents in San Bernardino, Inyo, and west Riverside Counties; 2) parts of Tulare County; and 3) core urban residents in Los Angeles County (Figure 27). All three of these areas generally coincide with low CRM, where CRM scores are in the 0-20th and 20-40th percentiles (Figure 6). Notably, CBGs experiencing the lowest Social Burden are found alongside some of the CBGs experiencing the highest Social Burden, with the low Social Burden CBGs occurring primarily in Los Angeles and Orange Counties, in those CBGs where CRM is high.

Disparities in Social Burden can be caused by a combination of three factors:

1. Low baseline attainment ability (i.e., low CRM)
2. Low baseline service accessibility (i.e., few facilities exist in the vicinity of where people live, those facilities that are available require high levels of effort and long travel distances to access) and availability (i.e., existing facilities provide critical services at low service levels).
3. High likelihood of critical service interruption (i.e., power outage occurrence).

Binned "blue-sky" Social Burden scores are shown separated into high, medium, and low groupings and mapped in Figure 27 for context.

In Figure 28, the product of the distance matrix (the many-to-many relationship between each CBG centroid and all facilities providing critical services in the study area), and the service levels associated with each facility and each critical service (Appendix A.2) are calculated and mapped to each CBG in the study area. This is used to summarize the disparities in service proximity and explore to what extent low baseline service accessibility may be a driver of Social Burden disparities. Figure 28 identifies parts of the SCE service area where critical services are abundant and alternative access points exist in close proximity to one another (Figure 28, top panel), those areas where service access is moderate (middle panel), and those areas where service access is poorer (bottom panel). Service access is predominantly clustered around Los Angeles County and, as Figure 28 illustrates, service access decreases radially towards the fringes of the service area. Overall, the degree of service access is spatially consistent with Social Burden, with Burden scores increasing towards the edges of the service area in tandem with decreasing quantity of critical services. There is a notable exception. The most well-resourced parts of the study area in Los Angeles County are highly heterogenous in terms of CRM (Figure 6) and contain both some of the lowest-ranking CRM percentile CBGs as well as some of the highest-ranking ones. These locations are also subject to some of the highest and lowest Social Burden scores, respectively. This study did not explore whether there is causality in these findings – for example, whether there is some underlying social architecture that causes both low-ranking and high-ranking CRM scores to co-exist in a region with high density of services, and for this reason we only summarize these observations and do not propose explanations for them. However, the results can be used to understand the primary drivers behind high (or low) Social Burden scores in specific CBGs, as well as to design appropriate intervention strategies for minimizing blue-sky or black-sky Social Burden.

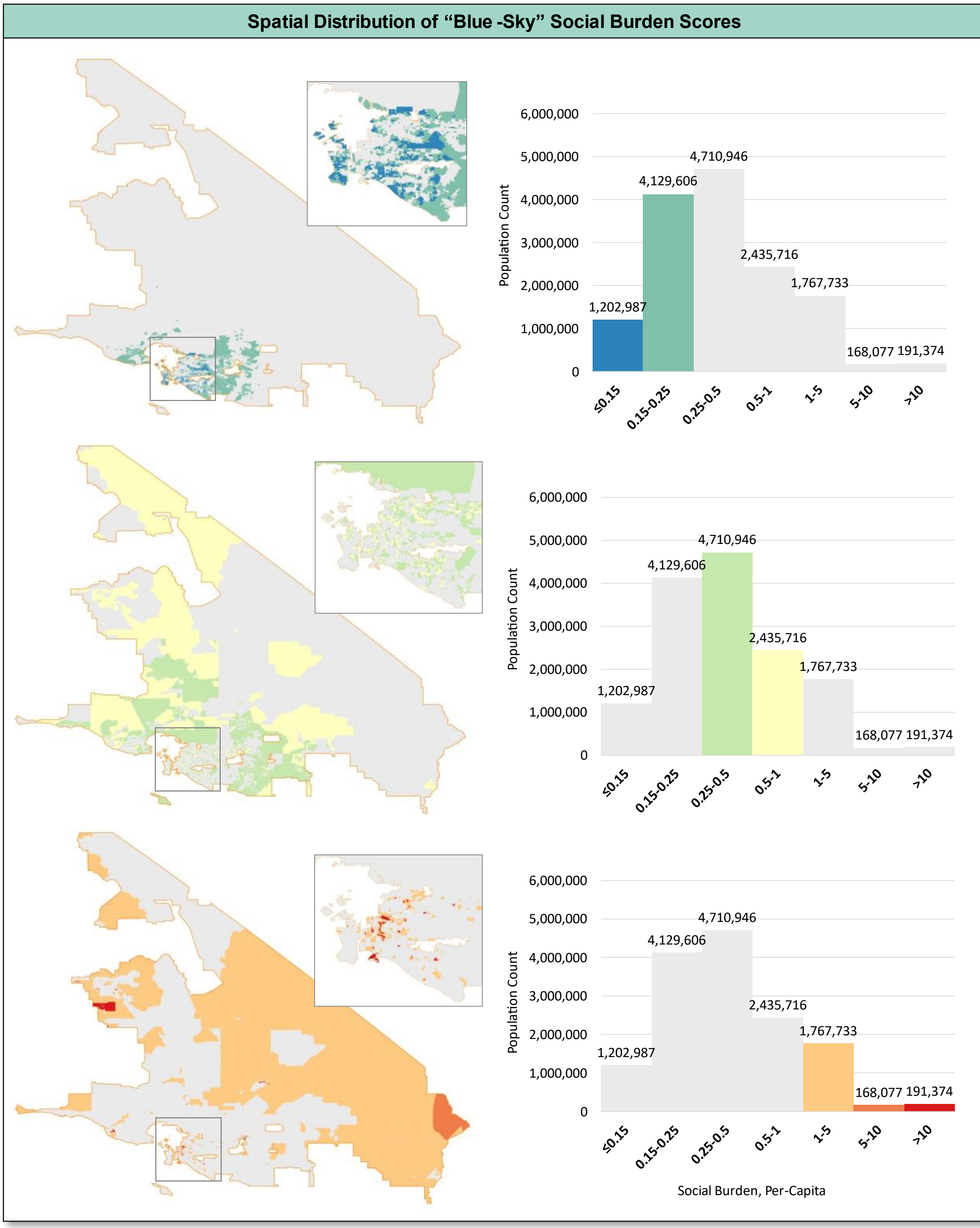

Figure 27. "Blue-Sky" Social Burden score distribution across the SCE service area

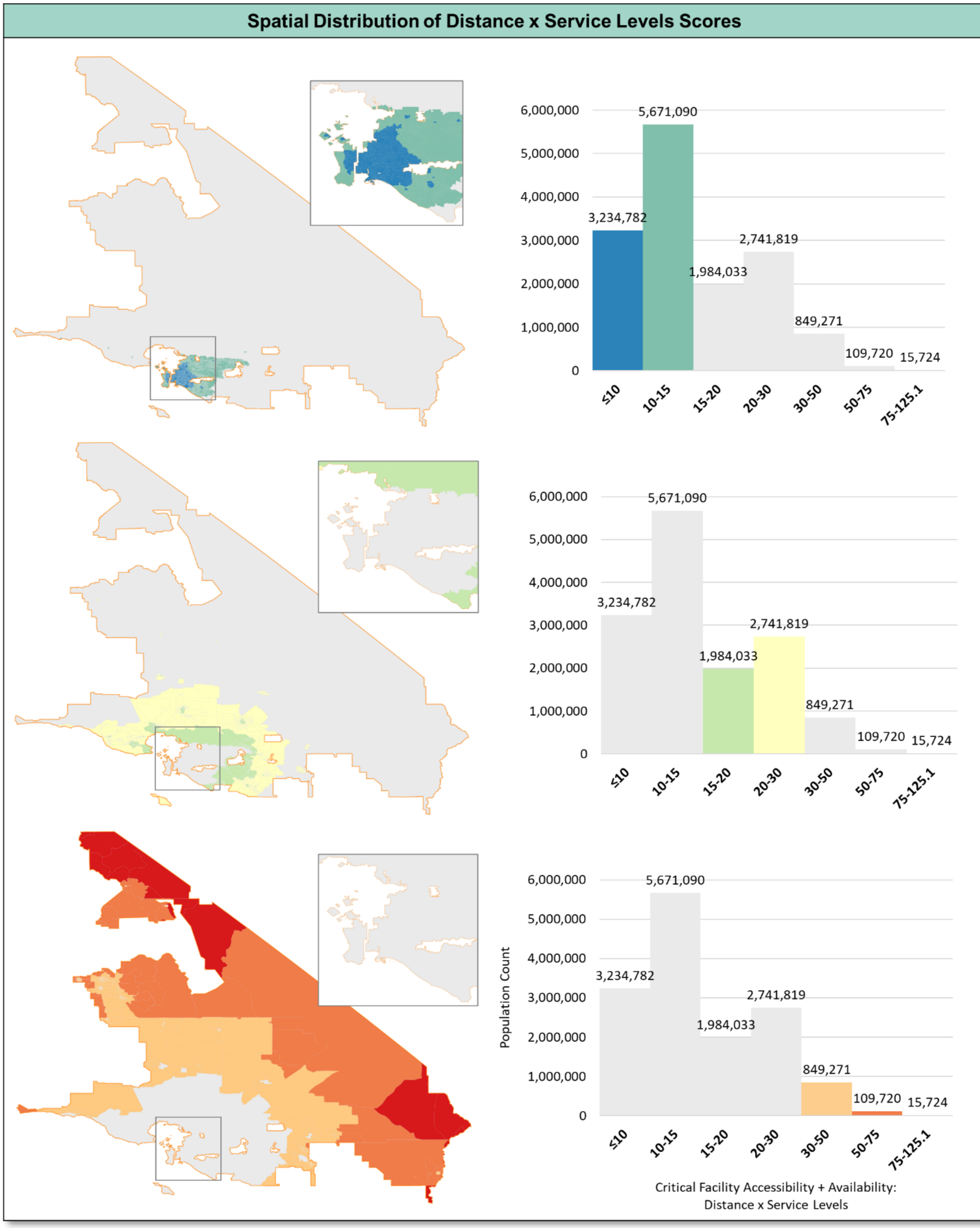

Figure 28. "Blue-Sky" critical service distance and service level distribution across the SCE service area

5.3. Implications for Community Resilience to Outages

Power outages render existing services included in the "blue-sky" Social Burden calculation non-operational under "black-sky" conditions. The total number of facilities is reduced and the services they provide are proportionally reduced. All else being equal, the greater the number the facilities (and their corresponding services) that are rendered offline by the outage, the greater the resulting increase (differential) in Social Burden would be. However, it must be noted that different CBGs have different levels of access to critical services, and different CBGs have different underlying levels of sensitivity and adaptive capacity as estimated by the CRM.

Overall, the Social Burden results suggest that relatively small-scale power outages may not lead to significant impacts for electric utility customers that live where critical services are abundant and a high number of alternative access points exists in close proximity to locations temporarily impacted by power loss. The eight outages explored in this study were located in areas with relatively high critical service density. However, with a 50,000 square mile and 15-million customer service area, the value and redundancy of services merits further investigation. Facilities which individually (e.g., a single hospital, a single retail superstore) provide high levels of service in small communities cannot unilaterally serve a population of 15 million as is the case with the SCE service area. Further refinements are anticipated to address these issues in subsequent phases of this project.

Although the ripple effects of these eight outage scenarios extend to CBGs outside the outages themselves, the biggest impact (i.e. the highest Social Burden differential values) is borne by those living near the location of the outage – in CBGs that intersect with the outage polygons. In these communities, outages exacerbate existing stress on populations with pre-existing vulnerabilities and limited adaptive capacity even if they live in close proximity to alternative access points and significantly more so if they do not. However, the majority (72%) of Social Burden scores are attributed to long-term community wellbeing (social infrastructure), which is not changed by a power outage. This is not a characteristic that can be significantly influenced by the electric utility, or any other utility in isolation or collaboration, over short time horizons. Long-term actions are required if the CRM is to be improved. Meanwhile, it is important to target electric investments that minimize the likelihood, severity, and duration of power outages in low-CRM communities. The intersection of low CRM and low service availability can be used to inform the location of high-priority CBGs in need of early intervention.

5.4. Relative vs Absolute Social Burden

To date, Social Burden has been used to inform relative decisions, e.g.: to rank the value of alternative mitigation options in reducing Social Burden, or to rank the need for local interventions within the broader community, or to understand the relative importance of maintaining certain facilities that provide critical services powered and operational over other facilities that contribute less to burden reduction. The Social Burden metric has not, yet, been used to establish absolute cut-off criteria identifying "acceptable" and "unacceptable" levels of burden or providing recommendations about the necessary level of intervention/investment to reduce burden to an "acceptable" amount. This study presents raw (absolute) Social Burden scores. However, their categorization (binning) and the discussion is relative and not currently intended to be interpreted in an absolute sense. When this report discusses "Low" or "Moderate" Social Burden scores and compares them to other CBGs with "High" or "Extremely High" Social Burden scores, that discussion is intended to reflect the nearly 4-orders of magnitude spread in blue-sky, black-sky, and differential Social Burden results and discuss the differences within the study area. It is not currently being used to recommend or establish formal cutoff criteria for what should constitute "actionable" amount of Social Burden – in this or any other study area.

Social Burden by its very formulation is always non-zero. There will always be some reasonable amount of burden that is associated with 'normal' access to critical services that does not warrant intervention. At the high end, lack of access to all critical services for an extended period of time will result in morbidity and mortality. Identifying the value of Social Burden at these two endpoints, as well as understanding how impact and Social Burden values scale along the curve between them, is critical for the maturation and adoption of the metric as a resilience investment planning aid. This was outside of the scope of the present study but will be included in future work.

