Johns Hopkins University
School of Advanced International Studies
Washington, DC

Enhancing Power Resilience in Southern California Amidst Wildfire Threat: A Comprehensive Analysis of Microgrid Integration Viability in San Bernardino County

A Project Submitted in Partial Fulfillment Of the Requirements of the Master of Arts in Sustainable Energy

Sheida Hooshmandi
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List of Abbreviations

Cal Fire – California Department of Forestry and Fire Protection

CAIFI – Customer Average Interruption Duration Index

CAIFI– Customer Average Interruption Frequency Index

CEC – California Energy Commission

CO2 – Carbon Dioxide

CPUC – California Public Utilities Commission

DOE – Department of Energy

DER – Distributed Energy Resource

EROI– Electricity Output Per Unit of Investment

GHG – Greenhouse Gas

Grid – Main electrical grid or microgrid

GW – Gigawatt

IOU – Investor-Owned Utility xi

IRR – Internal Rate of Return

kW – Kilowatt

kWh – Kilowatt-hour

LCOE – Levelized Cost of Electricity

Li-ion – Lithium-Ion

loan loss reserve(LLR)

MAIFI– Momentary Average Interruption Frequency Index

MW – Megawatt

MWh – Megawatt-hour

NEM – Net Energy Metering

NIFC – National Interagency Fire Center

NPV – Net Present Value

NREL – National Renewable Energy Laboratory

O&M – Operations and Maintenance

PSPS – Public Safety Power Shutoff

PV – Photovoltaic

REopt – Renewable Energy Integration and Optimization software

SAIFI– System Average Interruption Frequency Index

SAIDI– System Average Interruption Duration Index

Solar Photovoltaics(PV) plus storage – Solar Plus

SCE – Southern California Edison

TOU – Time of Use

USD – United States Dollars

ZEV – The Zero Emission Vehicle programme

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Chapter 1: Introduction

1.1 Executive Summary

The state of California is recognised as the U.S. state most at risk of wildfire and has experienced significant power disruptions, including preemptive electricity outages known as Public Safety Power Shutoffs (PSPS). These electricity shutdowns are implemented by utilities to reduce the risk of sparking power lines and igniting a wildfire, but can pose a significant challenge for electricity consumers, especially those in already under-served communities.

Distributed energy resources(DER), particularly behind-the-metre solar Photovoltaics(PV) plus storage(Solar Plus) systems have been proposed by a number of studies as a potential solution to enhance the resilience of energy infrastructure and reliability of generation during these outages; enabling residential and industrial properties to maintain essential operations when the main grid is unavailable.

Accordingly, this paper undertakes a multidimensional analysis of microgrid integration in Southern California's San Bernardino County, examining its financial viability, resilience benefits, and environmental implications.

By simulating outages at any time throughout the year and evaluating the survival probability, with and without solar plus integration, the study unveils a crucial finding: maintaining power supply during outages hinges primarily on the size of the solar PV system, outweighing the critical load factor and the community size.

1.2 Purpose of Research

This research analyses solar plus simulations of different sizes and building types in San Bernardino County, including one based around a hospital and one based around a university campus. The project evaluates the financial viability, health outcomes, and climate benefits associated with such integration into the grid in San Bernardino County. Hospitals and universities serve as anchor institutions that better host solar plus projects for the duration of the return period and beyond, while homeowners or retail businesses are more likely to relocate under shorter time horizons. Although the inspiration for supporting DERs is to provide backup electricity as a response to the upward trend in utility PSPS for wildfire caution, the financial justification for microgrids is due to the falling cost of solar energy and a project's ability to deliver electric bill savings. Microgrids are not only meant as backup electricity supplies during a power outage. The resiliency benefits are a by-product of running the microgrid as an electricity generator throughout the year, as evidenced in outputs from the NREL ReOpt simulator used during this study. Battery usage is not optimised to remain fully charged and static at all times during normal day-to-day operation. Simulations in this study show that economies of scale in solar and storage systems become economically viable when using lifecycle NPV as a metric, but the upfront capital costs may be prohibitive. High resilience during outages is achieved with larger solar PV size and battery storage capacity, requiring higher capital expenditures; necessitating innovative financial approaches. In the current political climate in the United States, and California more specifically, renewable energy development currently receives favourable levels of support, owing to the 2022 Inflation Reduction Act (IRA). Accordingly, this paper proposes policies and financing solutions that enable the project's long-term financial viability.

1.3 Research Question

This project will try to answer whether there is an economy of scale threshold where the DER makes financial and economic sensehttps://pvwatts.nrel.gov/ based on parameters such as the critical load factor, the size of the resident pool, and the amount of land available for a solar PV array project. While the outputs of the models are specific to the case study campuses explored in this project, the study introduces a method of leveraging NREL's PVWatts and ReOpt modelling tools that can be applied to any proposed microgrid site to assess the lifecycle NPV based on electricity demand, amount of land available for PV construction, and estimated critical load. Based on the predicted upfront capital costs and demographic setting compared to the lifecycle net present value, this project then suggests ways that microgrids can be incentivised. The findings of this research will inform policy-making on adopting community solar plus in Low to moderate-income (LMI) communities in efforts to mitigate the impacts of wildfire-related outages and enhance community resilience.

1.4 Summary of Findings

This project's broad findings include:

- The lifecycle NPV over a 25-year period improves with larger PV array size and available land by proxy. As cities make more space available to scale solar arrays, residents can derive more electricity off-the-grid and justify the upfront capital costs with projected electricity bill savings.
- Serving high critical load factors during power outages requires a larger battery capacity. There is a threshold where the lifecycle NPV becomes negative because a high critical load requires battery storage systems sizing that is so expensive that microgrid DERs are not financially viable.
- The probability of outage survival of varying duration at a random time is a function of battery capacity. The ReOpt model runs its optimization subject to a resiliency constraint that requires the system to be capable of satisfying the critical load for a certain duration on a particular day. However, the day-to-day operation of the microgrid does not expect that the batteries are fully charged at all times, but rather to buy and sell to the broader electric grid based on electricity arbitrage. Consequently, if the batteries are not fully charged at a given moment when a random power outage is simulated, the probability of surviving a long-duration power event is lower than what is expected for a resiliency system. This result is still broadly consistent with the model's primary function of optimising the lifecycle NPV objective function, instead of maintaining 100% resiliency at all times as the primary goal.

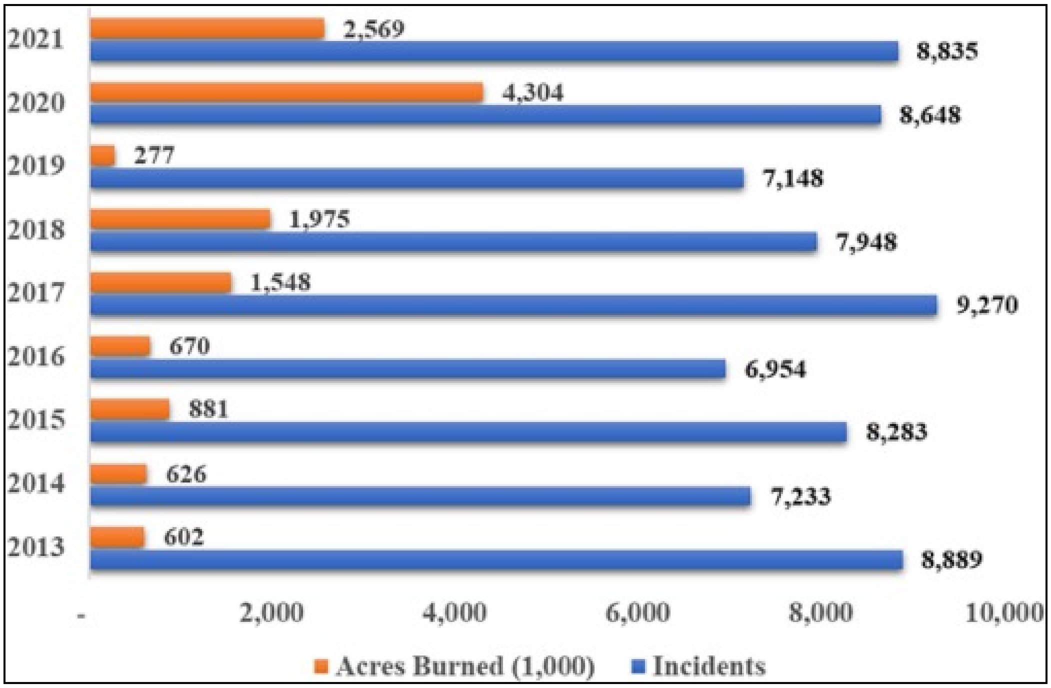
- While the outputs obtained in this project are specific to the campuses selected for the case studies, we can outline critical learnings that would apply to future projects. A microgrid with an anticipated electricity load with a positive NPV is necessary for financial viability, but it is also recommended that the lifecycle NPV exceeds the initial upfront capital costs: a suggestion meant to mitigate the effect of sticker shock. This paper recommends that the number of residents, critical load, and PV array size included in the microgrid project are varied to explore the sample space to find the points where the NPV and upfront capital costs crossover. This may not be achievable in all cases based on the amount of available land or high critical load factors (e.g. a hospital's life-saving operations). For example, in the baseline San Bernardino site selected with the given land constraints, the upfront capital costs consistently exceed lifecycle NPV savings across a broad range of a number of residents, while the baseline Redlands campus does achieve a crossover point. Varying the PV array capacity in both communities identified a region of the sample space where the lifecycle NPV does exceed the upfront capital costs, but would require stakeholder negotiations to make this land available for solar.
- This study suggests implementing policy measures, such as consolidated energy billing, to streamline billing, as well as, the local government acting as an anchoring institution to encourage the participation of low-and moderate-income (LMI) households in San Bernardino County as well as the use of tax-exempt municipal and green bonds to lower the upfront costs. Tax Exempt Municipal and Green Bonds are considered one of the most viable means of financing the Solarplud projects on both campuses.

Chapter 2: Background and Literature Research

2.1 California Wildfires

Wildfires have emerged as a significant concern worldwide, particularly in California. Over the past decade, the state has witnessed a yearly average of 7000 wildfires as depicted in Figure 1. In 2020, a new record was set when almost 9,000 fires erupted, and burned over 4 million acres.

Figure 1: Wildfire Events in California (2013-2021)

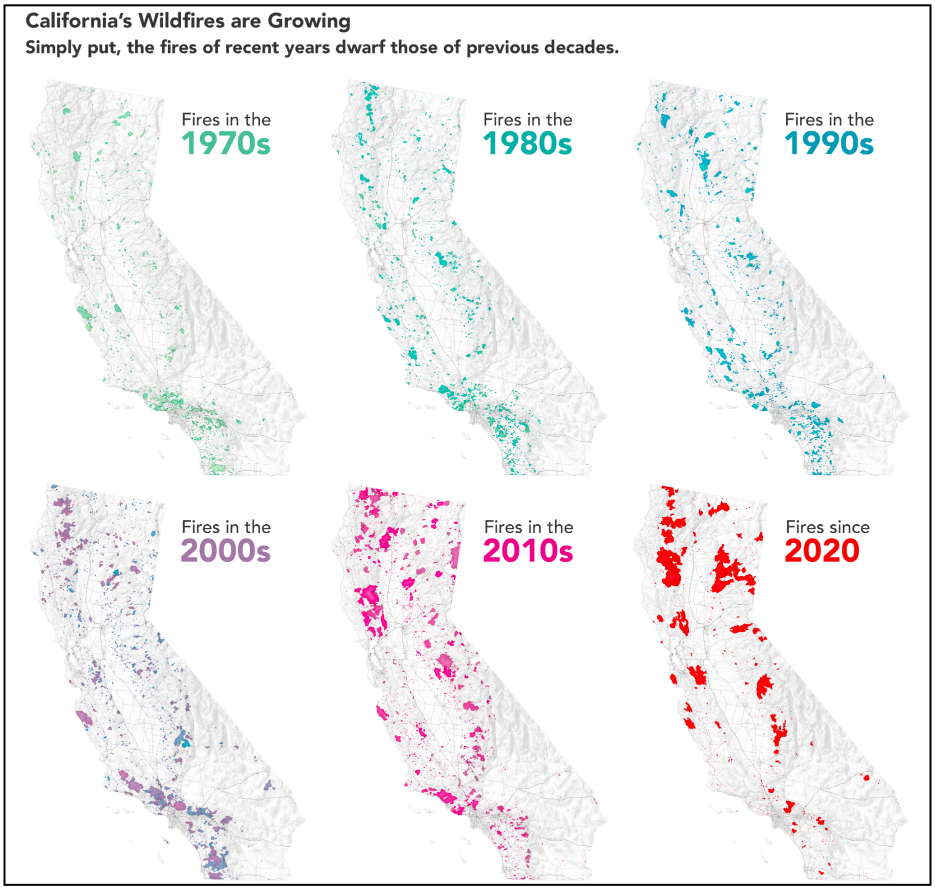


Source: CAL FIRE, n.d.

Between 1972–2018, California experienced a fivefold increase in the annual burned area, primarily as a result of more than an eightfold increase in summer forest-fire extent. According to Calfire, the California Department of Forestry and Fire Protection (2022), only three of the 20 largest wildfires in the history of the state occurred before 2003: the remaining 17 took place during the past 2 decades, with seven of them occurring in 2020 and 2021(Appendix A&B).

Between 1970 and 1980, 3% of the land in the state was burned, rising to 11% between 2010 and 2020. Figure 2 depicts the growing trend toward larger fires.(Wehner, et al. 2017, Parks & Abatzoglou, 2020; and, Calfire, 2021). These peaks in large fires have been linked to prolonged droughts, and changes in precipitation patterns.

Figure 2: Trends in California Wildfires 1970s - 2020s



Source: NASA(2021)

Wildfires have significant economic impacts in California, with damages in 2018 amounting to approximately $148.5 billion, or 1.5% of the state's annual GDP (Wang et al.,2018). Radeloff et al.(2020) states that the economic impact comprised $27.7 billion (19%) in capital losses, $32.2 billion (22%) in health expenses, and $88.6 billion (59%) in indirect losses. And this confirms Wang et al.(2018) findings which suggest the economic cost may go beyond the borders of

California and that most of the economic damages related to California wildfires may be indirect and could affect industry sectors and locations distant from the actual fires. For instance, 52% of the indirect economic losses, equivalent to 31% of the total losses in 2018, occurred outside of California.

2.2 Mitigation and Adaptation in California and Increased Risk of Wildfire

California has implemented several climate change mitigation policies directly and indirectly related to wildfires, including a target of 100% clean electricity, 100% new zero-emission vehicle(ZEV) sales by 2035, and a target of reducing Green House Gas(GHG) emissions to 85% below 1990 levels by 2045. For the first time in history, the state's plan targets reduction in GHG emissions and carbon sequestration in natural and working lands (NWL) and mandates that they will act as a "net source of emissions, not a sink"(California Air Source Board, 2022).California has also implemented the Vegetation Treatment Programme, which aims to reduce the amount of fuel available for wildfires by thinning forests and removing dead trees. Empirical evidence has demonstrated that the implementation of this programme can effectively reduce the intensity of wildfires and curb their spread (Stephens et al., 2016).

In addition to mitigation policies, California has implemented adaptation strategies to coexist with the wildfires but lower the damages. One of the main steps towards this goal is the change in the structure of the Office of Emergency Services, in order to include environmental risks and coordinate response efforts during emergencies, such as wildfires and another is the development of the California Wildfire and Forest Resilience Action Plan in 2021, which outlines strategies for reducing the risk of wildfires and improving the resilience of forests. The plan includes measures, such as improving forest management practices and increasing funding for wildfire suppression and prevention (California Natural Resources Agency, 2021). In addition, California has implemented measures to improve early warning systems for wildfires. For example, the state has deployed a network of weather stations and cameras to monitor conditions and provide early warnings of potential wildfires (The Legislative Analyst's Office (LAO), 2023).

According to Goss, et al. (2020), it is predicted that climate-driven wildfires ignited by aging infrastructure– like the CampFire– will experience a heightened frequency in the coming years. In response to the heightened risk of wildfires associated with utility infrastructure in California, the "Utility Wildfire Mitigation Program" has been developed. The programme mandates specific measures that utility companies must implement to lessen these risks. These include managing vegetation close to power lines and other infrastructure to prevent fires from starting and performing regular inspections to identify and repair any potential hazards. One of the most controversial aspects of the programme is the use of controlled power outages for safety reasons, also known as PSPSs. In times of elevated wildfire risk, utility companies may choose targeted power outages in certain areas to reduce the risk of wildfires caused by electrical infrastructure. While this approach may reduce the chances of wildfires, it can also cause disruptions and has been a contentious issue amongst Californians: schooling, business, and hospital services can be hindered leading to concerns over the fairness of such measures and its practicality. A study by Wong-Parodi(2020) also indicates that PSPSs are associated with poorer mental and physical health amongst Californians, worsened by past traumatic wildfire experiences.

2.3. Santa Ana Winds and Wildfire Season

Wildfire season in California typically spans from May to October, but wildfires can and do occur throughout the year(NIFC, nd). Along with a predicted increase in intensity, the number of large fire days is expected to rise too, as concluded by Dong et, al(2022): "from 36 days/year during 1970–1999 to 58 days/year under moderate GHG emission scenario and 71 days/year by 2070–2099 under a high emission scenario.”

The onset of autumn marks the beginning of the offshore wind season, characterised by irregular episodes of land-to-sea winds that cause a considerable shift in the usually damp onshore flow across the coastal region of California. These winds are known as "Santa Ana" winds in Southern California and "Diablo" winds in the San Francisco Bay Area(Abatzoglou et al., 2021). The wildfire burn areas are “3.5–4.5 times larger on Santa Ana days” than other days of the year (Billmire et. al, 2014).

Offshore winds typically occur during the autumn and early winter months (Abatzoglou et al., 2021), as they are primarily caused by strong surface pressure gradients resulting from early-season cold air masses over the Great Basin (Guzman-Morales et al., 2016). These winds lead to significant drying and warming of the air mass as they descend the western slopes of California's mountains.

As a result, California's wildfire season is usually "back-weighted," with the greatest risk of severe fires occurring during the autumn months when there is maximal annual vegetation dryness and desiccating offshore windstorms (Nauslar et al., 2018; Abatzoglou et al., 2018).

Luković et al. (2021) conducted an analysis revealing that California's already narrow wet season is becoming even shorter and more intense. The study’s observations spanned from 1960 to 2019 to document a considerable and statistically significant decrease in autumn (September–November) precipitation. A decline primarily driven by a reduction in November precipitation– historically the wettest month– ultimately resulting in wildfire season becoming longer in the future(Williams et al., 2019)

2.4 Southern California During Santa Ana Season: Risk of Wildfire and Outages

Southern California is prone to wildfires due to several factors. The region is characterised by a Mediterranean climate with cool, wet winters, but with hot, dry summers. Aside from natural causes, human activity also plays a significant role in wildfires in Southern California: Keely and Syphard(2019) emphasise that "humans are responsible for starting nearly all fires in this region".

The region has a high population density, and people priced out of Los Angeles proper have scattered eastward, pushing development into wildland areas; increasing the risk of financial loss[1].

Southern California is prone to power outages[2] particularly during heat waves when the demand for electricity is high. The region has an ageing power infrastructure vulnerable to failure. The power grid was built in the mid-20th century and has not kept up with the region's population growth and increased demand for electricity. The infrastructure itself is susceptible to wildfire damage, evidenced by the 2017 Thomas Fire (Tilley et al., 2018). Between 2000 and 2016, selected areas incurred over $700 million in damages to transmission and distribution systems due to wildfires (California's Fourth Climate Change Assessment, 2018). However, the total economic damages from wildfires were much higher across all sectors.

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[1] the number of housing units in the Wildland urban interface(WUI) in California increased by a million over the past two decades(Mewery and Punchard, 2021)

[2] From 2013 to 2020, PG&E, SDG&E, Southern California Edison, and PacifiCorp collectively carried out 51 PSPS (Public Safety Power Shutoff) events in various locations throughout California, affecting 3.2 million customers.

2.5 Public Safety Power Shut-Off (PSPS)

The California Public Utilities Commission (CPUC) has granted approval for California's investor-owned utilities to establish a planned power shut-off programme known as the Public Safety Power Shut-Off (PSPS). This initiative involves the temporary disconnection of power in specific regions during extreme weather conditions to minimise the likelihood of fires caused by electric infrastructure (CPUC, 2021). California has the highest number of power outages in the US. The state's utilities have reported a disconnection of power to more than three million customers, with the average duration of PSPSs being "41 hours between 2013 to 2020". As of 2019, over 2000 PSPS events impacted more than two million customers, as outlined in Table 1 (CPUC, 2021; EIA, 2023).

Table 1. Power Outages and Customer Impact in California (2017-2021)

Annual incidents and impact on customers in California due to disturbances, unusual events, and PSPS.

(Source: EIA and CPUC)

Major disturbances & unusual occurrences			**PSPS events**	
Years	**Incidents**	**No. of Customers Affected**	**Incidents**	**No. of Customers Affected**
2017	**22**	**1,447,933**	**66**	**20,820**
2018	**14**	**305,680**	**91**	**84,565**
2019	**24**	**2,673,653**	**2289**	**2,230,425**
2020	**37**	**2,352,300**	**2362**	**982,057**
2021	**20**	**1,224,510**	**509**	**288,492**

PSPS events can have significant economic costs, particularly for vulnerable populations such as low-income households and those reliant on medical services. Wing et al.(2023) estimate “welfare losses of up to 1% in some counties”, adding that PSPS events can also lead to increased hospitalisations due to heat-related illnesses and reduced air quality, as well as increased emergency response costs. Fisher-Vanden et al., (2023) suggest these preventative outages cost California $322M from the forgone consumption of the residential sector alone. While PSPS events are intended to prevent wildfires, there are concerns that they may actually increase the risk of fires by causing people to use backup generators and other equipment that can spark fires. As per Wheeler's (2020) observations, PSPS events may result in an increased dependence on diesel and gas-powered generators, which can release harmful pollutants into the air, worsening air quality and worsening respiratory illnesses which will ultimately result in incurring costs to the regional government.

2.6 Utilities’ Liabilities in Wildfires

The courts have consistently maintained the imposition of strict liability on electric utility companies and they are greatly susceptible to huge losses and responsible for all expenses associated with the harm to properties, expenses incurred for fire suppression, and other economic and environmental damages that may arise from a wildfire caused by the utility company under the doctrine of inverse Condemnation [3](Thurman 2022). In cases where utility equipment is found to have contributed to a fire, however, and to save them from bankruptcy

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[3] One example sheds a light on the importance of infrastructure improvement, is PG&E’s tower 27/222, whose failure is believed to have sparked the CampFire, which was constructed in 1921; the state’s largest utility’s transmission system remains incredibly old to this date. In 2018, in the aftermath of the CampFire, PG&E’s spending on infrastructure improvement was set at around 2 billion USD, however, this spending has been criticised because of a lack of records and data, prioritisation and transparency(Pawar,2021).

they may receive help for wildfire damages that exceed $1 billion(AB 1054). The bill establishes a Wildfire Fund worth $21 billion, in order to facilitate prompt compensation for future catastrophic wildfire victims by assisting utilities in meeting their financial obligations. Utilities need to be qualified in order to participate in the fund; subject to allocating a total of $5 billion over a three-year period towards mitigating wildfire risks(Dellinger, 2019).

Thurman(2022) argues that more should be required from utilities and they should be urged to participate in residential wildfire mitigation efforts in the homes of their lowest-income ratepayers as a prerequisite for accessing wildfire relief funds.

Traditionally, electric utilities have covered the costs of third-party liability, fire suppression, and other associated economic and environmental damages resulting from utility-caused wildfires through customer rates and liability insurance. Although recovery from electricity rates is not guaranteed, as demonstrated by the example of SDG&E's unsuccessful attempt to recover $379 million in Wildfire Expense Memorandum Account (WEMA) costs from 2007 wildfires (Kousky, et al., 2019). Nevertheless, with the rising incidence of wildfires and the continued application of the strict liability regime under inverse condemnation by the California Courts, utilities face enormous financial burdens due to the increasingly limited availability of insurance coverage or higher rates[4], which they must recover through customer rates or shareholder profits(CPUC, 2023). Scholars like Dellinger and Thurmans emphasise the essentiality of reevaluating the approach of uniformly imposing costs on all end-consumers through a flat fee and exploring alternative methods of addressing the cost-sharing burden.

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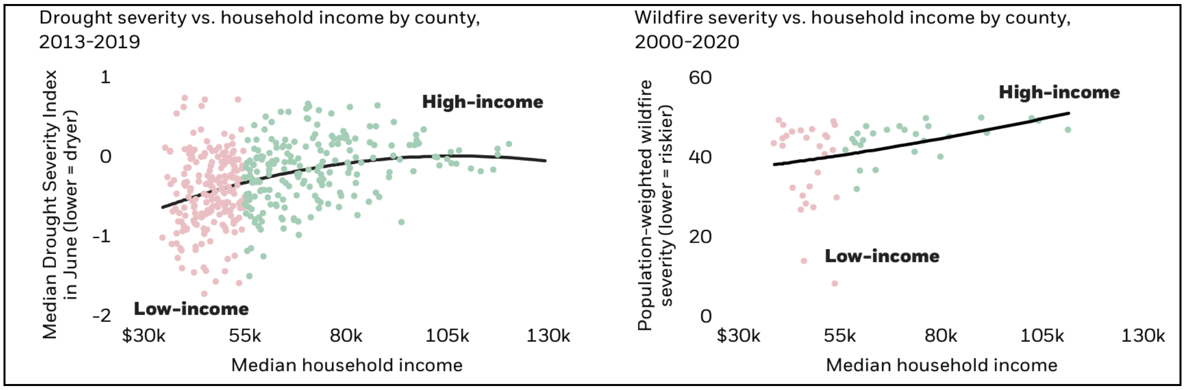
[4] PG&E and SCE have reported substantial insurance rate hikes, reaching approximately 25% and 24% respectively for the 2018/2019 period, with SCE also purchasing wildfire-specific insurance of around $1 billion (Kousky, et al., 2019).

2.7 Economic Growth in Areas Impacted by Wildfires

The most impacted counties by wildfires tend to have below median income, while they are also at higher risk for other types of natural disasters(Becker et al.(2022). These counties, including San Bernardino, have been disproportionately burdened by higher risks of heat and wildfire. The correlation between drought and wildfire severity, as well as the impact of county-level income, is visualised in Figure 3. Becker, et al.(2019) finds that drought severity is not substantially correlated with income in affluent counties, but it is in low-income counties. In addition, wildfire risk is generally higher in low-income counties, but most severe in a group of middle-income counties around the median cutoff.

Figure (3): The Relationship between Drought Severity and Household Income by County from 2013-2019



Source: Source: Becker et, al(2022)– Data from NASA, October 2021.

These fire-prone regions face long-term economic risks, such as a decrease in the availability of insurance and an increase in its cost. As a result, assets are at risk of becoming stranded, as sellers cannot find buyers who can insure their assets against the risk of wildfire. Other long-term damages include economic costs of health issues, lower educational achievement, and reduced lifetime income and wealth accumulation(Becker et al, 2022). While it is witnessed that federal relief funding typically helps the local economy in the aftermath of wildfires to rebound as Walls and Wibbenmeye(2023) posit, their findings also show that wildfires have a heavy localised effect on the unemployment(1.3% decrease in employment rate) and other economic indicators in the regions closest to the fire.