5.5. Applying Social Burden Results to Intervention Design and Evaluation

Social Burden analysis can be used to inform intervention in two ways. Prioritization of investment/intervention in CBGs can be based on absolute burden – ranking CBGs in order of need based on which areas are the most at risk (high to low "blue-sky" Social Burden), and/or which areas are the most impacted (high to low "black-sky" Social Burden) (Figure 29). The selection of appropriate intervention can then be based on the Social Burden differential, including, in particular, its deconstruction into long-term community social well-being (i.e. attainment factor/CRM) versus critical service availability (i.e. distance matrix from CBGs to facilities and critical service levels). This secondary evaluation can provide insights into what interventions, under whose jurisdiction, are going to be impactful (Table 12).

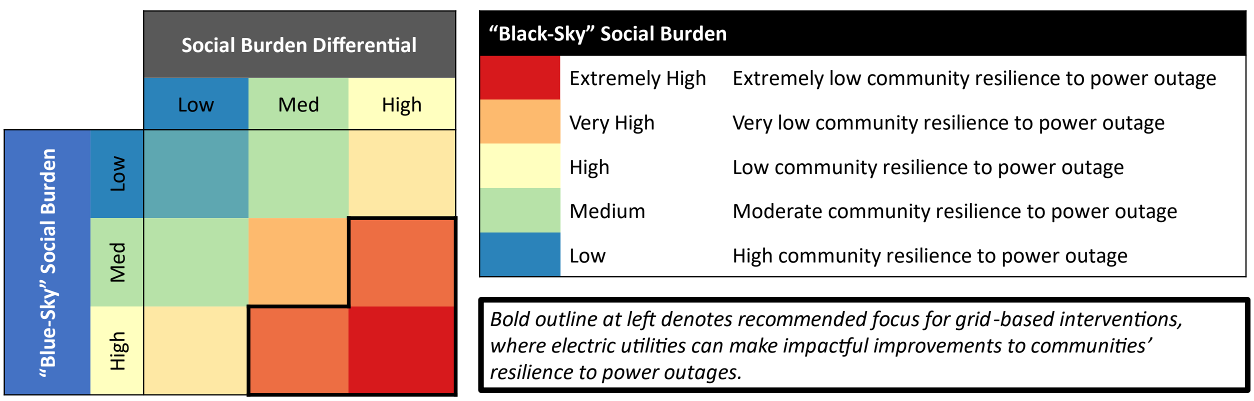

Figure 29. Relationship between "blue-sky" Social Burden, "black-sky" Social Burden, and community resilience to power outages.

Interventions by electric infrastructure owners and operators (electric utilities) stand to reduce the likelihood, extent, and/or duration of outages and *reduce "black-sky" Social Burden by minimizing the Social Burden differential.* These interventions can include prevention–e.g., line hardening or undergrounding power lines to prevent outages from taking place; mitigation–e.g., construction of microgrids to provide backup power during a grid outage to facilities providing key critical services to the community, and/or restoration–e.g., prioritizing the dispatch of crews to areas with the highest Social Burden scores first.

Interventions by non-electric infrastructure owners and operators as well as by local jurisdictions can reduce "black-sky" Social Burden by minimizing *both* "blue-sky" Social Burden and the Social Burden differential.

- *Reduce black sky by reducing blue sky:* Investment in non-electric physical infrastructure in CBGs that are under-served by critical services reduces Social Burden both day-to-day "blue-sky" and during outage "black-sky" situations by increasing the accessibility and redundancy of critical services. Examples of such interventions that reduce "black-sky" Social Burden by reducing "blue-sky" Social Burden include the expansion of service availability—e.g., siting additional grocery stores and food banks in areas identified to be food deserts or expanding public transportation hours and routes in areas with limited transportation options and low car ownership. Non-electric infrastructure owners and operators can also reduce "black-sky" Social Burden by decreasing the Social Burden *differential* via the installation of backup generators, thereby helping to mitigate the impact power outages would have on the continued provision of critical services.
- *Reduce black-sky by reducing differential:* Likewise, local jurisdictional authorities have the means to reduce "black-sky" Social Burden both via driving down Social Burden *differential* and therefore mitigating the impact of outages by targeted expansion of facilities providing critical services during emergencies (e.g. resilience centers, cooling hubs), as well by improving the baseline "blue-sky" Social Burden and thereby setting communities up for better "black-sky" outcomes by making longer-term investments in social supports to promote economic development and public health in CBGs where CRM is low.

Considering the challenges associated with the valuation of investments for low-probability (though high-consequence) events, quantifying the added "blue-sky" Social Burden reductions that would be realized by communities daily–rather than focusing on hypothetical reductions in "black-sky" Social Burden alone—can demonstrate more immediate ROI for non-electric interventions. This is another reason for collaboration with partners outside the energy sector, as these investments are outside the purview of electric utilities but can pay dividends by making communities more resilience to electric utility-owned power outages.

Table 12. Social Burden decision points and examples of potential interventions.

Intervention Categories and Representative Examples		Will Reduce High Black-Sky Social Burden by Driving Down:	
		Blue-Sky **Social Burden**	**Social Burden** ***Differential***
Electric Infrastructure Owners & Operators	Microgrids, line hardening, undergrounding, prioritized restoration		✓
Non-Electric Infrastructure Owners & Operators	Expansion of services and construction of new facilities	✓	
Non-Electric Infrastructure Owners & Operators	Installation of backup generators		✓

Intervention Categories and Representative Examples		Will Reduce High Black-Sky Social Burden by Driving Down:	
		Blue-Sky **Social Burden**	**Social Burden** ***Differential***
Local Jurisdictional Authorities	Rezoning, economic development initiatives, public health supports	✓	
Local Jurisdictional Authorities	Expansion of Community Resilience Hubs, Cooling Centers		✓

Large gains in resilience can be made by prioritizing projects that enhance CRM and/or increase critical service access in relatively few CBGs. Social Burden can be decreased by increasing proximity to services, or by increasing attainment ability (CRM). Impactful mitigations would address the sensitivity and adaptive capacity factors that contribute to these CBGs currently ranking low on CRM scores (refer to Tables 4 and 5 to review sensitivity and adaptive capacity indicators). Because the majority of the highly burdened CBGs are located in Los Angeles and Orange Counties (Figure 28, inset) where service proximity is already very high (refer to Figures 3, 24, and 26), placing additional facilities would be less impactful than increasing CRM scores. However, in outlying rural areas at the edges of the SCE service area, increasing critical service access possibly co-located with population clusters in community resilience hubs to further decrease distance to services, can be an impactful addition to social interventions designed to improve CRM.

6. CONCLUSIONS

6.1. Key Findings

Social Burden integrates and extends insights about equity and community resilience compared to the understanding provided by Southern California Edison's existing Community Resilience Metric (CRM). By integrating the CRM as the Social Burden attainment factor, the resulting analysis described in this report was able to capture differences in vulnerability and adaptive capacity across the SCE service area (the study area) with greater nuance than previous Social Burden studies which relied on median household income alone. The CRM is responsible for 72% of the Social Burden with critical service availability (i.e. their proximity to where people live and the level of service) accounting for another 23%. Social Burden analysis enhances utility and stakeholder understanding of the impacts that outages may have on people by providing a quantitative estimate that changes in response to different outage scenarios. Although outside the scope of the present phase of this work, the analysis has the potential to be extended to understand tradeoffs between different "what if" adaptation or mitigation measures with the benefits (i.e. reduced Social Burden) being directly comparable across a wide range of mitigation and adaptation scenarios.

In this case study, as in most real-world applications, neither the physical infrastructure landscape nor the social one was perfectly homogenous. This was further exacerbated in this case study by the size of the IOU service area and its geographic and socioeconomic diversity. Large gains in "blue-sky" equity can be made by prioritizing targeted investment in non-electric critical services in relatively few census block groups. Although reduction of "blue-sky" Social Burden is outside the direct purview of the electric utility (as the grid is fully powered and is not introducing additional burden to the population and, therefore, electric grid-related interventions have no means by which to reduce Social Burden), these findings can be leveraged by organizations that have a more diverse stake in public utilities and infrastructures. Improvements to baseline service availability and/or people's CRM scores would improve "black-sky" Social Burden outcomes as well, thus alleviating some of the hardship associated with power outages.

The Social Burden results also highlighted the high degree of service redundancy within the SCE service area, which means that when partial power outages render some critical services unavailable, many alternatives remain. The SCE service area is generally well-resourced although within its population distribution there are large tracts of land with low population and low service density. Social Burden, as it was applied in this study, measured the availability of critical services (where people *can* go, not where people *do* go). In each one of the eight scenarios analyzed in this study, less than 1 percent of all locations that provide critical services throughout the SCE service area would lose power. Although the outages do impact critical services, many alternatives exist to serve the population. If all four heat and all four flood scenarios were to hypothetically occur at once, the resulting power loss would still result in only 2.2% of all critical service-providing locations in the SCE service area going offline. Thus, with >97-99% of critical services continuing to be available, the increase in Social Burden would be expected to be controllable. Six out of the eight hypothetical power outages explored in this study increased each individual census block group's Social Burden by 10% or less, with a median increase of just under 2.5%. For example, the Baldwin flooding outage scenario and the Laguna heat outage scenarios were predicted to raise Social Burden by up to 49% (Baldwin) and 17% (Laguna) in some CBGs within the outage footprint, with a median increase of approximately 5%. However, when averaged across all SCE customers, the Social Burden differential of each outage was calculated to be 0.5% or less, indicating that the higher outage impacts remained localized, even for the Baldwin and Laguna scenarios.

6.2. Accomplishments

This study demonstrated how Social Burden can be applied to equitable resilience evaluations for large study areas and provided broad regional insights while maintaining the ability to explicitly represent local-scale differences in ability and service access. This study represents the single largest Social Burden evaluation performed to date both in terms of population captured and the geographic extent of the study area. The previous largest Social Burden study was recently completed for the territory of Puerto Rico by Sandia National Laboratories in 2023 [45]. At nearly 50,000 square miles the SCE service area covers close to 10 times the area of Puerto Rico and serves a 15-million customer base that is nearly 5 times the population of Puerto Rico. The large computational problem of solving for Social Burden for a matrix of 15 critical services, over 9,000 population groups, and over 33,000 facilities–- a many-to-many problem containing over 4.5 billion nodes–- was performed without the need for high-power computing using open-source, user-friendly tools (i.e., the QGIS Social Burden plugin [15]) that have been developed by Sandia National Laboratories as part of its ReNCAT ecosystem explicitly to assist with the transfer of these metrics and methodologies into the hands of stakeholders: communities, utilities, and regulators.

This study marks the first successful direct integration of a composite metric (Southern California Edison's Community Resilience Metric (CRM)) into the Social Burden formulation. The integration of CRM is unique in that it extends previous Social Burden analyses that have predominately relied on median household income (or less commonly, median residential land value) alone. The CRM integration allows the Social Burden analysis performed in this study to completely capture the multi-faceted aspects of disparities, not only in terms of economic ability but also in other adaptive capacity and sensitivity factors that are part of people's social and physical landscapes and result in different day-to-day and post-disaster experiences.

This is the first study to perform a statistical analysis on the Social Burden results to understand the results in their social and physical infrastructure contexts. Although surveys had been used in the past to understand the metric's alignment with lived experiences during and following large-scale outages, this study is the first to perform a rigorous numerical analysis of the metric, its inputs, and predictions. It sets a precedent and establishes a methodology by which to evaluate future Social Burden studies, in particular ones where new metric integration alternatives are being explored. It provides more transparency and trust in the results and allows a new understanding of the sensitivity of the results (i.e. Social Burden outcomes) to changes in the social versus physical environment, including the likely impact of different types of power and non-power sector mitigations. This work is already being extended to perform retrospective analyses of other past Social Burden projects to gain insights about differences in Social Burden composition across different types of communities (e.g., across different scales, locations, socio-economic means, and structures).

Finally, this study paves the way to the first integration of Social Burden directly into utility climate adaptation planning decisions. The integration of this analysis into utility climate adaptation planning also contributes to goals set out in the CPUC's Environmental and Social Justice (ESJ) Action Plan.

6.3. Results Application and Other Analysis Use Cases

The "blue-sky" Social Burden results can help electric utilities understand which parts of their service area, down to the census block group level, may be home to communities that may merit additional focus to ensure grid planning decisions avoid exacerbating existing inequities. However, the "black-sky" Social Burden and the differential between "blue-sky" and "black-sky" burden is necessary to fully justify higher priority status for restoration, reliability upgrades, or outage mitigation measures where grid outages may be a significant contributor to overall burden. The "blue-sky" Social Burden results are also informative and actionable for other, non-electric utilities and planners. They can help inform the understanding of disparities and gaps in the accessibility of individual critical services, as well as in the composite gaps of multiple services. Because Social Burden analysis is spatially explicit and the analysis performed in this study mapped Social Burden down to the census block group level, the results can integrate directly with urban planning processes like rezoning and land use reclassification to remove barriers and incentivize the siting of additional critical service-providing infrastructures in areas where Social Burden analysis has identified deficiencies. Ideally, this work would be undertaken in cross-sector collaboration between electric and other relevant authorities so that power outage and resilience planning measures can be identified in tandem.

IOUs prioritize projects from portfolios tailored to multiple different planning objectives. There is a need for "what if" scenario evaluations that are capable of spanning across portfolios, including the evaluation of "bonus" scenarios that explore the impacts of non-grid investments (e.g., investments in other critical infrastructure) and of changes to the social landscape of communities.