2.8 Emission Costs of Using Backup Generators Fire-Prone Areas

The growing concerns surrounding grid reliability due to frequent power outages have led to a rise in demand for alternative energy resources, particularly propane and diesel generators. Generac, which holds approximately 75% of the U.S. backup generators(BG) market, has witnessed a stock price increase of almost 800 per cent since the end of 2018, the New York Times revealed in a 2021 article: "Climate Change Calls for Backup Power, and One Company Cashes In". The law also works to Generac's advantage as the United States mandates emergency and standby power systems through legal requirements. NFPA 70: National Electric Code (NEC) outlines emergency power, legally required standby power, and optional standby power (NFPA, 2022a). The increase in the use of propane and diesel generators is not limited to households and small businesses: as of January 2023, there were 11,208 diesel BG installed in public buildings and critical facilities across the 22 air districts in California, with a cumulative capacity of about 4 GW(Wing et al., 2023). According to a study by Hwang, Tongsopit, & Kittner(2023), the replacement of diesel backup generators in one building with a DER storage, has the potential to reduce over "10,000 tons of CO2 emissions over a 20-year period" and save society almost "$3 million".[5]

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[5] It is essential to keep in mind that the negative effects of diesel generators may escalate even more with updated assessments of the social cost of CO2. For instance, the United States Environmental Protection Agency (EPA) released a preliminary external review in November 2022, which proposed a fresh methodology for approximating the social cost of carbon. They projected that by 2030, the cost could vary from $140 to $380 per metric ton of CO2, based on distinct discount rates (U.S. EPA, 2022).

The use of fossil fuel BG can pose health issues that form a climate-change-induced negative feedback loop. These generators have high life-cycle environmental costs, emitting GHGs and air pollutants like nitrogen oxides (NOx), sulphur dioxide (SO2), and particulate matter (PM2.5) and many studies have found that these pollutants have adverse effects on human health (Jakhrani et al., 2012; Yilmaz and Dincer, 2017; Tong and Zhang, 2015; Sothea and Oanh, 2019). Propane[6] generators are labelled as a cleaner alternative to diesel generators by several measures, but can still produce a large amount of carbon monoxide (US Consumer Product Safety Commission, 2023). Hence, moving away from the fuel-intensive BG would not only help California with its net-zero goals, save costs and benefit the state's economy but also create substantial health benefits.

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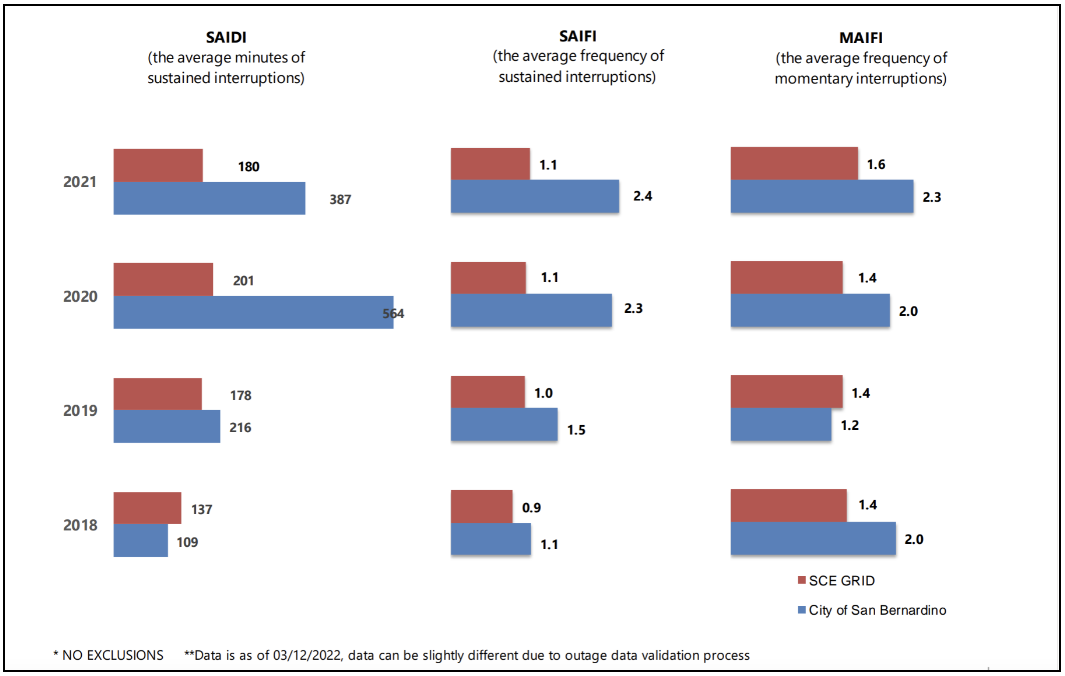
[6] Propane, also known as Liquefied Petroleum Gas (LPG), is produced as a by-product of processing natural gas and refining crude oil.

2.9 Reliability of the Grid in San Bernardino and Redlands

Based on the reliability report published by SCE Edison, the city of San Bernardino has experienced above-average power disruption across multiple measures of defining power interruptions. In Figure 4, the average minutes of sustained interruption(SAIDI), the average frequency of sustained interruption(SAIFI) and the average frequency of momentary interruption(MAIFI) of electricity distribution in the city of San Bernardino have all exceeded the average rate of Southern California Edison grid interruptions at least from 2020 onwards.

Figure 4: Circuit Reliability - City of San Bernardino (2018-2021)

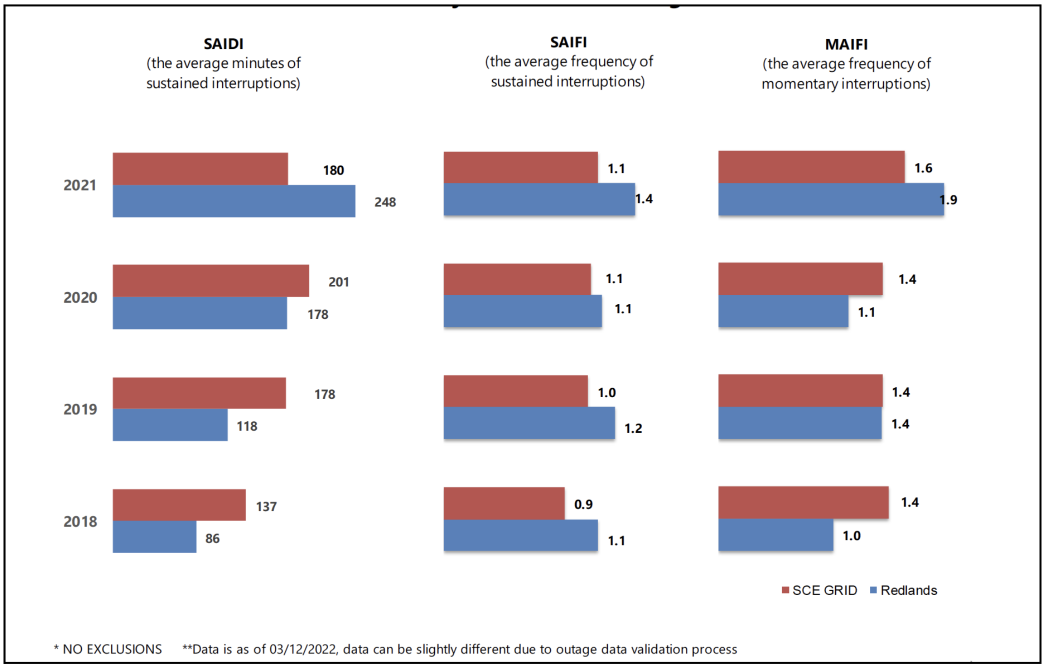


* NO EXCLUSIONS **Data is as of 03/12/2022, data can be slightly different due to outage data validation process

Source: Southern California Edison

Equipment-related outages, PSPS and operational issues are the main causes of such interruptions in the city of San Bernardino. The city of Redlands also experienced above-average interruption, in terms of frequency, and duration as seen in Figure 5. Equipment failure, and weather-related events like fire and PSPS are reported as the main causes of interruption.

Figure 5: Circuit Reliability - City of Redlands (2018-2021)



* NO EXCLUSIONS **Data is as of 03/12/2022, data can be slightly different due to outage data validation process

Source: Southern California Edison

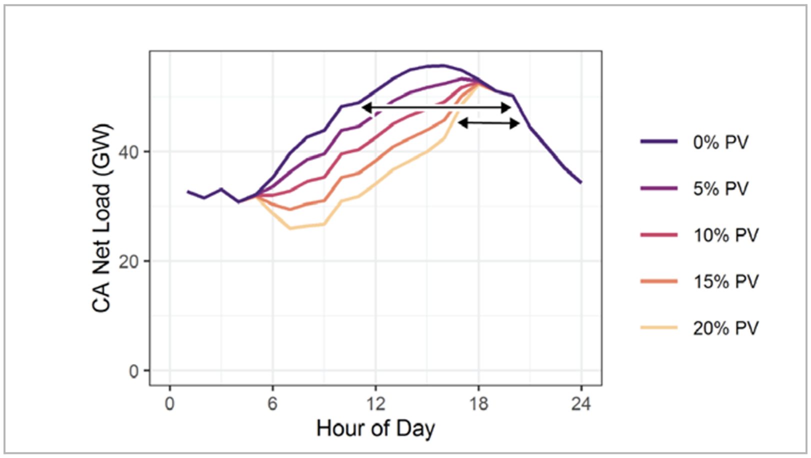
2.10 Promoting Renewable Energy through Grid Resilience

Promoting renewable energy technologies such as solar PV plus has been suggested as a viable solution to improve grid resiliency and reduce the risk of outages. However, the extent of these benefits depends on the size of the PV array, the amount of demand, and electricity rates (Bertsch et al., 2017; Quoilin et al., 2016). The average PV array size in solar plus(8 kW- residential) is larger than in a PV-only configuration (4 kW). Battery storage increases both capacity and the economic value of solar PV(Prasanna et al., 2021).

The market of storage systems is expected to expand exponentially due to the growing demand, as solar PVs reach a record low levelized cost of energy storage. Promoting battery storage systems is also backed by recent legislative steps, such as Order 2222 (FERC 2020), allowing

DERs to take part in regional wholesale capacity, energy, and ancillary service markets as well as conventional utility-scale generation(Prasanna et al., 2021). Resiliency is not the only benefit, solar plus systems change the shape of the net load and therefore help with reliability and demand management. As seen in Figure 6, the net load varies during a peak day in California, where the contribution of solar PV alone increases from 0% to 20% of the annual load. In regions that experience a peak demand period (typically from midday to evening), a notable outcome of increased deployment of solar PV is a decrease in the duration of the peak net load period. Consequently, this contributes to a shorter storage duration (and hence lower costs) required to ensure firm capacity[7].

Figure 6: Increased Deployment of PV and Reduced Duration of Peak Net Load Period



Source: Blair, Nate, Chad Augustine, Wesley Cole, et al. 2022

2.11. Emissions reduction

Solar plus technologies have been recognized as effective solutions to reduce GHG emissions in Southern California. As of January 2023, California possessed over 17,500 megawatts of utility-scale solar power capacity, the highest amount among all states. If we add the small-scale facilities, the total solar capacity in California was almost 32,000 megawatts(EIA, 2023). When

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[7] According to the EIA definition, firm capacity or firm power refers to the amount of power that is supposed to be accessible at all time during the guaranteed or agreed commitment period, even in undesirable conditions.

combined with energy storage systems, PV systems can significantly reduce emissions during peak hours when electricity demand is high. Results from the study conducted by Raugei, et al,.(2020) show that transferring a *quarter* of renewable electricity generation into storage would be effective at reducing California's grid GHG emissions by "*half*" and "reducing demand for non-renewable electricity by 66%", while also resulting in a "10% increase in the overall EROI" (electricity output per unit of investment).

2.12 Electricity Microgrids and Distributed Energy Sources

A. Smart Microgrids

The CPUC has established a plan and a comprehensive goal for a Smart Grid in California, which mandates the state's investor-owned utilities to initiate grid modernisation for obtaining a smart grid. The Smart Grid is an automated and widely distributed energy delivery network that facilitates the two-way flow of electricity and information. It has the ability to monitor power plants, customer preferences, and even individual appliances. The grid incorporates the advantages of distributed computing and communication to provide real-time information, enabling the near-instantaneous balance of supply and demand at the device level (DOE, nd)

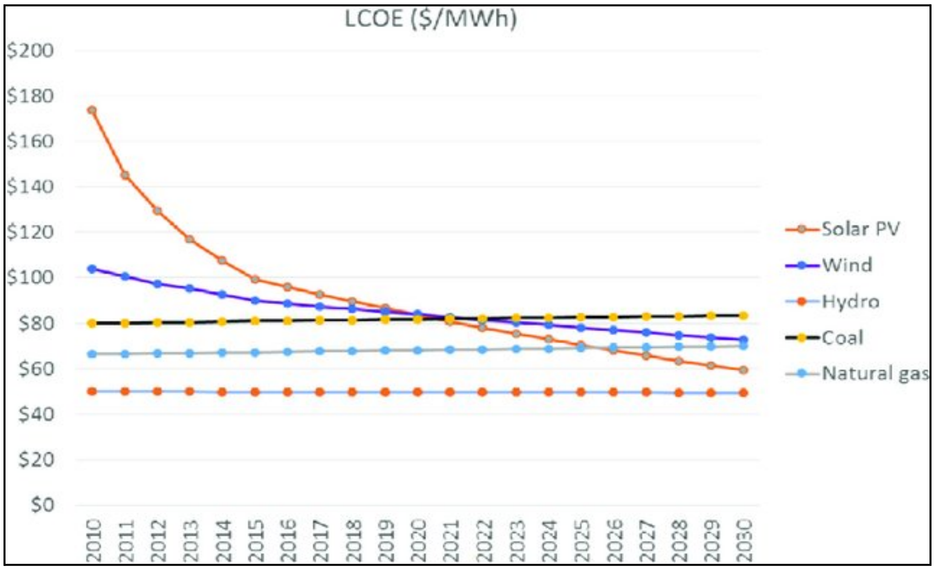
In November 2021, the US President signed a bipartisan infrastructure law that included $65 billion for modernising the grid. This funding supports the development of new transmission lines, smart grid technologies, clean energy solutions, and cybersecurity measures. In addition, Southern California Edison(SCE), the main utility company in the region, will invest $75B in grid modernisation in 2030-2045, integrating renewables and storage as well as serving the load growth as the electrification increases (SEC, 2019)

B. Non-conventional Sources

1. Solar PV:

California's sunny weather conditions make it a favourable location for solar energy projects, with the state emerging as a leader in the deployment of large-scale solar power plants and being home to over 1 million solar roofs in both residential and commercial settings (California Energy Commission, 2021). California Solar Initiative Programme(CSI) and net metering policies that allow solar panel owners to sell any excess generation back to the grid have helped with advancing the wider adoption of solar technology in the state. The capital cost reductions in the solar industry have also played a major role. The global weighted average levelized cost of electricity (LCOE) of utility-scale PV plants decreased by 88% from 2010 to 2021, with the cost per kilowatt hour (kWh) dropping from USD 0.417 to USD 0.048. In 2021, there was a year-on-year reduction of 13% and this trend is expected to continue through 2030 as depicted in Figure 7 (IRENA, 2022)

Figure 7: Levelized Cost of Energy: Solar PVs



Source: NREL(n.d)

2. Battery storage:

California is currently adding battery storage at a faster rate than any other grid in the country. Batteries are typically charged when electricity prices are low and store energy for users to use when electricity prices are high so that users will save money through lower electricity bills(California ISO, 2021). Battery storage also serves as a means of capturing overflow electricity generated from the solar panels, and can also be used to store excess energy for “rainy day” scenarios such as power outages.

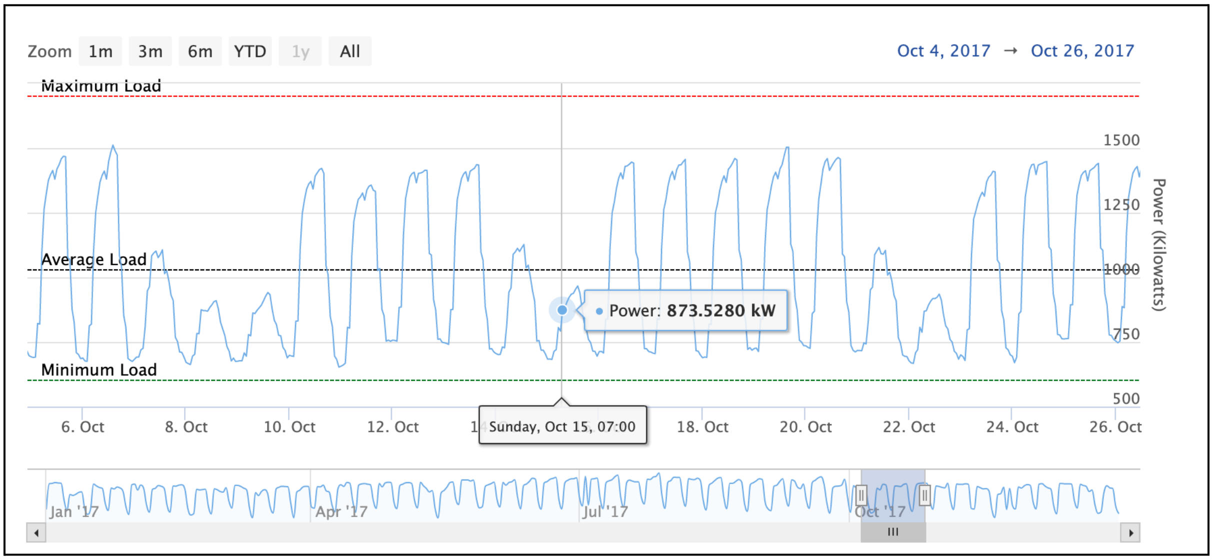
During California's heatwave in September 2022, the addition of new battery energy storage (BES) units played a critical role in preventing blackouts. This was a completely different scenario from the heatwave in August 2020, when a peak demand (46.8 GW) caused blackouts. By contrast, there were no blackouts during the September 2022 heatwave, despite a higher demand of 51.4 GW, due to the added 3.4 GW BES capacity(ICF, 2023).

Chapter 3: Quantitative Model and Methodology

3.1 Timing

This study imposes a resiliency constraint for the NREL ReOpt optimisation model based on the high likelihood of PSPS events in Southern California in mid-October at the intersection of the onset of Santa Ana winds and the tail-end of the summer wildfire season. Within this time frame, a 12-hour outage period on October 15 –beginning at 7 AM– is identified as a critical time window for modelling expected outages at the locations under study.

Figure 8: Critical load profile in the selected time frame (Source: NREL Reopt)



3.2 Location

San Bernardino County experiences one of the highest solar irradiances in the whole United States. The county government has over 15% of land rights, not including public land controlled by state or federal agencies or incorporated cities(San Bernardino County, nd). This study focuses on two communities located within close proximity to one another in San Bernardino County, with distinct demographic differences. San Bernardino Downtown has a higher concentrated population density and is land constrained. In contrast, the city of Redlands has acres of undeveloped land on the margins of a university campus land that could be used for solar and storage projects. Assessing both of these locations would provide a holistic view of the challenges of developing renewable projects in different settings and the relevant enabling policies.

3.3 Demographics and Income

The choice of San Bernardino and Redlands presents an opportunity to test case studies with different population densities. Redlands primarily comprises single-family homes and residence halls, and apartments close to the university campus, while San Bernardino Downtown has a mix of single-family homes and low-rise apartments.

San Bernardino is a less affluent community where private residences may have limited financial resources to cover the upfront capital costs of rooftop solar or a microgrid. In this city, microgrids may be perceived as more of a public good that relies on public investment for financial viability. The community's demographics highlight the importance of considering the potential inequities and disparities in access to microgrid technology, which could widen existing socio-economic divides. Redlands is a more affluent community where private residents have greater financial means to make private investments in microgrid projects. Redlands is also the home of a private university with a rotating student population but owns residential dorms and undeveloped land that would make the long-term finances of microgrid development appealing. In the long run, the availability of private financing or using a portion of the university endowment to yield lifecycle benefits would increase the likelihood of implementing microgrids in this community. It also allows for deploying more advanced and customised microgrid technologies.

3.2 Resilience

In this paper, NREL(2019)'s definition of grid resilience is used, which emphasises "the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions through adaptable and holistic planning and technical solutions." In this study, a system which provides a temporary energy source for short-duration power outages to get residents and institutions through a short blackout or brownout period is simulated to have a short-term solution to supply a certain threshold of electricity supply. When there is no emergency, the microgrid actively supplies electricity locally and participates in electricity arbitrage with the broader electricity grid.

Supplying power for a few extra hours using backup battery storage gives residents enough time to pack and charge up electronic devices at night in case an approaching wildfire is imminent, and residents ultimately need to evacuate for safety. This becomes rather challenging when hospitals need to vacate their premises. As aforementioned, hospitals across many California counties lie near wildfire-risk zones(Bedi et al., 2023), and microgrids may become more necessary to give health systems the critical time to relocate patients to safety.

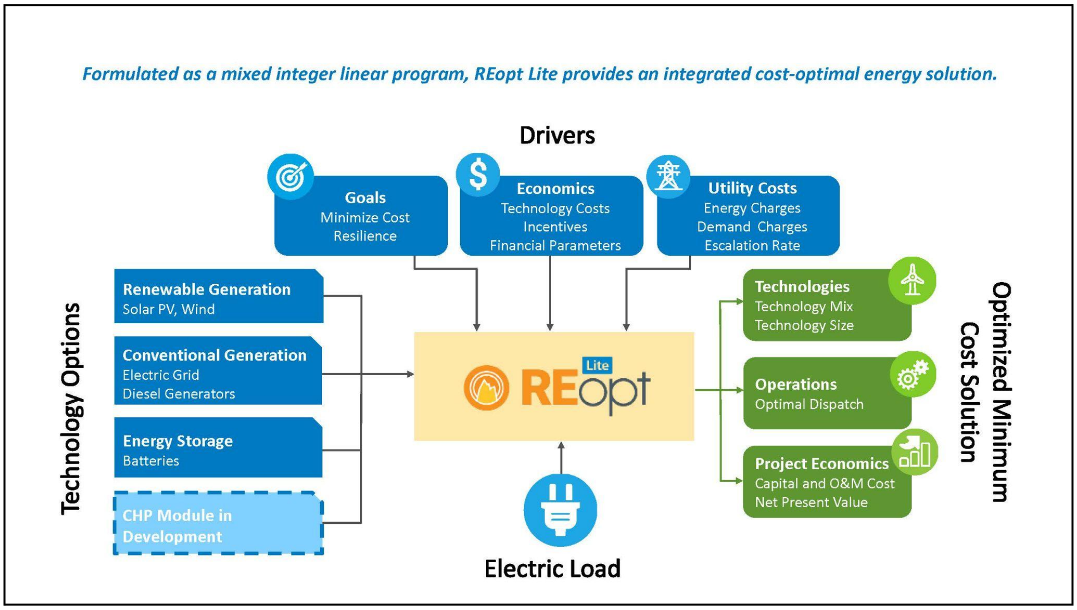
3.3 Methodology for System Modelling: A Comprehensive Overview

i NREL ReOPT Model

The REopt model developed by NREL is a techno-economic policymaking support model that recommends an optimally sized mix of renewable and distributed energy, conventional generation, and energy storage technologies; provides a dispatch strategy for operating the technology mix at maximum economic efficiency; and estimates the net present value of implementing those technologies. When resiliency is selected by the user, ReOpt imposes a constraint that the battery size output of the model must be adequate to satisfy the critical load requirements on a specified date for a power outage of a specified duration. Since battery technology is still relatively expensive, the NPV life-cycle cost can quickly become negative if: 1) the battery size must be large to store electricity for a power outage of long duration and high critical load factor: or 2) land constraints limit the size of PV arrays so that the savings from avoided electricity bill costs over the return period do not exceed the upfront capital costs of supplying the battery technology, and costs of the PV.

As seen in Figure 9, the REopt model evaluates the trade-off between the upfront cost of a DER adoption and the savings made across multiple fields while also recommending an optimal size and dispatch. In addition to its financial feasibility assessment, REopt simulates thousands of outage scenarios to determine if the regular day-to-day operation of the microgrid is adequate to survive an unannounced power outage of a given duration at a randomly selected time. We use the ReOpt model to compare the probabilities of power outage survival under different combinations of optimal solar PV array size and battery capacity (NREL, n.d)

Figure 9: Re-Opt Inputs and Outputs



Source: NREL(n.d.)

The NREL RE-Opt model optimises the amount of PV and battery storage necessary to satisfy a resiliency constraint of supplying a certain fraction of electrical load at a given time for a given duration on a certain date. The model relies on a series of utility rates and load cases for different types of buildings: the ReOpt model refers to pre-set load profiles, identified by building type if the user does not input one. The model optimises lifecycle NPV as the objective function, taking into consideration the capital and operating costs of technology and money saved from the local generation of electricity instead of paying for electricity from the utility electric grid. Another constraint that ReOPT works with is the maximum PV array size. This is an input for the model in this research study that was calculated from NREL's PVWatts tool calculator.

ii. NREL PVWatts: Mapping Tool for Solar Energy Assessment

In this study, a second NREL development tool named PV Watts tool is used to outline usable parking lots and rooftop space in the communities of interest to size potential PV array projects.

The user sketches a polygon outlining the boundaries of a potential PV array at the project location. The tool is designed to estimate the energy output and value of solar energy systems and presents its findings in both monthly and daily summaries, utilising historical weather data and the latitude and longitude of the map location.

The PVWatts tool allows users to input the usable fraction of surface space (=0.5 by default: PVWatts site, in the model), and the surface of the PV array comes out to be about half of the surface area of a location site. For the purpose of this study, a potential spot where PV arrays could be installed is mapped out on the PVWatt calculator, and the output is an estimate of the size of the PV array based on the map site, which is then used as the maximum PV size parameter input in the NREL ReOpt model.

Figures 10 and 11 show the mapping of the PV array for both San Bernardino Hospital and Redlands University.