The "black-sky" Social Burden results are unique to the specific outage scenarios for which they are calculated; thus, in addition to the limitations of the Social Burden formulation itself, the results are also subject to the caveats, assumptions, and limitations associated with the scenarios. However, with those caveats in mind, the Social Burden results provide an estimate of how the outage may impact people as facilities that normally provided critical services temporarily suspend operation. The metric provides utilities and regulators with a way to evaluate how different hypothetical or historic outages impact different communities under current conditions (with no further investment in resilience), as well as to evaluate alternative resilience proposals as to their potential impact on the resilience of communities to grid outages and the equity of the distribution of the outage impacts.

The Social Burden analysis demonstrated in this pilot application can be re-run to understand the impacts on people of alternative:

- Natural and man-made hazards and their corresponding power outage scenarios
- Enhancements to both electric and non-electric infrastructure
- Hazard mitigation planning
- Changes in populations' underlying adaptive capacity and/or sensitivity.

6.4. Limitations and Future Work

In all Social Burden projects to date, including the pilot phase of the SCE, CPUC, and Sandia partnership described in this report, the Social Burden results are provided as they are, without any a-priori determination or recommendation of whether particular Social Burden values are 'acceptable' or 'unacceptable'. This enables the metric to be used to prioritize or sequence interventions in a relative sense, e.g., prioritize interventions that yield higher predicted Social Burden improvements over those with lower impact scores, or prioritize interventions for communities with higher Social Burden scores before similar investments in communities with lower Social Burden scores. However, it does not answer questions such as: what an "acceptable" level of Social Burden is; how much variability in Social Burden among communities is a meaningful, actionable amount; and at what point (i.e. at what Social Burden value) should a utility or other entity invest in interventions. More work is required, including extensive work with multiple stakeholders and communities, to develop and validate a framework by which "acceptable", "high", and “low” Social Burden scores could be identified such that Social Burden scores could be evaluated not only in relative, but also in absolute, terms. This future work will also need to address the question of scaling, and whether the impact of an outage scales linearly with increasing Social Burden scores, or whether communities’ lived experiences indicate that the impact is non-linear, and that there may be inflection points, or thresholds, beyond which the impacts move from challenging to catastrophic.

Similarly, this analysis did not consider time-varying impacts, or cascading impacts on infrastructure. No interruption to supply chains was considered that might extend the duration of an outage or decrease the service level at powered facilities over time, even if the grid continues providing electric power. Sandia has recently advanced its ReNCAT tool to simulate variable-duration power outages and calculate the Social Burden to people associated with different durations of loss of critical services. However, more research and stakeholder and community engagement will be needed to ground-truth outage experiences to better understand how outage durations relate to critical service needs and access and resilience impacts predicted by equity tools or metrics. This study did not consider unique medical needs that may require certain individuals to continue receiving services at their homes, which cannot be readily substituted (without causing harm and disproportionate hardship) by off-site care at hospitals, clinics, etc. The expansion of the Social Burden metric into a variable-duration formulation can support this type of analysis of specific acute needs as well. Acute individualized medical need can be incorporated if such data exists, although there are non-trivial challenges to balancing the potential benefits of capturing this information in a utility prioritization-informing metric, like Social Burden, with the privacy concerns of identifying vulnerable individuals down to the specific household level. However, even without high-precision data, a variable-duration Social Burden will enhance our representation of public health impacts of outages [46]. Additionally, because people will always experience some amount of Social Burden (even when the grid is fully functional and infrastructure is equitably distributed across a geographic area), more research and stakeholder and community engagement will be needed to establish baselines for what constitutes acceptable levels of Social Burden.

Next, understanding the potential geographic footprint of a future climate-driven power outage is a critical step to evaluating the potential community impacts from that outage and prioritizing locations for resilience investments. Utility power flow models can be used to estimate the potential geographic footprint of a given outage resulting from climate-driven equipment failure. However, these models are time-intensive to set up, computationally intensive to run, and have limited scalability. Therefore, they cannot be feasibly used to screen for all potential outage impacts due to a variety of potential causes. More streamlined tools are needed to enable estimates of potential outage footprints due to climate-driven events while accounting for existing system redundancies (and, where possible, to make reasonable assumptions about outage duration).

In this initial study, the SCE service area was evaluated all at once for each hypothetical outage scenario. Social Burden impacts were calculated for all customers, taking into account all facilities providing critical services, throughout the full extent of the service area. Effectively, this assumes that customers could be negatively affected by the loss of a critical facility over 100 miles away during an outage, and that during “blue-sky” conditions that same facility is contributing positively to alleviating burden of customers 100 miles away. Despite the diminishing influence of a critical service with distance already built-in to the Social Burden calculation, this simplification of a critical service’s “sphere of influence” may require further refinement. For equitable resilience planning at large scales (such as SCE’s 15 million person, 50,000 square mile service area), more research is needed to better understand the appropriate geographic scope at which power outages and the loss of individual services may affect customers: for example, the probable service areas of different types of facilities (e.g., cell towers, grocery stores, hospitals, etc.), how those service areas may differ in urban, rural, and tribal communities, and how they may vary with outage duration as individuals adjust their willingness to travel long distances if closer alternatives remain offline. More follow-on work would then also be needed to validate how service levels are estimated, and to ensure that they are consistent with any updates in the representation of geographic scopes of services. Refining and validating these assumptions with communities and other stakeholders could help inform better estimates of potential resilience impacts on DVCs and other communities.

Similarly, more research is needed to improve geospatial methodologies to better account for locations of different populations and to reduce bias, especially in rural and remote parts of large utility service territories. In this initial study, distance measurements were calculated from the centroid of CBGs to point locations of critical services to estimate the effort needed to reach those services. Effectively, this assumed that a CBG's entire population was located as its centroid. While this may be a reasonable simplification for relatively small urban CBGs, it does not sufficiently account for the geographic realities of rural areas, where both people and critical services are likely to be located along major roadways. Using point locations for critical services but CBG centroids to estimate population locations therefore has the potential to significantly magnify estimated urban/rural disparities in calculated Social Burden. Better understanding the impact of simplifications about the location of people at a CBG centroid, or straight-line distance calculations between CBG centroids and critical service providing facilities, will be important to ensure that Social Burden results do not inadvertently over- or under-emphasize travel hardships in rural and dispersed areas. Although network (path) distance methods have been added to ReNCAT since the analysis described in this report has been completed, more work will be needed to address the computational demands of solving network routing (rather than centroid-to-centroid) distance for study areas the size of SCE's service area. This should be explored in parallel with the critical services "sphere of influence" bounding follow-on work described above.

Institutionalizing Social Burden analysis within utility climate adaptation planning will require iterative evaluation of climate-driven impacts to a utility's distribution system. Sharing the full set of utility data required to perform this calculation can be challenging, and contracting with a third party can raise challenges in performing such evaluations when needed to fit into utility planning decisions. Developing user-friendly tools and interfaces, and ensuring they are sufficiently computationally lightweight for utilities to integrate into their own planning, will be an integral part of the adoption of such tools and metrics to inform decision-making around investments. Institutionalizing Social Burden will also require the development of framework that could enable the integration of Sandia's Social Burden metric into the SCE Climate Adaptation and Vulnerability Assessment (CAVA) process.

Finally, a fundamental and unaddressed gap remains to develop an augmented value of service (VoS) framework that appropriately addresses the diversity of impacts across customer types and outage types, in particular including new methodologies to appropriately value long-duration outages and to appropriately differentiate the impact of outages for different customers, particularly low-income customers. The geospatial analysis of the ReNCAT tool could be a key component of this VoS framework, either as a qualitative augmentation to the framework or (ideally, is feasible) a quantitative modifier to the VoS results. This sort of framework enables utilities to consider the potential tradeoffs of proposed investments, which allows them to make better decisions about what investments to propose and enables stakeholders and PUC staff to more easily review proposals and ultimately make decisions.

6.5. Closing

Sandia National Laboratories, Southern California Edison, and the California Public Utilities Commission worked together to better understand how the Social Burden metric can help inform equity and climate resilience planning within a California electric utility's service area. This report marks the completion of the pilot phase of the partnership. To date, a Social Burden assessment was performed for the Southern California Edison service area – a case study capturing roughly 40% of California's population. In addition to the development of a critical facilities and services database, the activities completed in this phase included the baselining of "blue-sky" Social Burden, the evaluation and integration of SCE's Community Resilience Metric into the Social Burden formulation, and the evaluation of hypothetical climate-driven threats to the power system and SCE's operations in relation to their expected social impact on people during an extended-duration outage. This work represents an important incremental step towards the use of equitable resilience valuation by utilities in infrastructure investment decision-making, with next steps to be explored in subsequent phases of the partnership.

REFERENCES

[1] Wachtel, A., Melander, D., and Jeffers, R. Measuring Societal Infrastructure Service Burden. No. SAND2022-2029R. Sandia National Lab. (SNL-NM), Albuquerque, NM (United States), 2022.

[2] California Public Utilities Commission. Environmental & Social Justice Action Plan. Version 2.0. April 7, 2022. Retrieved from https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/news-and-outreach/documents/news-office/key-issues/esj/esj-action-plan-v2jw.pdf

[3] U.S. Energy Information Administration. (2024) In-Brief Analysis. Retrieved from: https://www.eia.gov/todayinenergy/detail.php?id=61303#:~:text=On%20average%2C%20U.S.%20electricity%20customers,in%202022%20compared%20with%202021.

[4] Ericson, Sean, Jordan Cox, Michael Abdelmalak, Hannah Rabinowitz, and Eliza Hotchkiss. 2022. Exceedance Probabilities and Recurrence Intervals for Extended Power Outages in the United States. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5R00-83092. https://www.nrel.gov/docs/fy23osti/83092.pdf.

[5] Nateghi, R., Guikema, S. D., & Quiring, S. M. (2011). Comparison and validation of statistical methods for predicting power outage durations in the event of hurricanes. Risk Analysis: An International Journal, 31(12), 1897-1906.

[6] Chen, B., Yang, Z., Zhang, Y., Chen, Y., & Zhao, J. (2020). Risk assessment of cyber attacks on power grids considering the characteristics of attack behaviors. IEEE Access, 8, 148331-148344.

[7] Governor's Office of Planning and Research (OPR). *Carbon Neutrality Overview*. Available at Carbon Neutrality by 2045 - Office of Planning and Research

[8] Southern California Edison (SCE) Countdown to 2045 Whitepaper. September 2023. p. 4

[9] SCE Adapting for Tomorrow Whitepaper. May 2022. p. 3

[10] California Public Utilities Commission (CPUC). Climate Adaptation. Available at Climate Change (ca.gov)

[11] CPUC Decision 20-08-046. August 2020. p. 4

[12] Southern California Edison's Service Area Fact Sheet. Updated April 25, 2019. Retrieved from https://download.newsroom.edison.com/create_memory_file/?f_id=5cc32d492cfac24d21aecf4c&content_verified=True

[13] Southern California Edison. 2022. AL 4793-E. Retrieved from: https://edisonintl.sharepoint.com/teams/Public/TM2/Shared%20Documents/Forms/AllItems.aspx?id=%2Fteams%2FPublic%2FTM2%2FShared%20Documents%2FPublic%2FRegulatory%2FFilings%2DAdvice%20Letters%2FPending%2FElectric%2FElectric%5F4793%2DE%2Epdf&parent=%2Fteams%2FPublic%2FTM2%2FShared%20Documents%2FPublic%2FRegulatory%2FFilings%2DAdvice%20Letters%2FPending%2FElectric&p=true&ga=1

[14] QGIS.org, 2023. QGIS Geographic Information System. QGIS Association. http://www.qgis.org

[15] Hart, O.E., and Moog, E. QGIS Social Burden Plugin (2023) GitHub repository, https://github.com/sandialabs/QGIS-social-burden-plugin

[16] Wachtel, A., Melander, D., & Hart, O. (2022). ReNCAT: The Resilient Node Cluster Analysis Tool (No. SAND2022-10888R). Sandia National Lab. (SNL-NM), Albuquerque, NM (United States).

[17] Agrawal, A. W., Blumenberg, E. A., Abel, S., Pierce, G., & Darrah, C. N. (2011). Getting around when you're just getting by: the travel behavior and transportation expenditures of low-income adults (No. CA-MTI-10-2806). Mineta Transportation Institute.

[18] Casey, J. A., Fukurai, M., Hernández, D., Balsari, S., & Kiang, M. V. (2020). Power outages and community health: a narrative review. Current environmental health reports, 7, 371-383.

[19] Jeffers, R. F., Baca, M. J., Wachtel, A., DeRosa, S., Staid, A., Fogleman, W. E., … & Currie, F. M. (2018). Analysis of microgrid locations benefitting community resilience for Puerto Rico (No. SAND-2018-11145). Sandia National Lab. (SNL-NM), Albuquerque, NM (United States).

[20] Gunda, T., Wachtel, A., Khadka Mishra, S., & Moog, E. (2023). Quantitative approaches for including equity in risk and resilience infrastructure planning analyses. Risk Analysis.

[21] Jenkins, K., McCauley, D., Heffron, R., Stephan, H., & Rehner, R. (2016). Energy justice: A conceptual review. Energy Research & Social Science, 11, 174-182.

[22] Day, R., Walker, G., & Simcock, N. (2016). Conceptualizing energy use and energy poverty using a capabilities framework. Energy Policy, 93, 255-264.; https://www.sciencedirect.com/science/article/pii/S0301421516301227

[23] Homeland Infrastructure Foundation-Level Data (HIFLD). Retrieved from https://hifld-geoplatform.hub.arcgis.com/

[24] California Department of Transportation. Retrieved from: https://gisdata-caltrans.opendata.arcgis.com/

[25] The California Governor's Office of Emergency Services (Cal OES) GIS data hub. Retrieved from: https://gis-calema.opendata.arcgis.com/

[26] OpenStreetMap. © OpenStreetMap Contributors.