Figure 10: PV Installation Map at the Community Hospital of San Bernardino Parking Lot

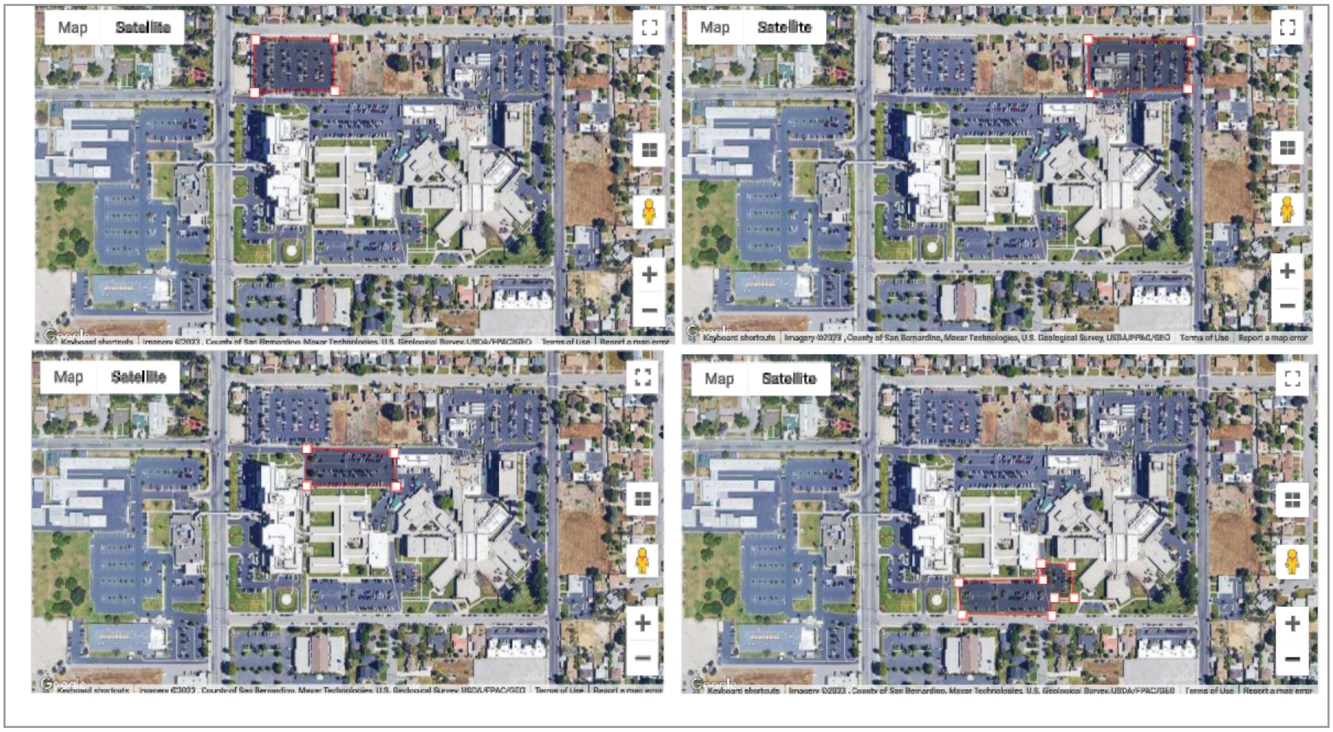
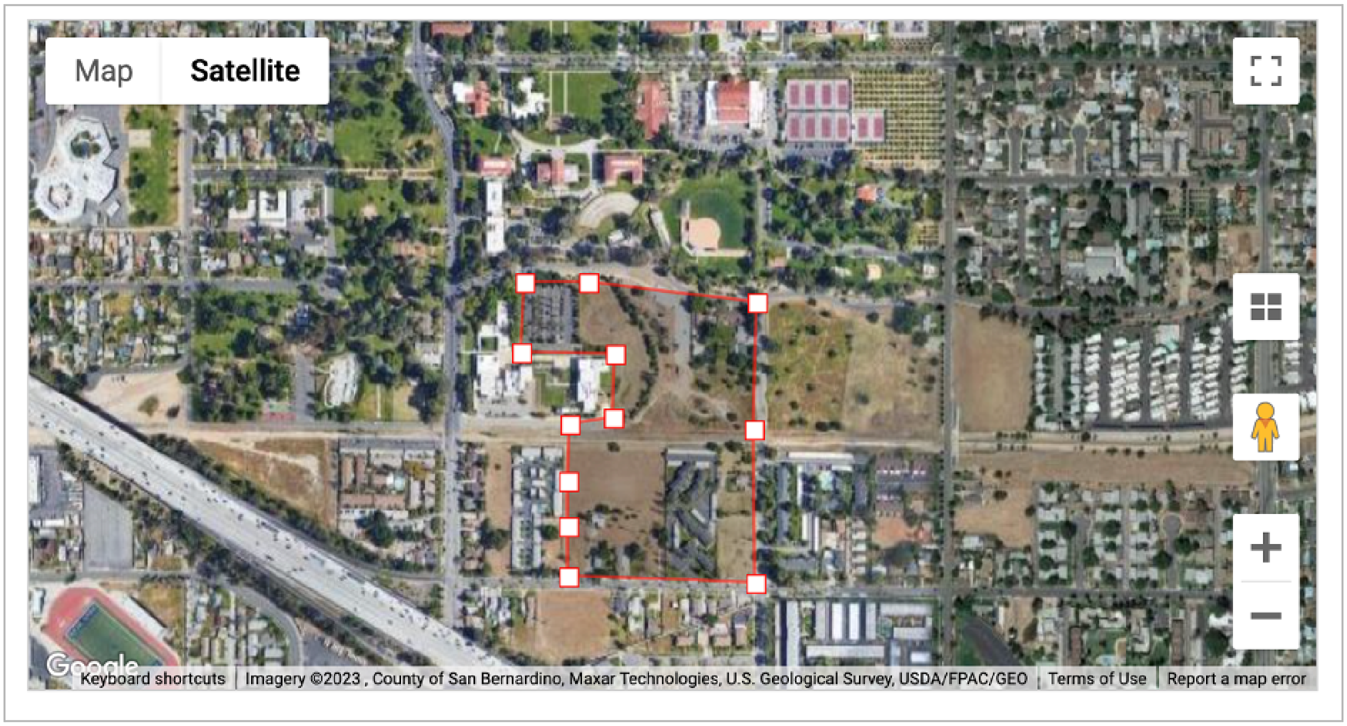


Figure 11: PV Installation Map at the Redland University's Main Campus



Chapter 4: Case Studies and Results

All scenarios are modelled in the county of San Bernardino in Southern California. The choice of San Bernardino as the site location is mainly due to the fact that forests surround this county and it is on the passage of Santa Ana winds, particularly near Cajon Pass. The national forest in San Bernardino is historically one of the most wildfire-prone forests in the whole United States. In addition, the increased air pollutants in the past decades have increased susceptibility to wildfires (Grulke et al., 2008). Temperatures in the region can soar to over 100 degrees Fahrenheit during summer, causing vegetation to dry and become highly flammable. San Bernardino regularly experiences Santa Ana winds at speeds up to 70 miles per hour. Regarding socioeconomic specifications, the family poverty rate in San Bernardino County is higher than the average in California and nationwide. Hence, San Bernardino serves as a representative case for conducting a qualitative analysis of a population with socioeconomic limitations.

For the purpose of this study, two different campuses were designed for Re-Opt simulation. In designing both campuses, critical load percentage input is a crucial consideration. The baseline case study in the Re-Opt model assumes a critical load of 50%, which may not be sufficient for institutions such as hospitals with life-saving or emergency operations. New research published in the American Journal of Public Health finds that 95 per cent of California's in-patient capacity[8] is "within 3.7 miles of a high fire threat zone of the wildfires"(Bedi et al., 2023). The critical load input can also be considered as a measure of the level of willingness amongst residents to reduce their electricity consumption during power outages. The critical load factor is

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[8] In–Patient capacity refers to the maximum amount of beds available for patients staying overnight. This capacity also takes into account the number of staff available, resources and medical equipment and supplies available(Valdmanis, Bernet, & Moises, 2010).

considered as one of the independent variables in different variable scenarios, in addition to the number of participants or inhabitants pooled into the microgrid and the PV array size.

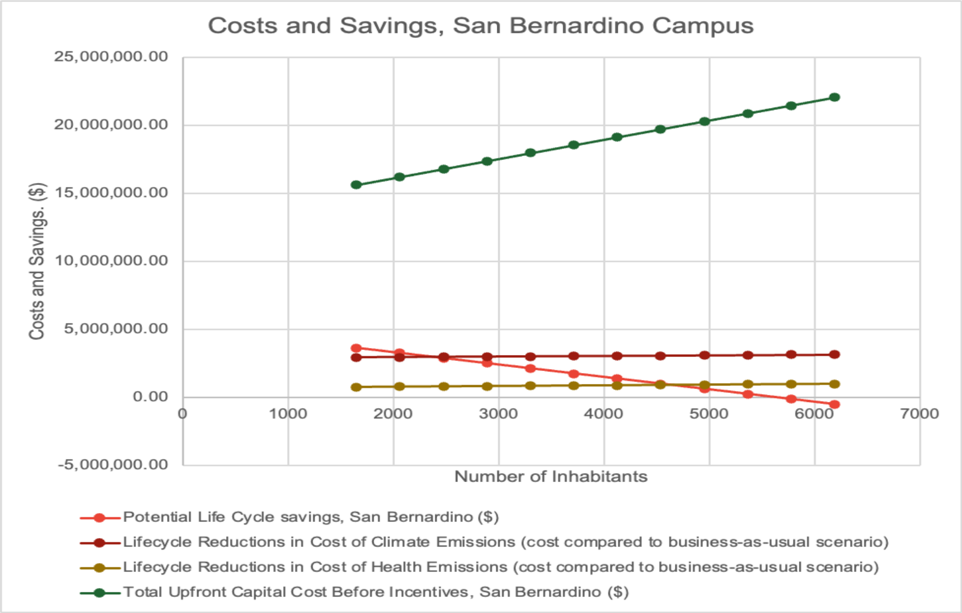
In terms of design philosophy, two campuses, in San Bernardino downtown and Redlands, offer two scenarios when it comes to resilience and financial assessment: 1) pairing residences with hospitals, with considerations for a high critical load ratio, and 2) pairing residences with universities, which offer more land resources for potential construction of Solar+ projects. Using data on electrical usage in California, REopt creates an hourly load curve estimate for the year based on the annual electrical consumption and building type of a particular segment. These load curves are combined to create a custom load curve for the modelled campuses. With this load curve and the aggregated data from parameter inputs, the entire community systems are modelled for each scenario, which includes combining residences (represented as mid-rise apartments) with either the hospital or the university buildings (represented as secondary schools). ReOpt calculates financial metric outputs for each scenario, including the life-cycle net present value and upfront capital cost for each simulated campus. The inputs and assumptions for each scenario can be found in Appendix C and D, and the outputs from the assessment of each scenario can be found in Appendixes K-P.

4.1 San Bernardino Downtown Case Study

Scenario 1: Increased Number of Residents

In this scenario, the primary focus is on the pairing of a hospital campus (consisting of 6 hospital buildings with ReOpt's default electricity load profiles) with a varying number of mid-size apartment buildings ranging from 10-75. The aim was to examine how increasing the number of residents pooled into the microgrid would affect optimal battery size, the probability of surviving power outages, and the cost outputs. Figure 12 shows a decreasing trend in potential life savings NPV as the number of residents participating in the microgrid increased. In contrast, the upfront capital cost increases with the number of residents, as resiliency requirements push the amount of battery capacity higher. The cost savings from health benefits and emissions reduction still have a positive relationship with the number of residents but with a subtle increase. It is important to note that by designing a campus to accommodate the six hospital buildings, medical services predominate energy consumption, and residential usage contributes a minority of it.

Figure 12: Potential Life Cycle Savings Trend with Increasing Number of Residents



Source: Author(2023)

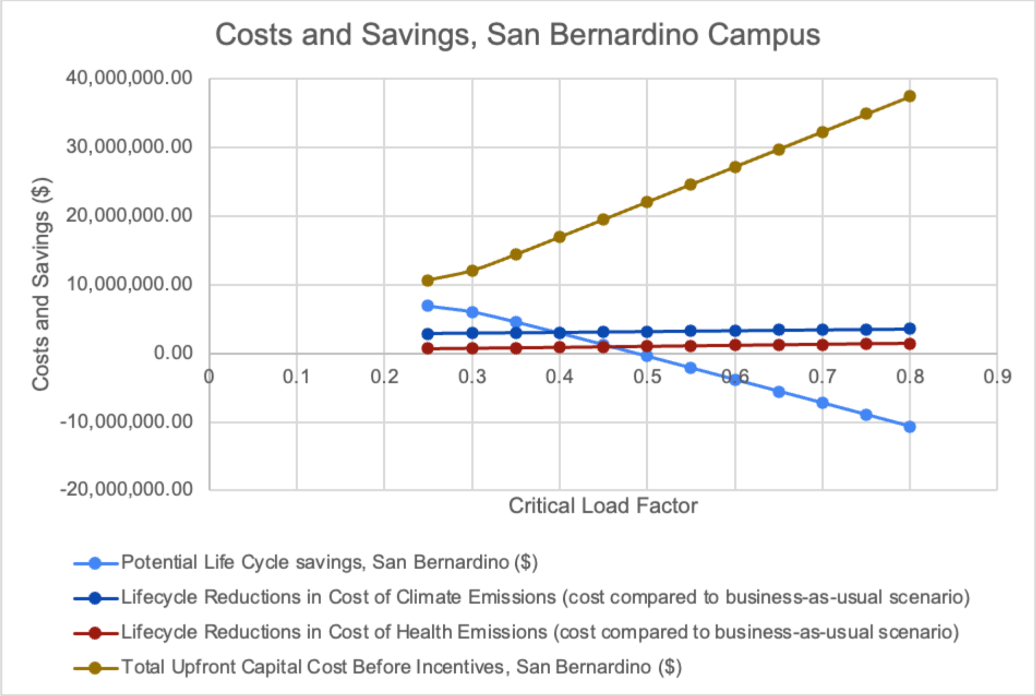
As seen in Appendix F, as the number of residents increases, the required battery capacity increases to satisfy the resiliency constraint. The graph featured in Appendix G indicates the probability of surviving an outage to be only slightly correlated with the number of residents, and the 6h probability of survival is between 20-35%; while longer period survival rates are negligible. These results mean that while the combination of PV and battery storage capacity are capable of surviving a pre-planned 12h power outage on a pre-selected date, the battery capacity is usually not fully charged under normal day-to-day operations, and the probability of surviving a long duration power outage is low.

In conclusion, the size of the PV and battery configuration designated is probably too small to accommodate a large number of residents, so in order to survive a power outage we would need to increase the amount of battery storage. However, increasing the size of the battery is going to be costly and would leave us with a negative NPV for the project.

Scenario 2: Increased Critical Load Factor

In this scenario, the aim is to evaluate how changes in critical load ratio can impact the size of the battery storage system necessary to satisfy the resiliency constraint and the project's financial viability, or in other words life-cycle NPV. Based on Figure 13, increasing the critical load factor reduces the life-cycle savings and any critical load beyond 50% will result in negative NPV. This implies that primarily the hospital would need to forgo a lot of electricity usage in order to profit or break even in terms of costs.