[27] FEMA, Community Lifelines Implementation Toolkit, version 2.0, 2019 [Online]. Available: https://www.fema.gov/sites/default/files/2020-05/CommunityLifelinesToolkit2.0v2.pdf

[28] U.S. Census Bureau. 2022. Retrieved from https://www.census.gov/programs-surveys/geography/about/glossary.html#:~:text=Block%20Groups%20(BGs)%20are%20statistical,data%20and%20control%20block%20numbering.

[29] https://docs.scipy.org/doc/scipy/reference/generated/scipy.stats.percentileofscore.html

[30] https://plugins.qgis.org/plugins/QGIS-social-burden-plugin-main/

[31] https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/infrastructure/resiliency-and-microgrids/resiliency-and-microgrids-events-and-materials

[32] https://www.youtube.com/watch?v=QKM_L9YcHmg

[33] https://www.youtube.com/watch?v=6eD-dUGaWXk

[34] https://www.youtube.com/watch?v=e0ZxqXuCLyg

[35] Dargay, J. M. (2001). The effect of income on car ownership: evidence of asymmetry. Transportation Research Part A: Policy and Practice, 35(9), 807-821

[36] Cervero, R., Sandoval, O., & Landis, J. (2002). Transportation as a stimulus of welfare-to-work: Private versus public mobility. Journal of Planning Education and Research, 22(1), 50-63

[37] Sanchez, T. W., Shen, Q., & Peng, Z. R. (2004). Transit mobility, jobs access and low-income labour participation in US metropolitan areas. Urban studies, 41(7), 1313-1331.

[38] https://jamanetwork.com/journals/jamapsychiatry/fullarticle/211213

[39] https://nhts.ornl.gov/briefs/PovertyBrief.pdf

[40] http://www.advancingstates.org/sites/nasuad/files/full-report-caregiving-in-the-united-states-01-21.pdf

[41] Loh, P., Estrella-Luna, N., & Shor, K. (2023). Pandemic Response and Mutual Aid as Climate Resilience: Learning From Community Responses in the Boston Area. Journal of Climate Resilience and Climate Justice, 1, 8-19.

[42] Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models using lme4. arXiv preprint arXiv:1406.5823

[43] Hastie, T., Tibshirani, R., Friedman, J. H., & Friedman, J. H. (2009). The elements of statistical learning: data mining, inference, and prediction (Vol. 2, pp. 1-758). New York: springer.

[44] https://ourworldindata.org/what-is-the-gini-coefficient

[45] Baggu, M., Burton, R., Blair, N., Sengupta, M., Harris, T., Barrows, C., Sky, H., Gevorgian, V., Keen, J., Smith, E., Campton, M., Jena, S., Yang, J., Williams, T., Das, P., Elsworth, J., Joshi, P., Weiner, C., Morris, J., ... Chait, M. (2024). Puerto Rico Grid Resilience and Transitions to 100% Renewable Energy Study (PR100): Final Report. https://doi.org/10.2172/2335361

[46] Do, V., McBrien, H., Flores, N. M., 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(1), 2470.

APPENDIX A. CRITICAL INFRASTRUCTURE

A.1. Critical Infrastructure Database

Table A-1 provides information regarding the source of each facility sector included in the facilities database created as part of this project.

Table 13. Sources of facility data.

Facility Type	Data Source	Data Link, if publicly accessible
Air Ambulance	CalTrans	https://gisdata-caltrans.opendata.arcgis.com/datasets/e21246e58c6f46edb39aa5a1639bc2ad_0/explore
AM Radio Station Transmitter	HIFLD	https://hifld-geoplatform.opendata.arcgis.com/datasets/am-transmission-towers-1/explore
ATM	QuickOSM	key = amenity, value = atm
Bank Branch	HIFLD	https://hifld-geoplatform.opendata.arcgis.com/datasets/fdic-insured-banks/explore
Bus Station	QuickOSM	key = amenity, value = bus station
CalTrans Maintenance Facility	CalOES	https://gis-calema.opendata.arcgis.com/datasets/CalEMA::caltrans-maintenance-facilities/explore
Car Rental	QuickOSM	key = amenity, value = car rental
Cellular Tower	HIFLD	https://hifld-geoplatform.opendata.arcgis.com/datasets/cellulartowers/explore
Clinic	QuickOSM	key = healthcare, value = clinic
Convenience Store	QuickOSM	key = shop, value = convenience
Cooling Center	Sourced by Southern California Edison	
Cruise Line Terminal	HIFLD	https://hifld-geoplatform.opendata.arcgis.com/datasets/cruise-line-terminals/explore
Drinking Water Access Point	QuickOSM	key = amenity, value = drinking water
Electric Utility Service Center	Sourced by Southern California Edison	
Electric Vehicle Charging Point	DOE Alternative Fuels Data Center	https://afdc.energy.gov/fuels/electricity_locations.html#/analyze?country=US&region=US-CA&fuel=ELEC&ev_levels=all&access=public&access=private
Emergency Medical Service	HIFLD	https://hifld-geoplatform.opendata.arcgis.com/datasets/emergency-medical-service-ems-stations/explore
Fast Food	QuickOSM	key = amenity, value = fast food
Ferry Terminal	HIFLD	https://hifld-geoplatform.opendata.arcgis.com/datasets/ferry-terminals/explore

Facility Type	Data Source	Data Link, if publicly accessible
Fire Station	HIFLD	https://hifld-geoplatform.opendata.arcgis.com/datasets/fire-stations/explore
FM Radio Station Transmitter	HIFLD	https://hifld-geoplatform.opendata.arcgis.com/datasets/fm-transmission-towers/explore
Food Bank	QuickOSM	key= social facility, value = foodbank
Gas Station	CalOES	https://hub.arcgis.com/datasets/ec575b2693f64199866bc18744d232fe/explore
Greengrocer	QuickOSM	key = shop, value = greengrocer
Grocery Store	QuickOSM	key = shop, value = grocery
Hospital	HIFLD	https://hifld-geoplatform.opendata.arcgis.com/datasets/hospitals/explore
Hotel	QuickOSM	keys = tourism, building, values = hotel, hotel
Landfill	CalOES	https://gis-calema.opendata.arcgis.com/datasets/CalEMA::calrecycle-active-soild-waste-facilities/explore
Local Emergency Operations Center	HIFLD	https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::local-emergency-operations-center-eoc/explore
Local Law Enforcement	CalOES	https://gis-calema.opendata.arcgis.com/datasets/CalEMA::local-law-enforcement-locations/explore
Metro Station	QuickOSM	key = railway, value = subway entrance
Microwave Service Tower	HIFLD	https://hifld-geoplatform.opendata.arcgis.com/datasets/microwave-service-towers/explore?filters=eyJMb2NTdGF0ZSI6WyJDQSJdfQ%3D%3D
Military Airport	CalOES	https://gis-calema.opendata.arcgis.com/datasets/CalEMA::caltrans-military-airports/explore
Money Transfer	QuickOSM	key = amenity, value = money transfer
Motel	QuickOSM	key = tourism, value = motel
Natural Gas Facility	HIFLD	https://hifld-geoplatform.opendata.arcgis.com/datasets/natural-gas-processing-plants/explore
Official Shelter	HIFLD	https://hifld-geoplatform.opendata.arcgis.com/datasets/national-shelter-system-facilities/explore
Oil Refinery	HIFLD	https://hifld-geoplatform.opendata.arcgis.com/datasets/oil-refineries/explore

Facility Type	Data Source	Data Link, if publicly accessible
Pharmacy	HIFLD	https://hifld-geoplatform.opendata.arcgis.com/datasets/pharmacies-/explore
Points of Distribution	Sourced by Southern California Edison (CCV/CRC pre-approved locations)	
Port	HIFLD	https://hifld-geoplatform.opendata.arcgis.com/datasets/principal-ports/explore
PSAP Facility	CalOES	https://gis-calema.opendata.arcgis.com/datasets/CalEMA::psap-911-service-area-boundaries/explore
Public Safety Communication Site	CalOES	https://gis-calema.opendata.arcgis.com/datasets/CalEMA::public-safety-communication-sites/explore
Public Use Airport	CalOES	https://gis-calema.opendata.arcgis.com/datasets/CalEMA::caltrans-public-use-airports/explore
Rail Operations and Maintenance Yard	QuickOSM	key = railway, value = yard
Rail Station	CalTrans	https://gisdata-caltrans.opendata.arcgis.com/maps/7ad7157d33384076ae3363bffb3ce2be
Retail Superstores	CalOES	https://gis-calema.opendata.arcgis.com/datasets/CalEMA::retail-superstores/explore
Sewer Pump	QuickOSM	key = man made, value = pumping_station
Sewer Treatment Plant	HIFLD	https://hifld-geoplatform.opendata.arcgis.com/datasets/epa-facility-registry-service-frs-wastewater-treatment-plants/explore
Supermarket	QuickOSM	key = shop, value = supermarket
Urgent Care Facility	HIFLD	https://hifld-geoplatform.opendata.arcgis.com/datasets/urgent-care-facilities/explore
Veterans' Health Administration Medical Facility	HIFLD	https://hifld-geoplatform.opendata.arcgis.com/datasets/veterans-health-administration-medical-facilities/explore
Water Purification Main Office	QuickOSM	key = office, value = water utility
Water Storage Tank	QuickOSM	https://gisdata-caltrans.opendata.arcgis.com/datasets/e21246e58c6f46edb39aa5a1639bc2ad_0/explore
Water Tower	QuickOSM	https://hifld-geoplatform.opendata.arcgis.com/datasets/am-transmission-towers-1/explore

A.2. Services to Sector Matrix

Table 12 provides information regarding the relationship between facilities and critical services, including their level of service on a scale of 0 to 5, and their effort parameters.

Table 133. Service levels and effort parameters by facility type

Facility Type	Effort Parameters		Critical Services														
	Zero Distance Effort	*Effort Per Foot*	Evacuation	Food	Water	Waste Management	Shelter	Medical Service	Medications	Security	Safety	Restoration	Fuel	Finance	Emergency Logistics	Communications	Transportation
Air Ambulance	0.4	0.05	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
AM Transmission Tower	0.005	0.005	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0
ATM	0.4	0.05	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0
Bank Branch	0.4	0.05	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0
Bus Station	0.4	0.05	3	0	0	0	0	0	0	0	0	0	0	0	0	0	4
CalTrans Maintenance Facilities	0.01	0.01	2	0	0	0	0	0	0	0	0	0	0	0	0	0	3
Car Rental	0.4	0.05	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Cellular Tower	0.01	0.005	2	0	0	0	0	0	0	2	2	0	0	0	2	4	0
Clinic	0.4	0.05	0	0	0	0	0	3	2	0	0	0	0	0	0	0	0
Convenience Store	0.4	0.05	0	3	2	0	0	0	0	0	0	0	0	0	0	0	0
Cooling Center	0.4	0.05	0	2	2	1	3	0	1	0	0	0	0	0	1	0	0
Cruiseline Terminal	0.4	0.05	3	2	2	0	0	0	0	0	0	0	0	0	0	0	2
Drinking Water Access Points	0.4	0.05	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0

	Effort Parameters		Critical Services														
Facility Type	***Zero Distance Effort***	***Effort Per Foot***	**Evacuation**	**Food**	**Water**	**Waste Management**	**Shelter**	**Medical Service**	**Medications**	**Security**	**Safety**	**Restoration**	**Fuel**	**Finance**	**Emergency Logistics**	**Communications**	**Transportation**
EMS	0.4	0.05	0	0	0	0	0	4	0	0	3	0	0	0	0	0	0
EOC	0.4	0.05	2	0	0	0	0	0	0	0	0	0	0	0	5	0	0
EV Charging	0.4	0.05	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Fast Food	0.4	0.05	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0
Ferry Terminal	0.4	0.05	2	0	0	0	0	0	0	0	0	0	0	0	0	0	3
Fire Station	0.4	0.05	0	0	0	0	0	2	0	0	4	0	0	0	0	0	0
FM Transmission Tower	0.005	0.005	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0
Food Bank	0.4	0.05	0	3	2	0	0	0	0	0	0	0	0	0	0	0	0
Gas Stations	0.4	0.05	0	1	1	0	0	0	1	0	0	0	4	0	0	0	0
Greengrocer	0.4	0.05	0	3	2	0	0	0	0	0	0	0	0	0	0	0	0
Grocery	0.4	0.05	0	4	3	0	0	0	2	0	0	0	0	0	0	0	0
Hospital	0.4	0.05	0	0	0	0	0	5	3	0	0	0	0	0	0	0	0
Hotel	0.4	0.05	0	1	1	0	4	0	0	0	0	0	0	0	0	0	0
Landfill	0.01	0.01	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0
Local Law Enforcement	0.4	0.05	2	0	0	0	0	0	0	5	0	0	0	0	0	0	0