Figure 13: Potential Life Cycle Savings Trend with Increasing Critical Load



Source: Author(2023)

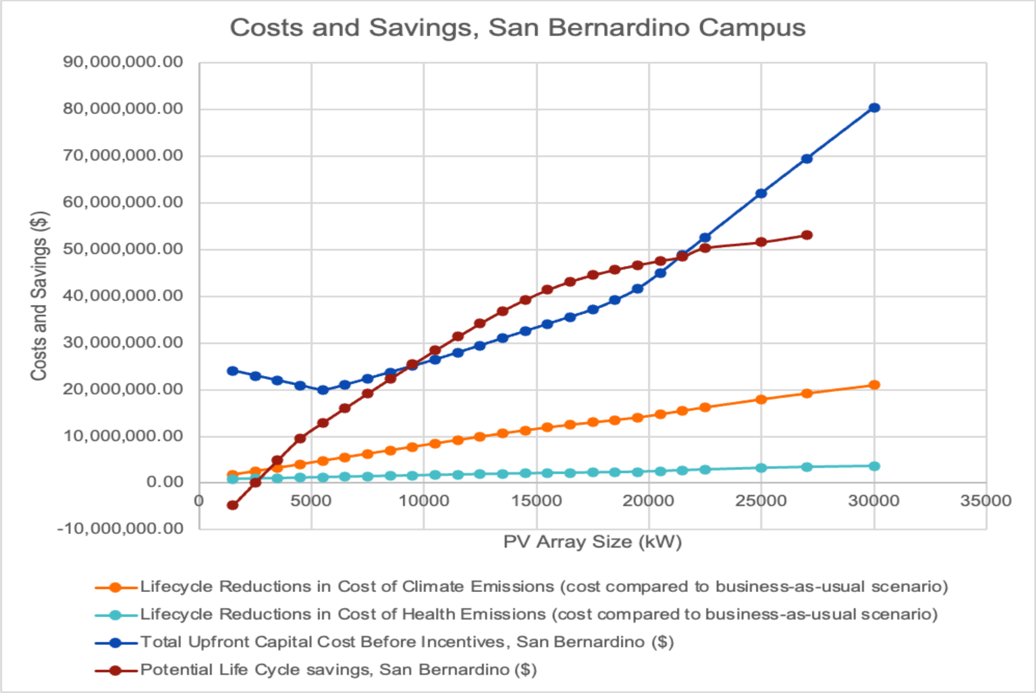
In the second part of scenario 2, the critical load factor is the independent variable and its impacts on the probability of surviving the outage and the optimal battery size are assessed. The figure displayed in Appendix H shows that as the critical load factor increases, the battery size also increases but the probability of surviving the outage remains roughly constant (see Appendix I). This can be justified by the fact that the optimal battery size increases just enough to meet the critical load ratio of electricity to maintain the same probability of surviving the outages of a given duration.

In conclusion, we would need to reduce the critical load factor in order to break even in terms of life-cycle NPV. Alternatively, we could make more land available for PV and storage configuration so that we can scale up the electricity derived from PV.

Scenario 3: Increase Solar PV Array Size

In scenario 3, this simulation looks into how an optimal solar PV array size can impact the outputs and cost savings. The optimal amount of PV is the maximum upper limit that is calculated based on the PVWatts mapping tool. Running simulations with different values of this variable tests, whether the NPV would increase based on making more land available. A larger PV array size requires more land, which is harder to secure in a community with higher population density, like San Bernardino downtown. The NPV crosses into positive territory when the solar PV array size exceeds 3500 kW(Figure 12). However, this PV array size would potentially require eminent domain or more parking lots and rooftop spaces than what is potentially available in San Bernardino Downtown. From the investment standpoint, any PV array size between 11500-21500 kW would make a more attractive investment, while any point outside this range yields upfront costs which exceed the NPV output.

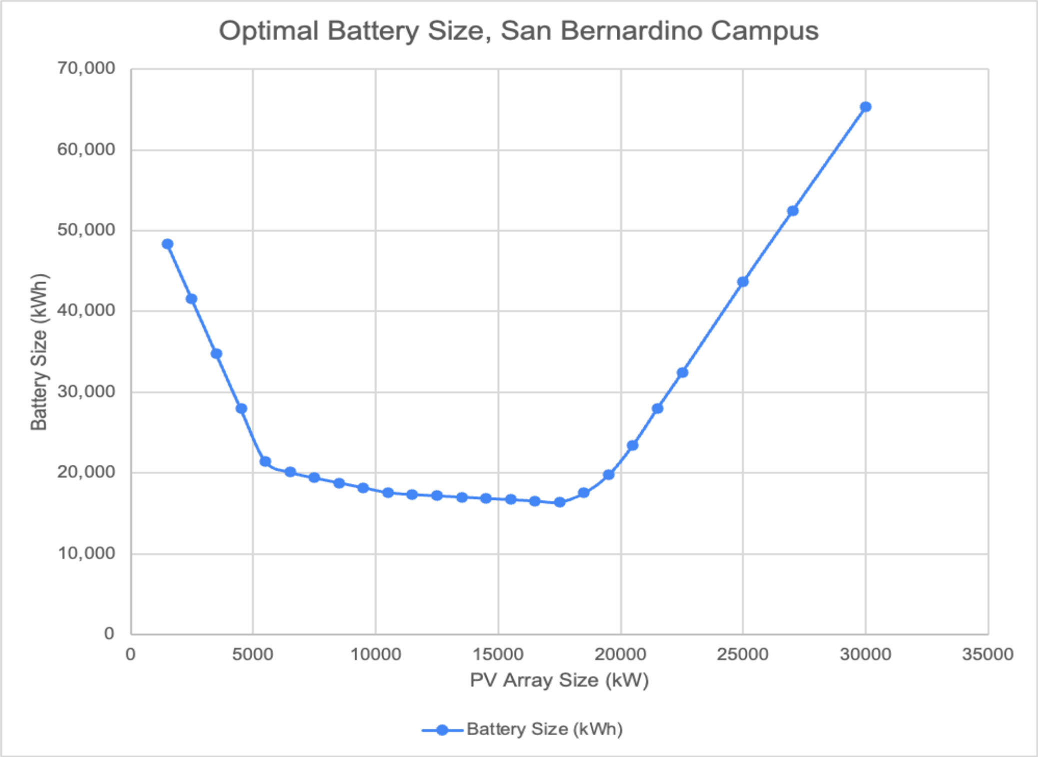
Figure 12: Potential Life Cycle Savings Trend with Increasing PV Array Size



Source: Author(2023)

In calculating the optimal battery size to satisfy the resilience constraint, as the PV array size increases, the required battery capacity decreases, meaning that the PV capacity is sufficient to supply more electricity during an outage and in daylight hours and the required battery capacity is reduced.

Figure 13: Optimal Battery Size with Increasing PV Array Size



Source: Author(2023)

The results from this assessment indicate that increasing the size of PV while decreasing the size of battery storage can maintain a constant probability of outage survival. As the PV size increases, it is able to generate more electricity to meet electricity demand during the day, and the battery storage requirements can be reduced while maintaining a consistent level of the probability of surviving the outage (See Appendix J). Beyond a certain PV array capacity threshold of around 18,000 kW, the electricity that can be derived from PV is significant enough that the optimisation calls for a dramatic increase in battery storage to capture the PV generation(See Figure 13).

Positive NPV is maintained with electricity bill savings but the upfront capital costs also increase significantly, resulting in a second crossover point at 22000 kW, where the upfront capital costs again start to outpace the lifecycle NPV. This indicates that there is a diminishing marginal return to PV capacity beyond a certain threshold while the upfront capital cost dramatically exceeds that of the long-term lifecycle NPV.

4.2 Redlands Case Study

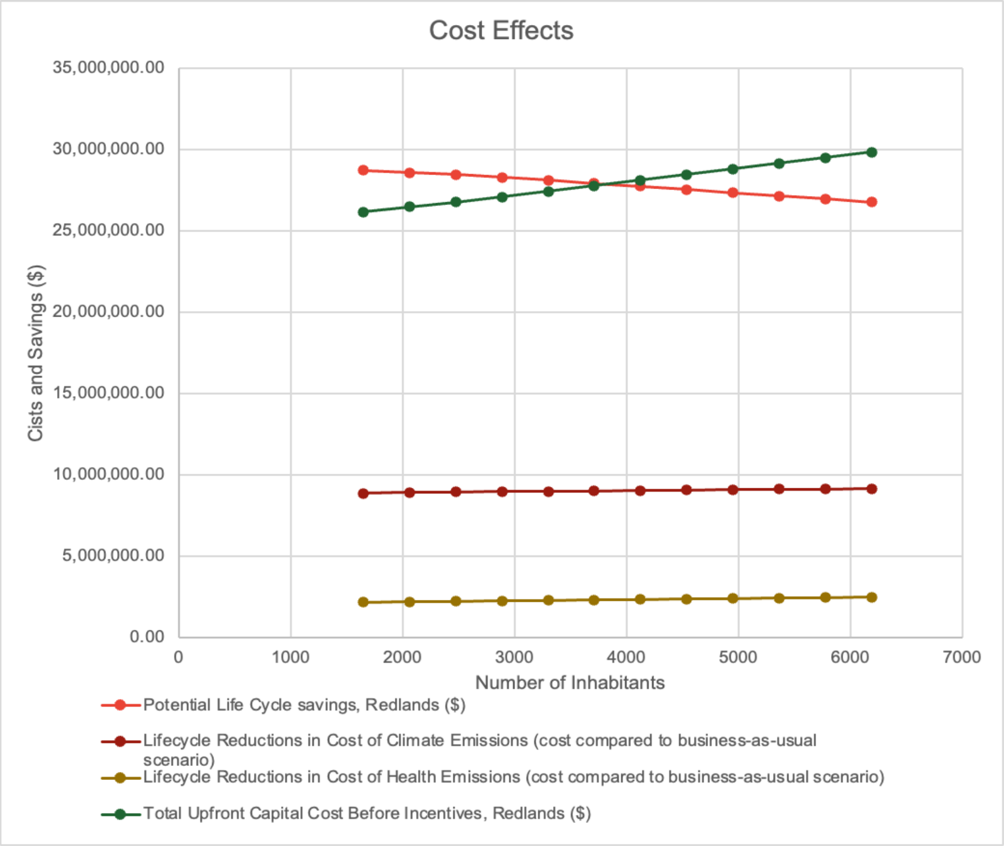
The primary motivation for running Redland community scenarios in the Re-Opt model is to explore a more affluent community with greater land resources and compare the feasibility of DER integration for grid resilience in a different setting to San Bernardino Downtown.

The second set of scenarios is centred around a university campus(represented by 20-40 secondary school buildings in the Re-Opt model) with various residential buildings(ranging from 20 to 75). A university campus provides ample space and land for solar plus configuration, and college endowments could enable higher capital investment in a microgrid as compared with the San Bernardino community hospital and the residential buildings around it. If the NPV over a 25-year period proves to be financially feasible, cost-sharing a microgrid project between a private university and wealthier residents would be considered more of a private good.

Scenario 1: Increased Number of Residents

Increasing the number of residents over a wider campus where houses are on larger lots and more land is available for solar PV development and battery storage installation increases the potential for DER integration. As an educational institution, the University of Redlands would also have lower critical load requirements than a hospital during a power outage. Holding PV capacity and the critical load constant, increasing the number of residents participating in the microgrid within a range of 1500-6000 residents yields a lifecycle NPV that decreases with population because additional battery storage is required to meet the electricity demand. Beyond ~4000 residents in the campus designed, the initial upfront capital necessary to undertake the microgrid exceeds the lifecycle NPV savings, as seen in Figure 14. By comparison, the student population at the University of Redlands consists of ~2700 undergraduates, many of whom would live around the campus. The University of Redlands's investment in a microgrid project to supply electricity to its academic halls and residences would be a practical undertaking.

Figure 14: Potential Life Cycle Savings with Increasing Number of Inhabitants - Redlands



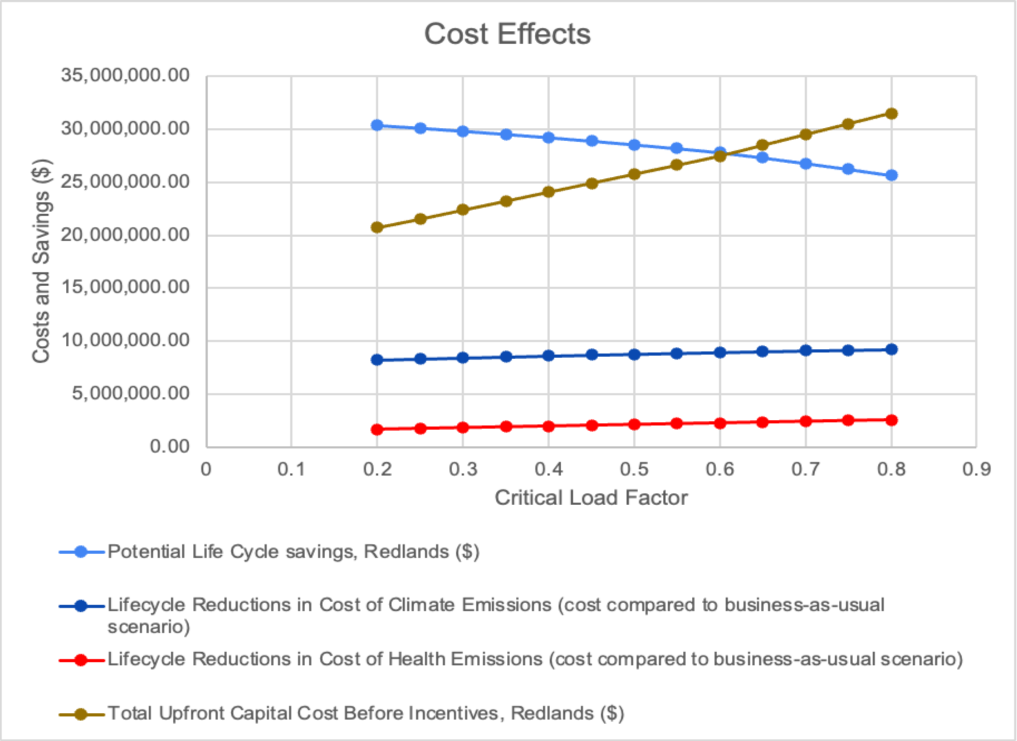
Source: Author(2023)

Scenario 2: Increased Critical Load Factor

The assumption is that the university and the residents in Redlands would have lower critical load factor requirements than the SB downtown residents and the hospital, but in order to study the impact of critical load changes on the cost, variable load factors are run through the Re-Opt model. The results show that increasing the critical load factor again requires more battery storage, and therefore life cycle savings decreases with increasing critical load factor (See Figure

15). Above a critical load factor of ~0.6, the initial sticker shock of initial capital costs exceeds the long-term lifecycle NPV savings of the project, which could make investors wary.