Facility Type	Effort Parameters		Critical Services														
	Zero Distance Effort	*Effort Per Foot*	Evacuation	Food	Water	Waste Management	Shelter	Medical Service	Medications	Security	Safety	Restoration	Fuel	Finance	Emergency Logistics	Communications	Transportation
Metro Station	0.4	0.05	3	0	0	0	0	0	0	0	0	0	0	0	0	0	4
Microwave Tower	0.005	0.005	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Military Airport	0.4	0.05	4	4	2	0	0	0	2	0	0	3	2	0	0	0	5
Money Transfer	0.4	0.05	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0
Motel	0.4	0.05	0	1	1	0	4	0	0	0	0	0	0	0	0	0	0
Natural Gas Facility	0.01	0.01	0	0	0	0	0	0	0	0	0	2	5	0	0	0	0
Official Shelter	0.4	0.05	0	2	2	1	4	0	1	0	0	0	0	0	1	0	0
Oil Refinery	0.01	0.01	0	0	0	0	0	0	0	0	0	2	5	0	0	0	0
Pharmacy	0.4	0.05	0	1	1	0	0	1	4	0	0	0	0	0	0	0	0
POD	0.4	0.05	0	4	4	0	0	0	2	0	0	0	0	0	2	0	0
Port	0.4	0.05	4	3	2	0	0	0	0	0	0	3	2	0	0	0	5
PSAP	0.01	0.005	0	0	0	0	0	0	0	4	5	0	0	0	0	0	0
Public Airport	0.4	0.05	4	4	2	0	0	0	2	0	0	3	2	0	0	0	5
Public Safety Comms Sites	0.01	0.005	4	0	0	0	0	0	0	0	0	0	0	0	4	0	0
Rail OM Yard	0.2	0.01	2	0	0	0	0	0	0	0	0	0	0	0	0	0	3

Facility Type	Effort Parameters		Critical Services														
	Zero Distance Effort	*Effort Per Foot*	Evacuation	Food	Water	Waste Management	Shelter	Medical Service	Medications	Security	Safety	Restoration	Fuel	Finance	Emergency Logistics	Communications	Transportation
Rail Station	0.4	0.05	3	0	0	0	0	0	0	0	0	0	0	0	0	0	4
Retail Superstore	0.4	0.05	0	4	3	0	0	0	2	0	0	0	0	0	0	0	0
Service Center	0.01	0.01	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0
Sewer Pump	0.01	0.01	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0
Sewer Treatment Plant	0.01	0.01	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0
Supermarket	0.4	0.05	0	4	3	0	0	0	2	0	0	0	0	0	0	0	0
Urgent Care	0.4	0.05	0	0	0	0	0	5	3	0	0	0	0	0	0	0	0
VA Medical Facilities	0.4	0.05	0	0	0	0	0	3	2	0	0	0	0	0	0	0	0
Water Purification Main Office	0.01	0.01	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0
Water Storage Tank	0.01	0.01	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0
Water Tower	0.01	0.01	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0

APPENDIX B. STATISTICAL ANALYSIS AND RESULTS

B.1. Introduction

The rationale for performing a quantitative statistical analysis was to understand the relationship between the SCE community resilience metric (CRM) and the Sandia Social Burden score. A deeper understanding of the relationship between the two metrics will help guide appropriate use cases and determine avenues for refinement in developing equity metrics. We investigated the relative contributions of the elements of the Social Burden score to provide a comparison between the information contained in the CRM and the information in the Social Burden score.

We emphasize that this analysis does not attempt to evaluate the "correctness" of either Sandia's Social Burden score or SCE's Community Resilience Metric. Such an analysis would be misguided. The goal of the resilience metrics is to capture opportunities and costs people experience in the process of acquiring needed services; Social Burden and CRM quantify those opportunities and costs in different ways. The goal of this analysis is to understand the specific opportunities and costs that are captured by each metric, how those are quantified, and the similarities and differences between how the two metrics represent people's experiences when they attempt to access needed services.

B.2. Methodology

Table A-1 provides information regarding the source of each facility sector included in the facilities database created as part of this project.

B.2.1. Variables of Interest

In order to understand the relationship between the CRM and the Social Burden score, we separated out the different quantities used to calculate the Social Burden score. The inputs to Social Burden are listed below and the relationships between them are given in Figure B-1.

- Service type: Communications, Emergency logistics, Evacuation, etc.
- Census block group: A combination of census blocks collected by the Bureau of the Census that is a subdivision of a census tract or block numbering area[8]
- Facility: A specific facility providing one or more service types, for example a specific gas station with a mini-mart that provides both Food and Fuel services.
- Level of service: On a scale of 0-5, the level of service provided by a specific facility for a specific service type. For example, a gas station mini-mart will most likely have a lower level of service for the Food service type than a grocery store.
- Effort: A calculated value that accounts for the distance between the census block group centroid and a specific facility, as well as the effort required to travel that distance.
- Attainment factor: The economic resources people in a census block group have at their disposal to attain their infrastructure needs (i.e., CRM or Median Household Income (MHI)).

[88] https://www2.census.gov/geo/pdfs/reference/GARM/Ch11GARM.pdf

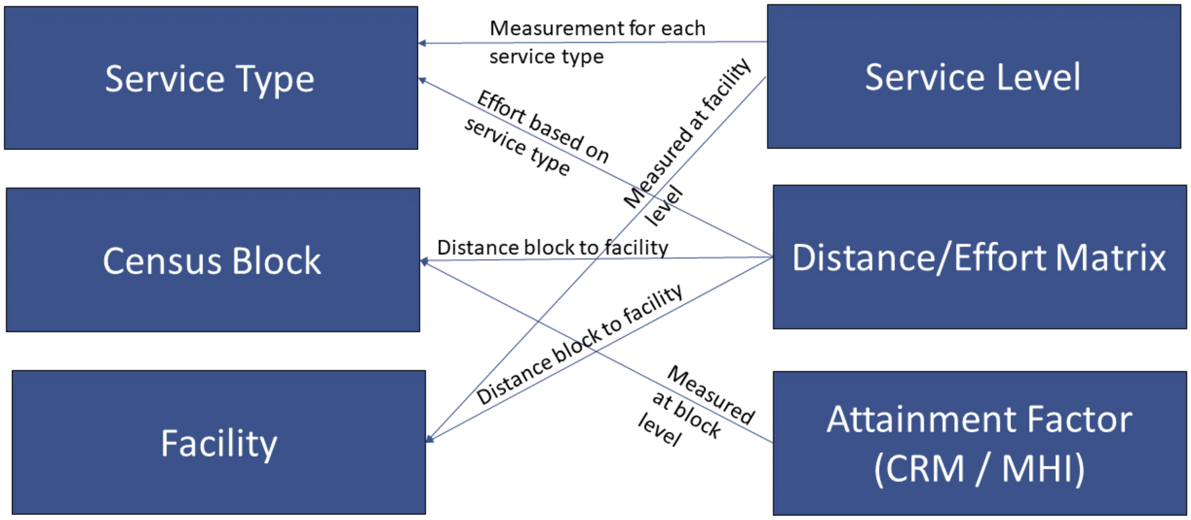

Figure B-1. Relationships among quantities contributing to the Social Burden calculation

B.2.2. Variables Used in Modeling

The Social Burden score is calculated using Equation B-1, and we modeled the Social Burden score using the variables listed in Table B-1. The relationships among the variables of interest take on neither a strictly hierarchical form nor are they crossed or nested. Because correlations among variables can produce misleading model results, we collapsed some variables of interest into surrogate metrics for modeling. Specifically, we calculated a "Facility Level/Effort" metric that accounts for the Level of Service of a particular facility as well as the Effort required to access that facility from each census block group. The Facility Level/Effort metric (Equation B-2) is the sum over all facilities of a particular service type, of the ratios of the service level for a facility and the effort required to access that facility from each census block group. This surrogate metric captures a cost-benefit calculation for accessing facilities from each census block group.

Table B- 1. Model variables and the information each provides

Variable	Provides information about:
Social Burden Metric ($Burden_{b,s}$)	Social Burden for a census block group (*b*) and service type (*s*)
Attainment Factor (A_b)	CRM or MHI for a census block group (*b*)
Facility Level/Effort ($FLE_{b,s}$)	Cost-benefit calculation, accounting for service level and effort to obtain service, for a census block group (*b*) and service type (*s*)
Service Type (*s*)	Service type (*s*)

For census block group *b*, service type *s*, and facility *f*, $D_{b,f}$ is the distance between the centroid of census block group *b* and facility *f*, $E_{0:f}$ and $E_{d:f}$ represent base-line effort and by-unit-distance effort to travel from the centroid of census block group to the facility, and $L_{f,s}$ is the level of service for a specific facility and service type:

$$Burden_{b,s} = \frac{1}{A_b * FLE_{b,s}}$$

Equation B-1. Social Burden calculation.

Where,

$$FLE_{b,s} = \sum^{f} \frac{L_{f,s}}{E_{0:f} + D_{b,f} * E_{d:f}}$$

Equation B-2. Facility Level/Effort calculation.

B.2.3. Leave-One-Covariate-Out Feature Importance Evaluation

To evaluate the contribution of each variable to the Social Burden metric, we measured the correlation between the calculated (true) Social Burden metric and the predicted Social Burden metric from a linear mixed model [53[9]]. Higher correlation between the predicted values and the true values indicates that the information provided to the model helps to explain the variation in the Social Burden scores. If variables are iteratively excluded from successive models and the predictive accuracy of those models are compared, we can quantify the contribution of each variable to the Social Burden score. This method of feature importance evaluation is sometimes called Leave-One-Covariate-Out (LOCO) [54[10]].

The full model included the variables Attainment Factor, Facility Level/Effort, and Service Type. To evaluate the effect of Facility Level/Effort, we removed that variable and compared the results of this second model to the full model. To evaluate the effect of Service Type, we ran a model that only included the variable Attainment Factor and compared the results of this minimal model to the second model. Preliminary data exploration suggested that a random effect for Service Type is appropriate for these data, therefore the full model included a fixed intercept, fixed effects associated with Attainment Factor and Facility Level/Effort, and a random intercept associated with Service Type. Model results were produced using the "lm4" package version 1.1-35.1 in the R programming language.

Let $SB_{i,j}$ be the Social Burden score for the *i*th census block group and the *j*th service type, β_0 is the global intercept, β_1 is the fixed-effects coefficient for Attainment Factor, β_2 is the fixed-effects coefficient for Facility Level/Effort, μ_j is the random intercept for the *j*th Service Type, and $\varepsilon_{i,j}$ is an error term such that $\varepsilon_{i,j}$ is independent of $\varepsilon_{x,y}$ for all $i \neq x$ and $j \neq y$. The two variance terms σ^2_ϵ and σ^2_μ describe the measurement error within and between service types, respectively. The "full model" takes the form:

$$\ln(SB_{i,j}) = \beta_0 + \beta_1 \ln(AF_{i,j}) + \beta_2 FLE_{i,j} + \mu_j + \epsilon_{i,j}, \epsilon_{i,j} \sim N(0, \sigma_\varepsilon^2)\ \mu_j \sim N(0, \sigma_\mu^2)$$

Equation B-3. Full model linear regression model with random intercept.

[9] [53] Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models using lme4. *arXiv preprint arXiv:1406.5823*.

[10] [54] Hastie, T., Tibshirani, R., Friedman, J. H., & Friedman, J. H. (2009). The elements of statistical learning: data mining, inference, and prediction (Vol. 2, pp. 1-758). New York: springer.

The "attainment factor and service type" model takes the form:

$$\ln\left(SB_{i,j}\right) = \beta_0 + \beta_1 \ln\left(AF_{i,j}\right) + \mu_j + \epsilon_{i,j}, \epsilon_{i,j} \sim N(0, \sigma_\varepsilon^2)\ \mu_j \sim N(0, \sigma_\mu^2)$$

Equation B-4. Attainment factor and service type linear regression model with random intercept.

And the "attainment factor only" model takes the form:

$$\ln\left(SB_{i,j}\right) = \beta_0 + \beta_1 \ln\left(AF_{i,j}\right) + \epsilon_{i,j}, \epsilon_{i,j} \sim N(0, \sigma^2)$$

Equation B- 5. Attainment Factor only linear regression model with random intercept.

An overview of which terms were included in each of the three models can be found in Table B-2.

Table B-2. Summary of models in the Leave-One-Covariate-Out configuration

Model	Terms Included
Full Model	Attainment Factor and Facility Level/Effort fixed effects, Service Type random intercept
Attainment Factor and Service Type	Attainment Factor fixed effect and Service Type random intercept
Attainment Factor only	Attainment Factor fixed effect

B.3. Results

B.3.1. Data Visualization

B.3.1.1 Community Resilience Metric (CRM)

Initial data exploration indicated that the relationship between CRM and the Social Burden score using CRM as the attainment factor appears logarithmic (Figure B-2), therefore we applied a natural-log (ln) transformation to both the Social Burden metric and the CRM for all analyses. After the ln transformation, the relationship between Social Burden and CRM appears linear and suggesting linear regression models are appropriate for these data. The intercepts of the fitted regression lines seem to vary by Service Type (Figure B-3), suggesting a linear mixed effects model with a random intercept term; box plots of Social Burden scores by Service Type confirm the appropriateness of this modeling choice (Figure B-4).