Figure 15: Potential Life Cycle Savings with Increasing Critical Load Factor - Redlands



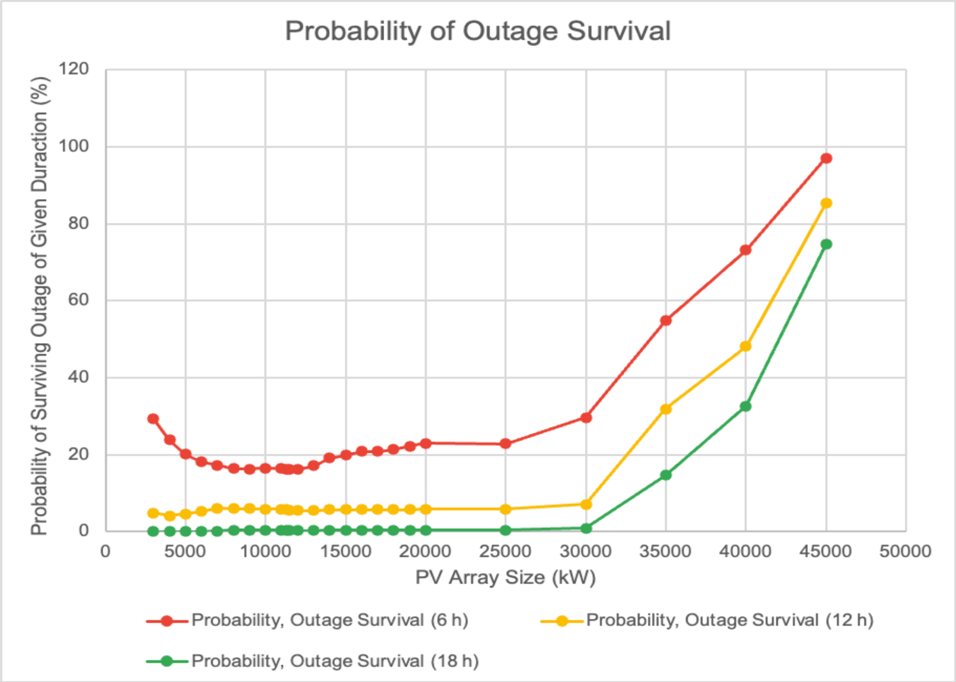
Source: Author(2023)

Scenario 3: Increased Solar PV Array Size

Operating under the expectation that the university campus is less space-constrained than San Bernardino downtown and that land is available for microgrid development as a private good, PV was scaled large enough so that the probability of surviving the outage reached very close to 100%. The potentially best-case scenario is depicted in Figure 16 in which Redlands University would be very generous with their space designation for renewable energy and could more or less guarantee a close-to-100% probability of surviving an outage. Substantial gains in the likelihood of surviving a power outage of 12h or 18h come at the expense of significantly expanding PV capacity and battery capacity. From a resiliency perspective, this might be ideal, but remains in the realm of the hypothetical because the economics of scale required for such a project would rival some of the large utility-scale solar projects proposed today.

Figure 18 identifies a larger tract of undeveloped land on the margins of the campus that could accommodate PV capacity increases under hypothetical scenarios where land is much easier to acquire.

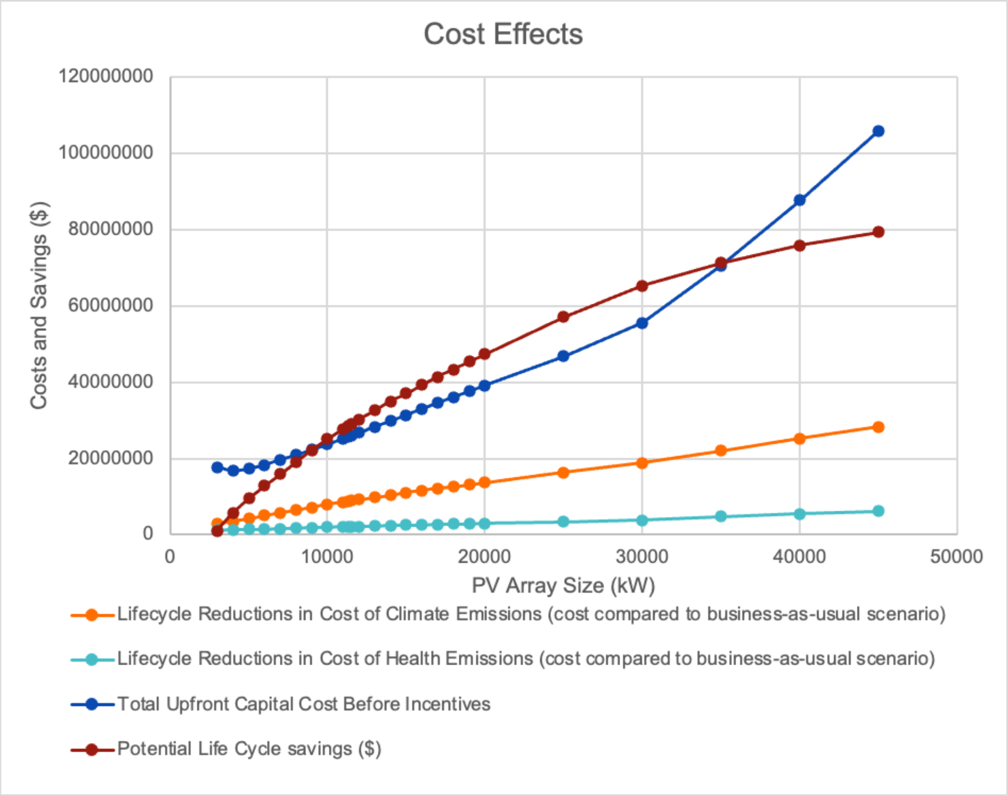
Figure 16: Probability of Outage Survival with Increasing Battery Size - Redlands



Source: Author(2023)

Beyond 35000 kW capacity, the life cycle savings start to plateau while the upfront capital costs start to increase exponentially as displayed in Figure 17. The original 11304 kW solar PV baseline case for the Redlands campus represents a combination of parameters where the lifecycle NPV does exceed the initial upfront capital costs. Moving to higher installed PV capacity in the sample space, while feasible, would draw closure to a utility-scale microgrid project but it is still useful to see the level of investments required to reach the high thresholds of resiliency that residents might consider ideal.

Figure 17: Life Cycle Savings with Increasing PV Array Size



Source: Author(2023)

Figure 18: PV Installation Map at the Redland University

Source: Outcomes of NREL PVWatts Solar Mapping Tool

Chapter 5: Discussion of Results

Positive contributions to a microgrid's NPV stems from the electricity bill reductions when relying on solar PV and battery storage: free sunlight and electricity utility bill savings essentially finance the purchase of battery storage to improve resiliency. The NPV of the microgrids also takes into account climate cost reductions and health cost reductions when comparing the business-as-usual scenario and the battery+PV scenario.

Battery storage is quite expensive, so as critical load factor increases (meaning more electricity demand needs to be met during the power outage), the NPV decreases significantly and initial capital cost increases as more battery power needs to be purchased. Depending on the timing of the power outage, the solar PV array size can supply part of the critical electricity demand during daytime hours.

ReOpt's NPV optimisation assumes that microgrids operate optimally with cost as the primary objective function. This means that the decisions about when to charge or discharge the battery and how much of the electricity generated by PV is directly used or stored for a rainy day are based on inter alia how to best minimise electricity bill costs. The system is not necessarily optimised to provide enough backup electricity at all times in order to protect exclusively against a power outage. Therefore, the probability of survival might seem particularly low, particularly in a 12 hours outage situation. That is, the batteries are rarely kept fully charged to protect against all power outages.

The survival rate refers to the number of power outages lasting 6 hours, 12 hours, or 18 hours the system can withstand within a year. While the ReOpt model performs its optimisation subject to the constraint that it must be capable of surviving a 12h-long outage on October 15 each year, the

Re-Opt model looks into the survival at any given time during the year and at any other date. The optimal battery capacity is sized so that the microgrid (if given advanced warning of an impending PSPS) would be able to store enough electricity to supply the critical load ratio of electricity. However, the optimal performance of the microgrid is not necessarily to keep the batteries charged at all times to protect against any and all power outages. The model looks into the likelihood that the batteries are adequately charged to enable the microgrid users to endure a power outage of a specific duration at the critical load ratio at any randomly simulated time. However, when determining the PV and battery resource outputs to begin with, we know that the resources are sufficient–in the best-case scenario–to survive the 12h power outage on October 15, the resiliency scenario entered. Regardless of the duration of outages, California's Investor-owned Utilities (IOUs) are obliged by CPUC to provide advance notice of at least 48 hours before the PSPS. Therefore, there is enough time for the batteries to be charged up to their maximum capacity using grid-supplied power right before the outage. This would potentially reduce the need for larger PV systems and help smaller systems to have more extended survival periods.

5.1 Discussion of Variables

i. PV Array Size

In the optimal output scenarios, the Re-Opt model maximises the PV array size and does not use any less than the maximum allocation of PV, as the campus is land-constrained. This means that the model determines that the most efficient use of available space was to install the maximum amount of PV panels possible. By doing so, the microgrid can generate as much electricity as possible from the sun's radiation during daylight hours and avoid purchasing electricity from the utility. This results in significant cost savings, reduced operating costs, and increased financial feasibility of the microgrid system.

ii. Number of Inhabitants

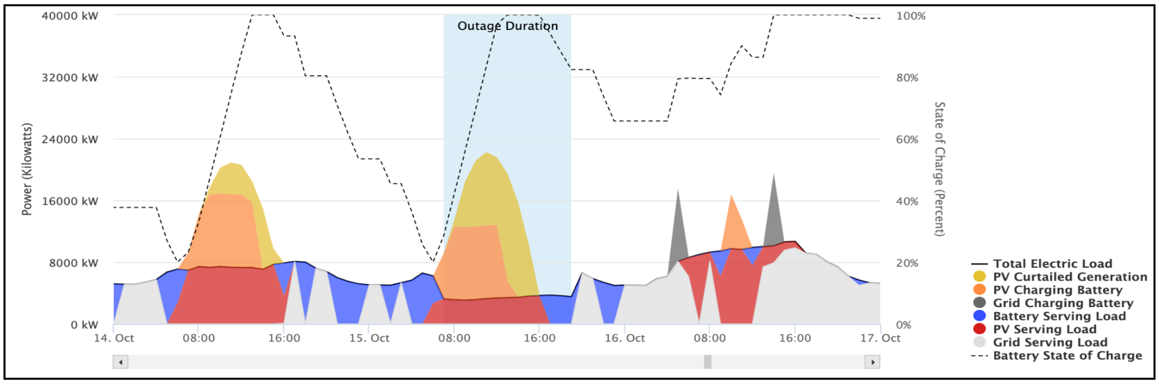
Increasing the number of residents increases the pool of shareholders and potential investors. It is essential to consider whether the upfront capital cost can be shared between the number of households and the anchoring institution (either the hospital or the university) and whether achieving a 25-year return is feasible given that people may move and relocate during a quarter-century.

iii.Outage Survival Probability

The survival rates fluctuate between (2-42%) for the outage duration of 12 hours. Observations indicate that the battery charging rate is considerably higher during maximum PV serving load periods. In the simulation conducted for the city of San Bernardino, in the scenario of the largest PV size, battery discharge becomes noticeable when the load is connected to the main grid, as illustrated in Figure 19.

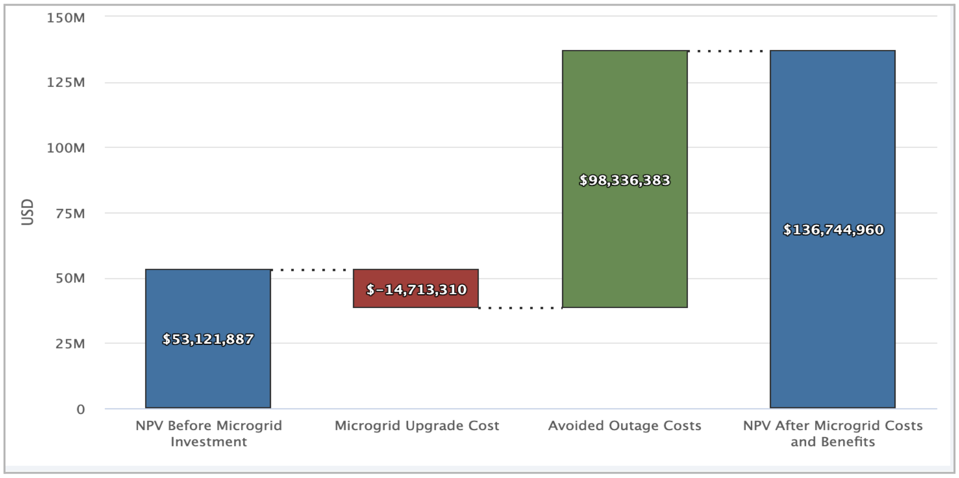
Figure 19: Maximum PV Array Size and Corresponding Supply During the Outage

Source: Author(2023) - Outputs from NREL Re-OPt Simulation



In the Redlands case study, the average probability of outage survival remains below 30%(See Appendix E) and only starts increasing in scenario 3 when the PV size array increases significantly. The cumulative effect of increased resilience on the NPV of the maximum PV size in this simulation is portrayed in the waterfall chart(Figure 20). Based on this chart, the expansion of solar plus systems to a microgrid (at 30% of total capital cost and savings of $100/Kw) offers benefits that exceed the costs of an outage resulting in $136,744960 NPV.