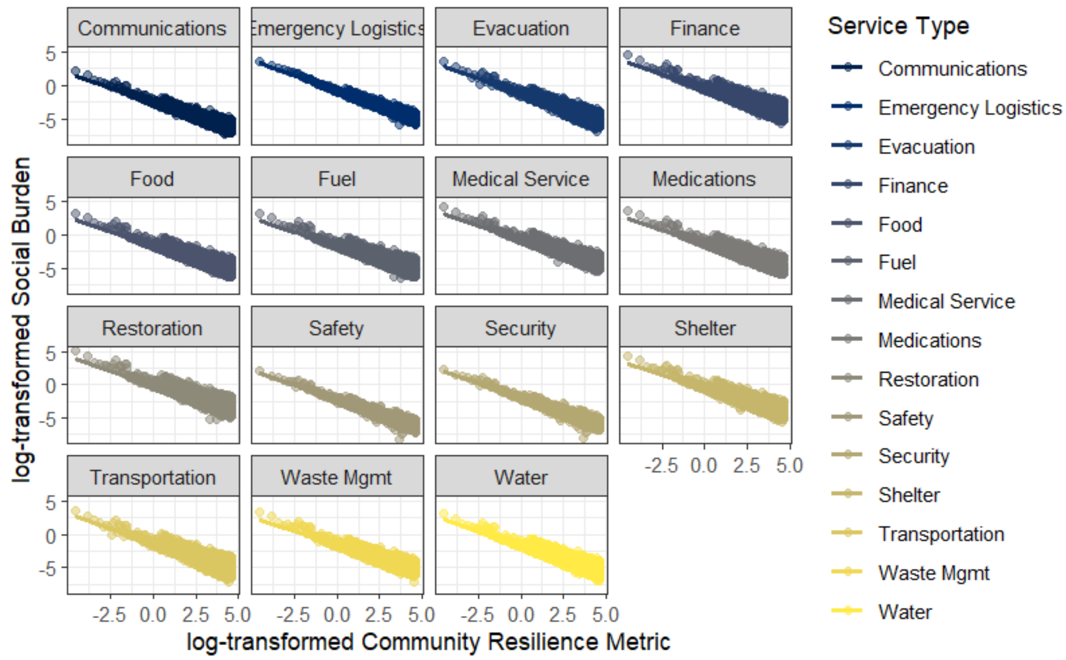

Figure B-2. Relationships between CRM and Social Burden, both natural-log transformed.

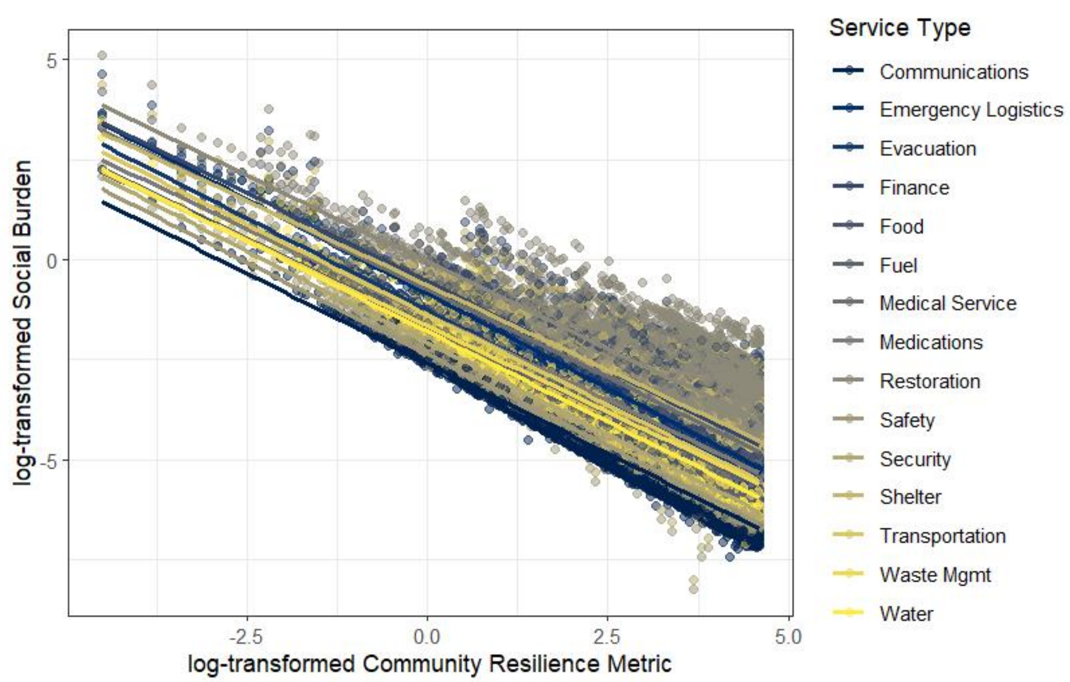

Figure B-3. Relationships between log-transformed CRM and Social Burden. The locations of the intercepts for the regression lines vary by Service Type.

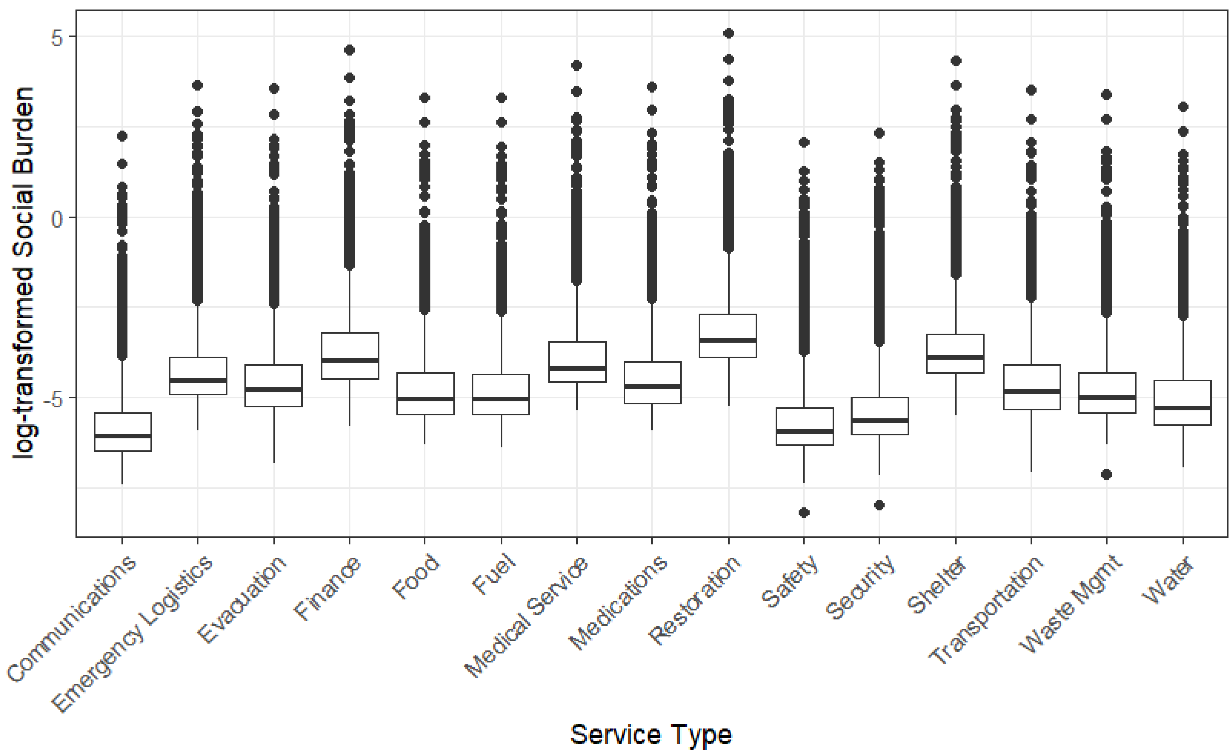

Figure B-4. Box plots displaying central tendency and variability of Social Burden scores for each Service Type using CRM as the attainment factor. The horizontal line in the middle of the boxes indicates the median score, which varies by Service Type.

B.3.1.2 CRM: Service Type and Facility Level/Effort

The value for the Facility Level/Effort metric is calculated per Equation B-2, and incorporates information on Service Type. Because correlated variables can produce misleading model results, we examined the influence of Service Type on the Facility Level/Effort values. Comparing Figure B-4 with Figure B-5, the variability in Facility Level/Effort is highly unstable, indicating that Service Type does not completely explain the variability in Service Level with respect to Social Burden score. Models that include Facility Level/Effort as a variable should therefore account for differences in Service Type (i.e., the full model includes both variables).

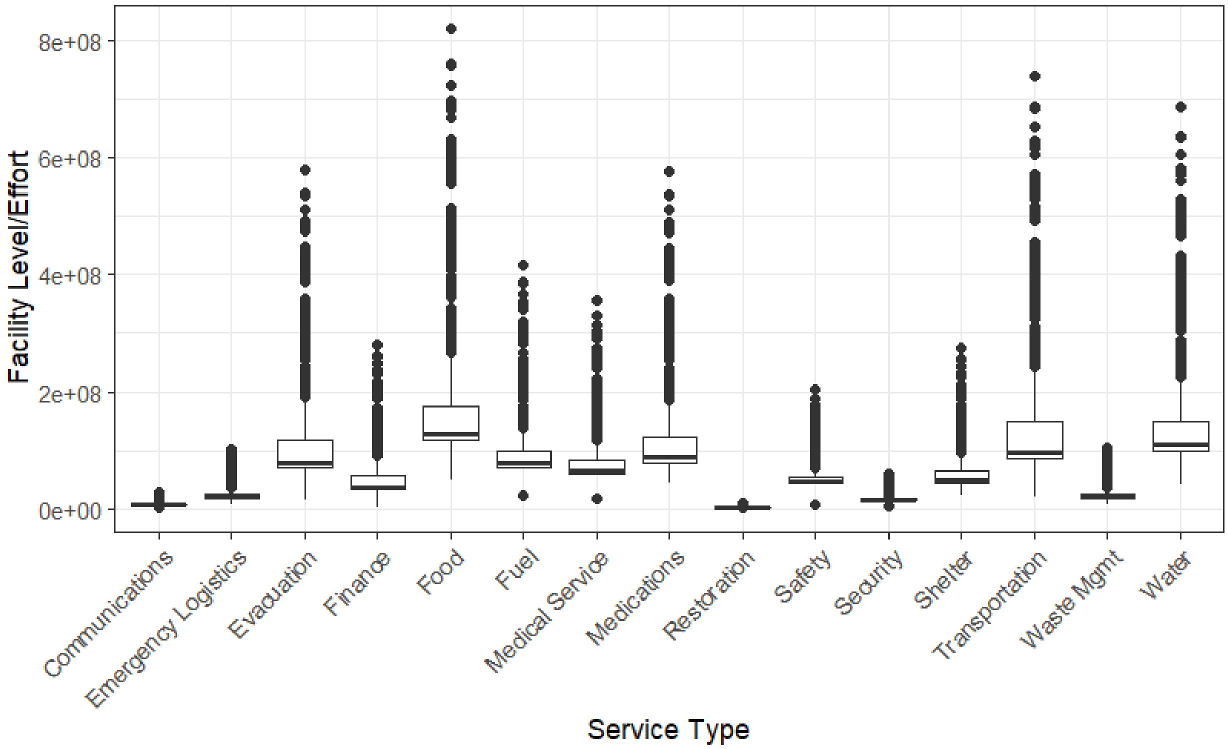

Figure B-5. Box plots displaying central tendency and variability of Facility Level/Effort (FLE) values for each Service Type using CRM as the attainment factor. The variability in FLE values across Service Types is highly unstable.

B.3.1.3 Median Household Income

A similar evaluation of the contributions to Social Burden scores was conducted with Median Household Income (MHI) serving as the attainment factor. Preliminary data exploration indicated that the relationships between MHI and Social Burden, and MHI and FLE were very similar to those related to CRM, therefore the same modeling strategy was used. The same set of linear mixed-effects models listed in Table B-2 were fit to the data in a leave-one-covariate-out configuration, and performance was evaluation using the calculated correlation between the predicted Social Burden scores and the true Social Burden scores.

The relationship between MHI and Social Burden is roughly ln-ln, similar to CRM and Social Burden, however data visualization indicates a somewhat higher level of non-linearity (Figures B-6 and B-7). This non-linearity is reflected in the slight right skew of the residuals of the full model (Figure B-8).

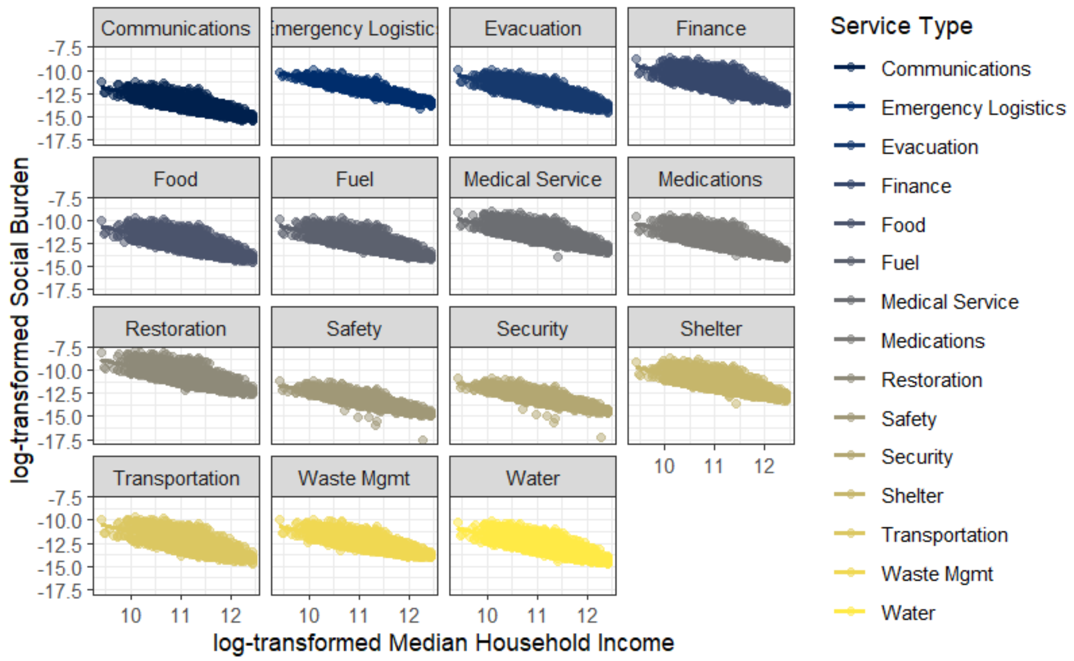

Figure B-6. Relationships between MHI and Social Burden, both natural-log transformed.

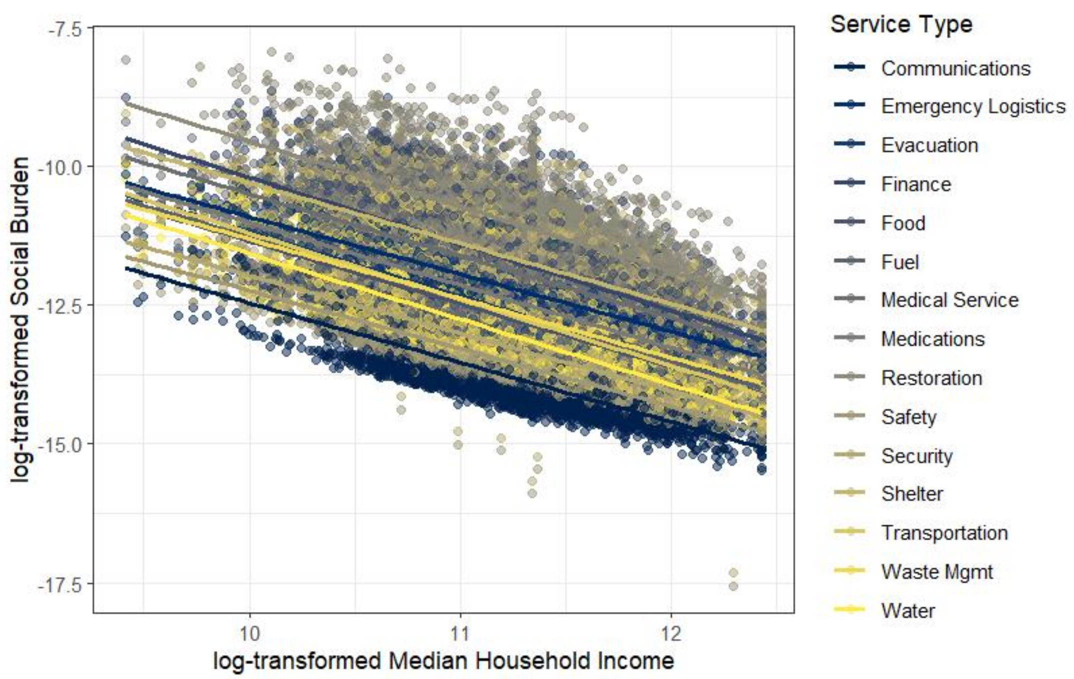

Figure B-7. Relationships between log-transformed MHI and Social Burden. The locations of the intercepts for the regression lines vary by Service Type.

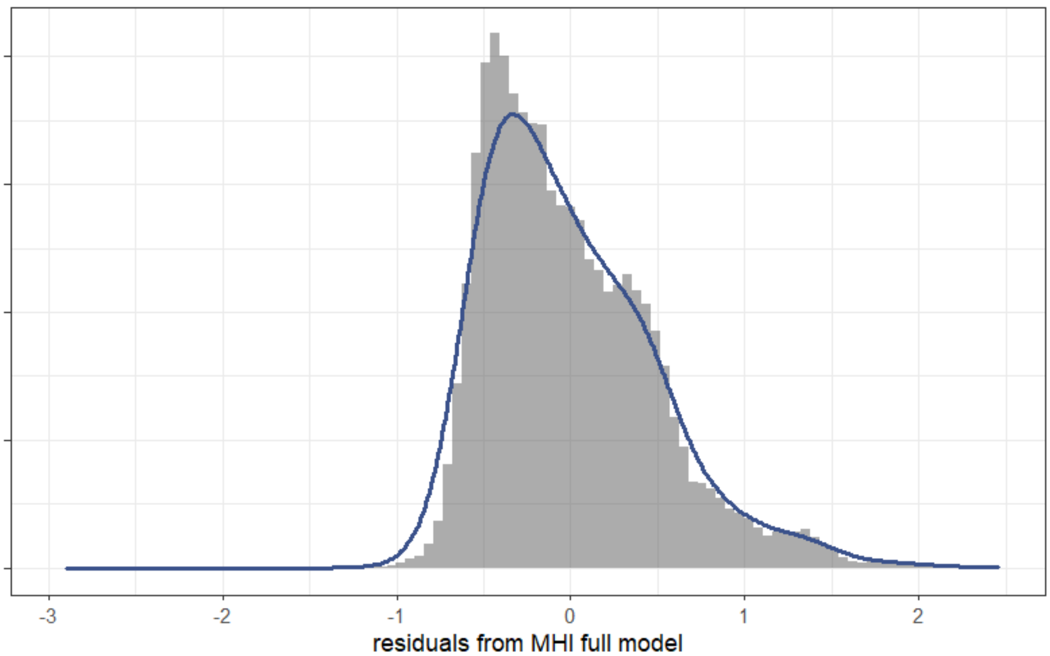

Figure B- 8. Residuals from the full model using MHI as attainment factor. The right skew in the distribution indicates non-linearities in the relationship between MHI and Social Burden.

B.3.1.4 MHI: Service Type and Facility Level/Effort

As is the case with CRM, a linear mixed-effects model with a random intercept for Service Type seems to be reasonable for MHI. The spread (variability) of the distributions of each Service Type is similar while the median (central tendency) of the distributions varies by Service Type (Figure B-9). Both the median and the variance of the Facility Level/Effort values vary widely across Service Types, with the transportation service type being particularly disparate from the others (Figure B-10).

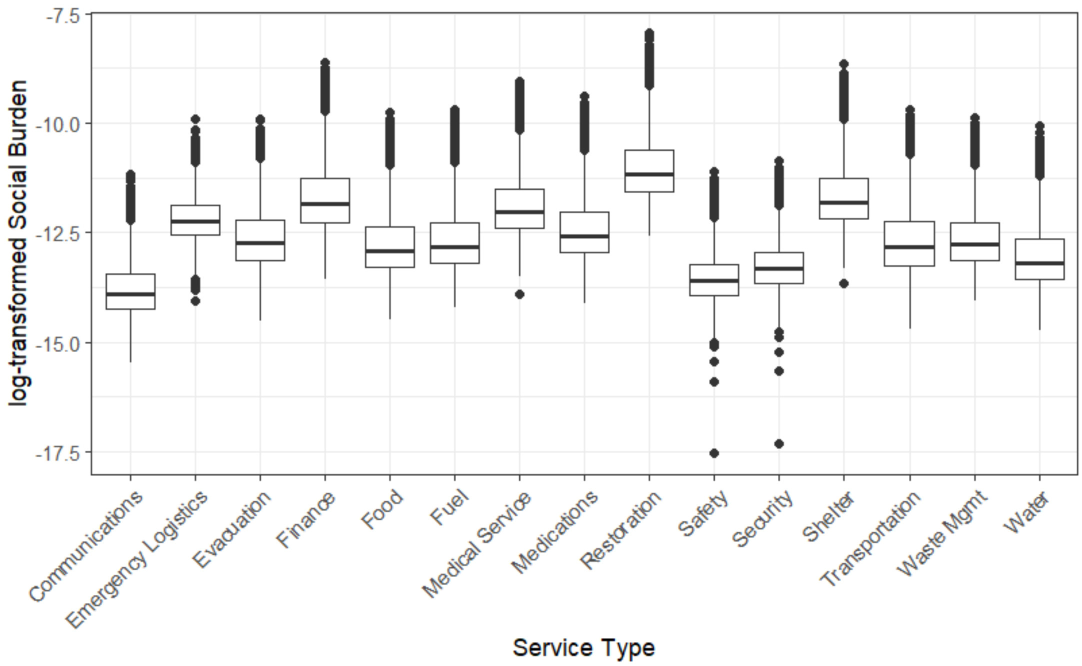

Figure B- 9. Box plots displaying central tendency and variability of Social Burden scores for each Service Type using MHI as the attainment factor. The horizontal line in the middle of the boxes indicates the median score, which varies by Service Type.

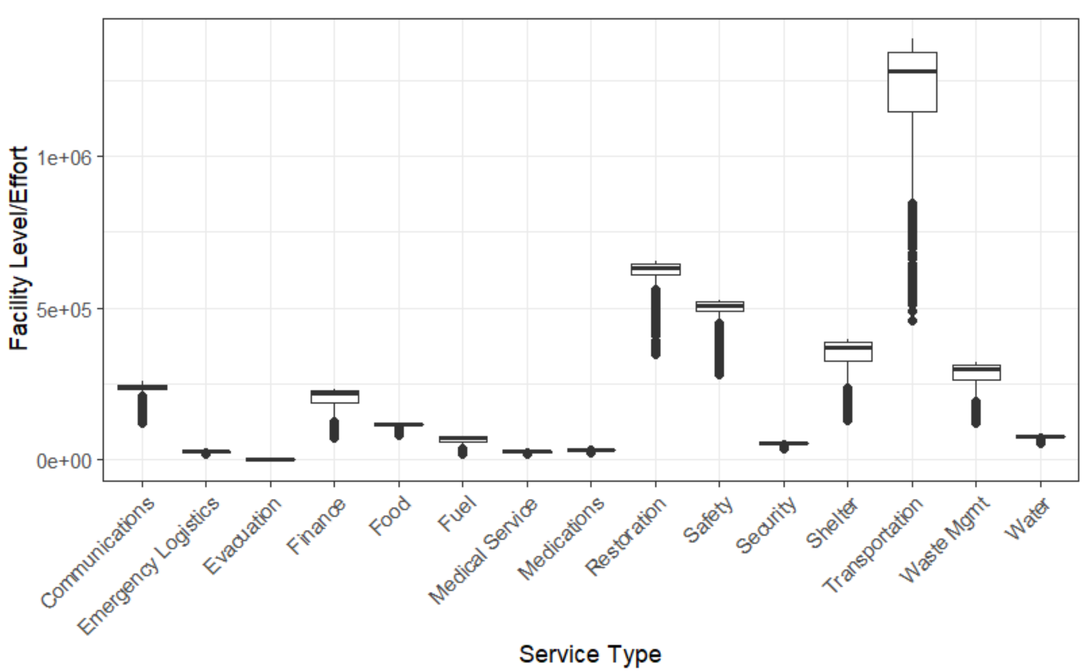

Figure B-10. Box plots displaying central tendency and variability of Facility Level/Effort (FLE) values for each Service Type using MHI as the attainment factor. The variability in FLE values across Service Types is highly unstable.

B.3.2. Model Results

Table B-3 summarizes the correlation between the "true" Social Burden values and those that are predicted by a CRM- or MHI-informed model for the three models included in the feature importance evaluation. The full model does not perfectly predict Social Burden scores because of non-linearity in the data, which accounts for approximately 5% and 8% of the variability in the Social Burden metric in the CRM and MHI models, respectively (Table B-4 and Table B-5). These values are the percent of information in the Social Burden metric that is not explained by the parameters in the model.

Table B-3. Summary of calculated correlation values between predicted and true Social Burden scores for CRM and MHI models

Model	Correlation between predicted and true values	
	CRM	MHI
Attainment Factor Only Model	0.72	0.51
Attainment Factor and Service Type	0.93	0.88
Full Model	0.95	0.92

Table B-4. Model estimates for fixed-effects parameters for the full model using CRM as the attainment factor. Asterisk indicates the estimate is significantly different from zero; i.e., that the variable contributes significantly to the Social Burden score.

Fixed Effects	Estimate	Std Error	p-value
Intercept	-1.684	0.2094	<<< .05
ln(CRM)*	-9.072e-01	1.046e-03	<<< .05
Facility Level/Effort*	5.202e-09	2.293e-11	<<< .05

Table B-5. Model estimates for fixed-effects parameters for the full model using MHI as the attainment factor. Asterisk indicates the estimate is significantly different from zero; i.e., that the variable contributes significantly to the Social Burden score

Fixed Effects	Estimate	Std Error	p-value
Intercept	0.92	0.52	0.1
ln(MHI)*	-1.07	3.92e-03	<<< .05
Facility Level/Effort*	-5.52e-06	3.68e-08	<<< .05

Despite the slight non-linearity in the data, both the MHI and the CRM models demonstrated a statistically significant relationship between the log-transformed attainment factor and the log-transformed Social Burden score ($p <<< .05$, Tables B-4 and B-5). The interclass correlation coefficient (ICC) measures the amount of variance that is explained by the random effect for Service Type; ICC values are 82% and 96% for the models using CRM and MHI, respectively, as the attainment factor.

The random intercepts for each of the Service Types are displayed below in Figure B-11. Random intercepts provide an estimate of the size and direction of the difference between the intercept for a particular group and the global intercept that would be estimated without the grouping structure. These values indicate that Restoration, Shelter, and Finance are associated with higher-than-average Social Burden scores, while Safety and Communications are associated with lower-than-average Social Burden.

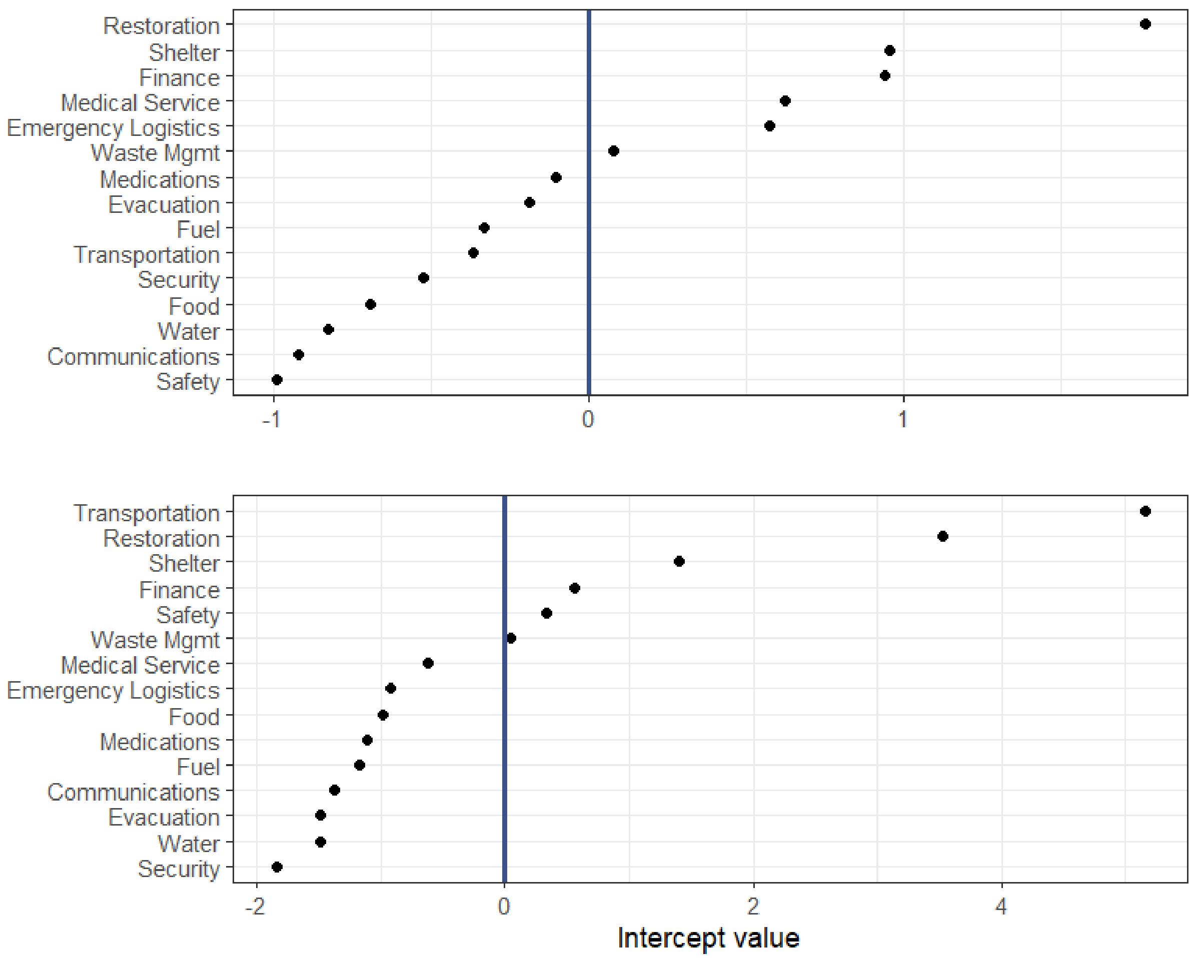

Figure B-11. Values for the random intercepts for each Service Type, for models using CRM (top) and MHI (bottom) as attainment factor. A value of zero (blue line) indicates the overall intercept if the model was fit without a grouping structure. Service Types with high intercept values are sectors associated with higher-than-average Social Burden scores

The fit of each model to the data was evaluated to ensure the models captured the relationships among the variables reasonably well (results not shown). To determine if including the Facility Level/Effort variable significantly improved model predictions, we compared the fit of two models: 1) the model that excludes the Facility Level/Effort variable, and 2) the full model that includes Facility Level/Effort. Models were re-fit using maximum likelihood estimation (rather than REML) and model fits were compared using analysis of variance (ANOVA) (Bates[3]).

For both the CRM- and MHI-based models, the full model is a statistically significant improvement from the model that does not include the Facility Level/Effort variable (Tables B-6 and B-7). We conclude that despite the relatively small contribution of the Facility Level/Effort term, this variable provides important information to the Social Burden score.

Table B-6. Statistical Test (ANOVA) for improved model fit, CRM

Model	BIC	Log Likelihood	Deviance	P-value
CRM and Service Type	169703	-84828	169565	
Full Model*	126055	-62998	125996	<<< 0.05

Table B-7. Statistical Test (ANOVA) for improved model fit, MHI

Model	BIC	Log Likelihood	Deviance	P-value
MHI and Service Type	71355	-35656	71312	
Full Model*	52788	-26367	52734	<<< 0.05

B.3.3. One-at-a-Time Regression

To evaluate the relative contribution of each Service Type to model performance we performed one-at-a-time regression in which a model was fit to a subset of the data corresponding to each Service Type, and the correlation between the predicted Social Burden values and the true values was evaluated. Similar performance among the individual models indicates that the non-linearity observed in the data is not dependent on Service Type.

In general, correlations between the true and predicted Social Burden scores are consistent across Service Types, with the exception of the Evacuation Service Type in the MHI model (Table B-8). While additional analysis would be needed to understand the drivers behind the lower correlations for Evacuation service in the MHI model, one potential driver could be the high number (6947) of electric vehicle charging stations. The quantity of charging stations, along with their high service level values for Evacuation, could be oversaturating the service type. Recall that service type accounts for more of the correlation between predicted and true values when using MHI than it does when using CRM (Table B-3).

Table B-8. One-at-a-Time Regression correlation values between predicted Social Burden scores and true Social Burden scores

Service Type	Correlation CRM Model	Correlation MHI Model
Evacuation	0.94	0.75
Food	0.93	0.92
Water	0.93	0.97
Waste Management	0.93	0.97
Shelter	0.92	0.97
Med Service	0.94	0.96
Medication	0.92	0.96
Security	0.97	0.95
Safety	0.97	0.95

Restoration	0.90	0.95
Fuel	0.92	0.99
Finance	0.91	0.98
Emergency Logistics	0.98	0.97
Communication	0.96	0.95
Transportation	0.91	0.96

To ensure that the linear mixed-effects model approach was appropriate, we evaluated the estimated coefficients for the variables in each one-at-a-time regression model—the intercept, the slope for the MHI term, and the slope for the Facility Level/Effort term. The boxplots of the coefficients displayed in Figure B-12 show that while the estimated intercepts varied widely across Service Types, whereas the estimated slope terms were more consistent. These results indicate that a linear mixed-effects model with a random intercept for Service Type is a suitable choice for the analysis.

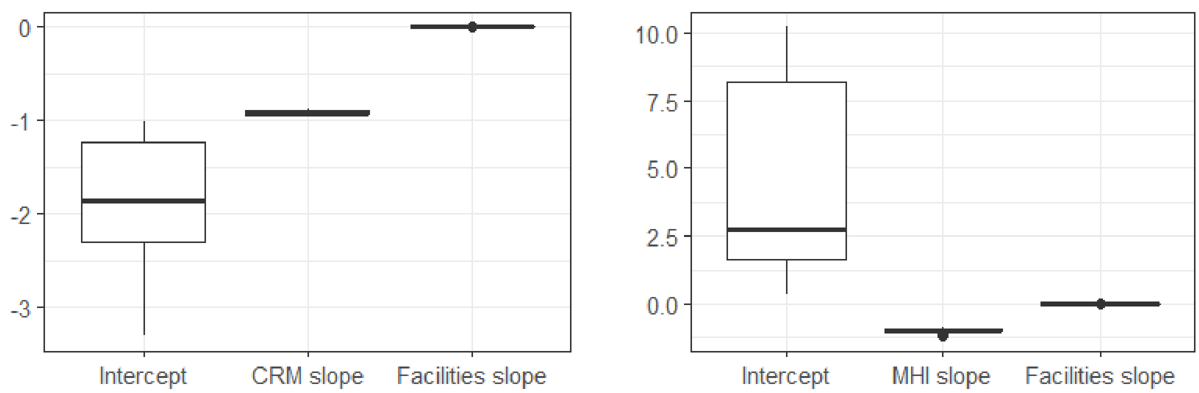

Figure B-12. Coefficient estimates for one-at-a-time regression models, for CRM- (left) and MHI- (right) based models. Each boxplot displays the distribution of 15 coefficients, one for each Service Type regression model. The high variability in the intercept terms indicates the mixed-effects model with a random intercept for Service Type is an appropriate modeling choice

B.3.4. Community Resilience Metric Transformation

Because the Social Burden score calculation requires a strictly-positive value for the attainment factor, before CRM values were input into the Social Burden calculation they were transformed by percentile rank. That is, if n is the number of CRM values, then the lowest value was transformed to $1/n$, the second-lowest value to $2/n$, etc., to the highest value which was transformed to 1. The distribution of the original CRM values was approximately normal, while the shape of the percentile-rank transformed values is approximately uniform (Figure B-13).

The transformation changed the variance (second moment: $E[(X - E[X])^2]$) of the distribution of CRM scores because it changed the expected distance between the variable and its mean. Since correlation is a standardized measure of the covariance between two variables, changing the variance of the CRM values affects the correlation between the CRM and the Social Burden score. The direction of this effect depends on the distribution of the Social Burden scores. Since the log-transformed Social Burden scores are normally distributed, the correlation is likely reduced by the transformation.

In future work alternative methods of transforming the attainment factor values might be considered to preserve the normal distribution of the data. For example, values could be shifted in the positive direction by the magnitude of the minimum value, or shifted in the same way then scaled by dividing by the mean to generate a distribution between 0 and 1 (Figure B-14).

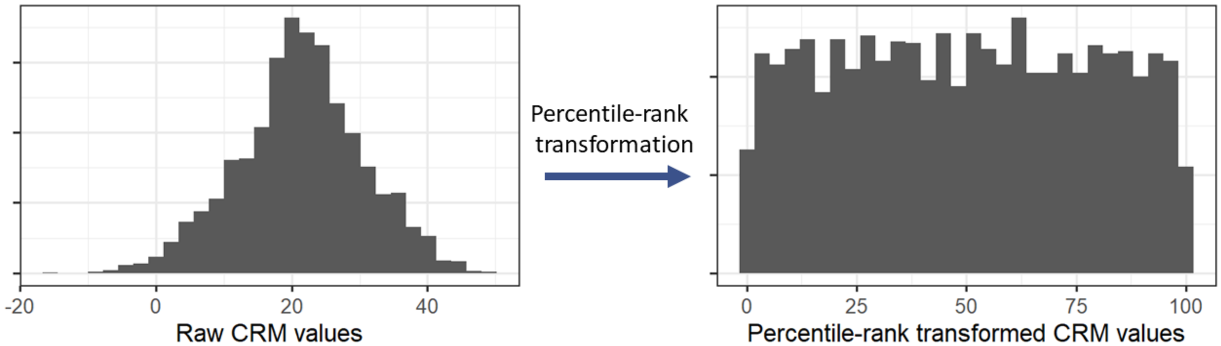

Figure B-13. CRM distributional change as a result of the percentile-rank transformation.

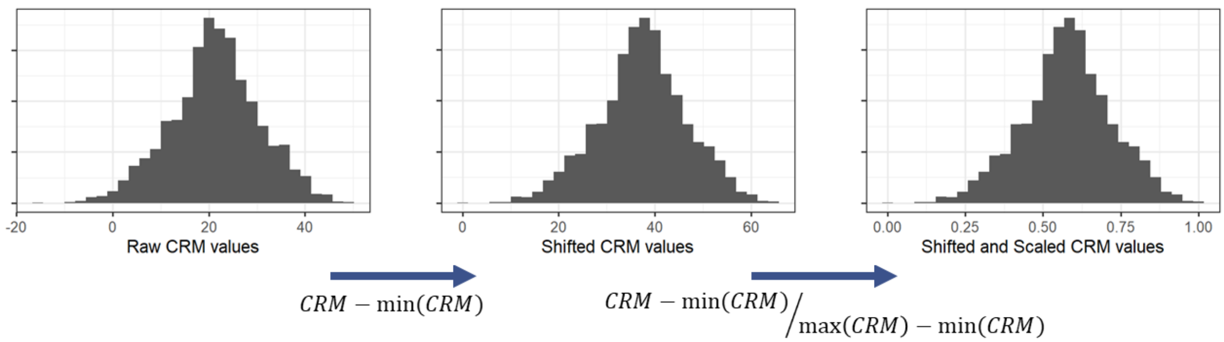

Figure B-14. Alternative CRM transformations. Note the change in the range of values on the x-axis. Left (raw): -16 to 49. Middle (shifted): 0 to 65. Right (shifted and scaled): 0 to 1.

B.4. Summary and Conclusions

Table B-9 summarizes the results of this analysis, and describes the relative contribution of each variable to the Social Burden score.

Table B-9. Estimated percent of information in the Social Burden score contributed by each variable

Model	Attainment factor	Service Type	Facility Level/Effort	Unexplained
CRM Model	72%	21%	2%	4%
MHI Model	51%	35%	6%	8%

The low contributions of the Facility Level/Effort values, which capture a cost-benefit trade-off for accessing critical services, may be explained by redundant information in that variable, since Service Type is used in calculating FLE but is also included as a separate variable in the models. Model results indicate that while the overall percentage of information contributed by FLE is small, it is nevertheless statistically significant, since model results change significantly when the variable is not included.

The values in Table B-9 describe the specific opportunities and costs that are captured by each metric, and the similarities and differences among the metrics' representations of people's experiences when they attempt to access needed services. The majority of the information in the Social Burden metric comes from the attainment factor, either CRM or MHI. About 25-40% of the information in the Social Burden score can be attributed to physical infrastructure-enabled critical services, and the inclusion of this information adds important content to the Social Burden calculation.

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