Figure 20: Effect of Resilience Costs and Benefits for Maximum Solar PV Size in the City of San Bernardino



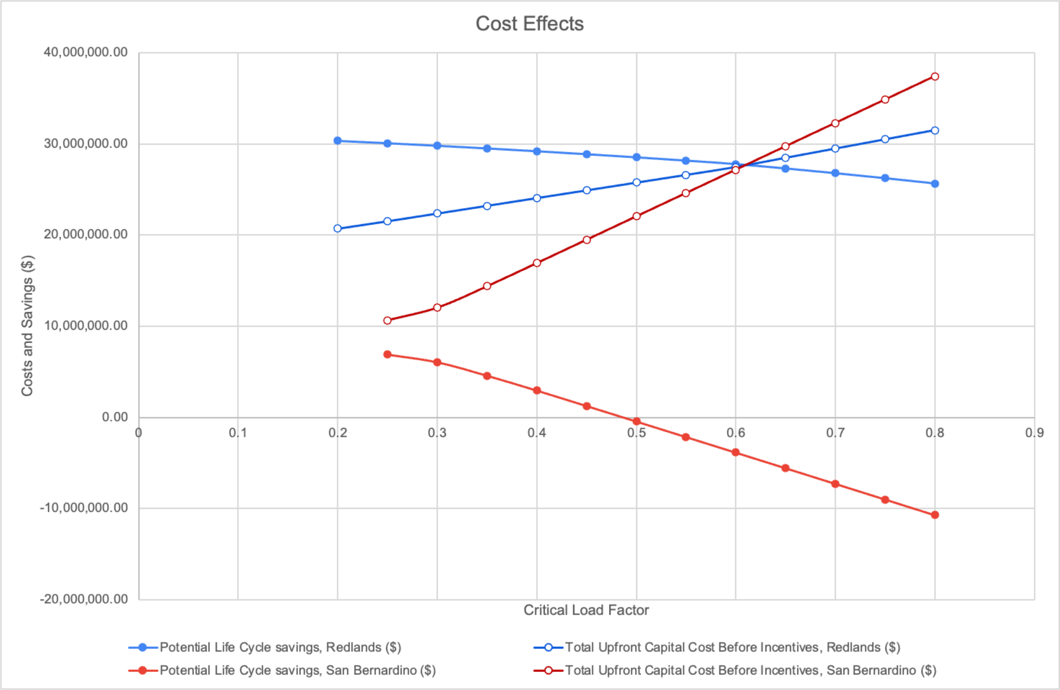
Source: Author(2023) - Outputs from NREL Re-OPt Simulation

With greater PV array size, the costs saved from generating local electricity and avoiding electricity bills can be directed to buying larger battery storage options, and the coupling of large PV and massive battery storage increases the chances of surviving a power outage of long duration. However, The caveat is that the upfront capital costs also increase significantly, thus likely putting such projects out-of-reach for lower-income communities or groups without significant outside financial support.

iv. Critical Load Factor

In scenario 2 of the San Bernardino case study, contrasting patterns are seen between the NPV and critical load factor, meaning the microgrid needs to supply a smaller critical load ratio that relaxes the battery storage constraint, resulting in a life-cycle NPV that is more positive. However, in the case of San Bernardino, the NPV becomes negative at a critical load factor of 0.5, which is suboptimal given the hospital's need to maintain the operation of life-saving equipment during the outages. The contrasting life-cycle NPV trend in between the two campuses, when it comes to the critical load factor changes, can be interpreted in the context of their respective anchoring institutions. For the hospital, higher electricity demand leads to higher expenses, and although investing in PV and storage might initially result in a loss, it may make sense, given the long lifespan of the institution and its close proximity to the forests and Cajon Pass where most wildfires occur. For Redlands, as the critical load factor reaches the high peak, the upfront capital cost undergoes a cross-over, resulting in decreased attractiveness for investors. However, private investment may still be viable if the NPV remains higher than the capital cost, and as depicted in Figure 21, any critical factor below 0.6 would satisfy the criterion and could yield in the desired NPV range.

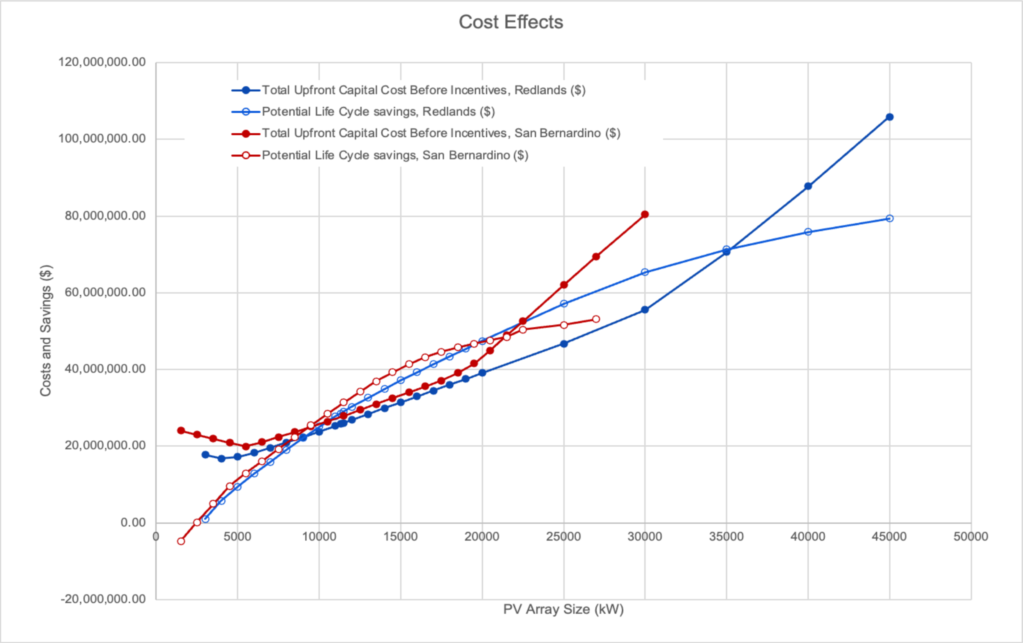
Figure 21: Cost Effects of Increase in Critical Load Factor - San Bernardino City



Source: Author(2023)

In the case of Redlands, the NPV remains positive throughout the critical load factor changes. This finding suggests that the allocated PV array space determined by the PVWatts tool is sufficient to provide cost savings from avoided electricity bills for all critical load ratios simulated. It can also be concluded that the electricity demands from the residents and the university campus can be adequately satisfied by the daytime electricity supplied by the combined battery and PV resources across a range of critical load factors. Figure 22 indicates that both solar and storage campuses can achieve financial viability by increasing the size of the PV array. The San Bernardino project needs to expand beyond the available land surrounding the hospital, while the Redlands project can utilise the space available on the university campus. However, the viability of both projects could be jeopardised when the life cycle saving exceeds the upfront cost(>35000 kW in Redlands and >21500 kW in San Bernardino, shown in Figure 22)

Figure 22: Cost Effect of PV Array Size Comparison: San Bernardino vs. Redlands



Source: Author(2023)

In Scenario 3 of the San Bernardino case study, the survival rate peaks for PV sizes above 22500kW but larger PV size does not guarantee higher survival rate and the average rate for 12-hour outages remains as 17%. The NPV curve begins to decline at this point, and therefore it can be interpreted that more land and space are needed for this microgrid project to become financially feasible. However, due to land constraints in downtown San Bernardino, it may be necessary to provide financial incentives, such as subsidies or gifting land to increase the feasibility of this microgrid deployment project. Varying the maximum size of the PV array and the battery storage has the potential to significantly increase the probability of surviving a long outage (in the case of Redlands Campus)—however, this comes with significant tradeoffs. The upfront capital needed to have a PV array about 4 times the initial baseline scenario is on the order of $100M— but the NPV of such a project is also very positive.

5.2 Avoided Emissions Cost

As previously discussed in this paper, reducing Californians' reliance on fossil fuel BG is advantageous for the state as it aims to decarbonize the grid and establish a more intelligent and resilient system in line with the transition towards a sustainable economy. Figure 22 illustrates the overall cost of generating electricity using propane in comparison to the total initial investment required to establish a solar PV configuration in San Bernardino and Redlands. This calculation involves dividing the annual electricity demand/consumption by 365 days, multiplying it by the critical load factor, and then halving the result to determine the electricity consumption during a six-hour outage.

Table 3: Comparing the total cost of Propane Generators vs the upfront cost of installing solar plus

Location	Annual Consumption (kWh)	Critical Load Factor	Estimated Electricity Consumption for 6h Outage (kWh)	Generator Efficiency	Propane Generator Fuel Consumption (kWh)	Cost of running propane generator ($/kWh)	Total Cost of Running Propane Generator for 6h Outage ($)
Redlands	88,692,660	0.5	30374	0.25	121,497	0.45	54,674
SB	88,377,453	0.5	30,266	0.25	121,065	0.45	54,480

Per estimates from: https://learnmetrics.com/generator-cost-per-kwh-diesel-propane-natural-gas-gasoline/

The numbers in the last column(Table 3) reflect the fuel costs of burning propane in a generator to restore electricity during a power outage of 6-hour duration: this is consistent with the annual number of hours of power loss in the city of San Bernardino. The baseline campuses designed in this thesis would be paying roughly $50K each year to restore a 50% critical load factor in a typical year in which power outages cumulatively last a total of about 6 hours. This cost does not include the secondary health and carbon emissions costs. Power outages are projected to increase in frequency and duration in the future as a result of climate change. Furthermore, in 2021, the state of California passed a law banning the sale of new portable generators beginning in 2028, so the option of having a propane or diesel generator to restore temporary power for short durations will be significantly curtailed in 4 years' time.

Moreover, solar plus storage systems provide benefits on a daily basis, ranging from reduced emissions and improved health to enhanced resilience and, ultimately, lower electricity bills for communities. On the other hand, a fossil fuel BG would only be utilised during power outages, and investing in them has no long-term benefits.

5.3 Income Effects on Microgrid Site Selection: Redlands vs San Bernardino

The adoption of solar plus systems has been less prevalent among Low-to-Moderate Income (LMI) households. In contrast, early adopters in California and the US tended to be high income with particular preference over the pay-back period(Wolske et al.(2017). Although the cost of PV and storage has decreased over time, high-income households still comprise the majority of adopters compared to LMI households(Barbose et al., 2020). According to O'Shaughnessy et al.(2022), "Median solar adopter income was about $110k/year in 2021"; higher than a nationwide median of $79k/year for all owner-occupied households and above the household median income in both San Bernardino and Redlands. O'Shaughnessy et al. adds that solar adopters tend to identify as "Non-Hispanic White", are primarily "English-speakers", and have "higher education", which is more similar to Redlands demographic while the majority of the population in San Bernardino downtown is non-white with no university education. When it comes to solar PV and battery combined, the adopter incomes are consistently higher, leaving incentivising such systems in our regions of study very challenging.

As listed in Table 2, the city of San Bernardino has a lower household median income compared to both state-wide figures and the Redlands. As well as having the highest poverty rate amongst all three while having almost triple the size of Redland's population. Moreover, there are more renters in San Bernardino downtown than in Redlands, which may lead to lower incentives for investing or participating in co-investment in community solar plus. Redlands, in contrast, has a higher than state-wide median household income figure and notably lower population density and poverty rates. LMI households in San Bernardino also face other barriers to adopting PV and storage, such as high initial expenses, limited access to financial tools, inadequate information, and language barriers. According to CalEnviroScreen (CES)[9]The City of San Bernardino deals with various types of socioeconomic challenges and is one of the disadvantaged communities (DACs), which based on the O'Shaughnessy et al.(2022) study tend to be non-adopters. San Bernardino does worse than Redlands in almost all indicators, particularly air pollution(Ozone) and economic indicators such as unemployment and poverty. Both San Bernardino downtown and Redlands have power plants in close vicinity. Therefore, deployment of solar plus in such communities helps reduce electricity consumption during peak hours, lowering electricity bills, especially for the LMI adopters, as well as yielding co-benefits such as lower emissions by adding renewable capacity to the grid (Krieger et al., 2016). However, financing these adoption remains the largest challenge which will be discussed further in this paper.

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[9] The California Environmental Screen(CES), is a geospatial mapping methodology introduced by the California Office of Environmental Health Hazard Assessment (OEHHA) in 2013.CES combines environmental burden and socioeconomic data at the census tract level in California. CES helps identify Disadvantaged Communities(DACs) within the state, which are defined as the census tracts that score in the top 25% statewide on the CalEnviroScreen 3.0 metric(OEHHA, nd).

Table 2: Demographics and Income Levels Comparison: Redlands vs. San Bernardino – Source: US Census

Population	**Redlands**	**San Bernardino**	**California**
Population Estimates, July 1, 2021, (V2021)	73,288	222,203	39,142,991
Population Per Square Mile	2032.9	3,574.7	253.7
Housing			
Owner-occupied housing unit rate, 2017-2021	58.60%	48.80%	55.5%
Income & Poverty			
Median household income (in 2021 dollars), 2017-2021	87,184	70,287	84,097
Persons in poverty, per cent	8.70%	20.90%	12.3%

As discussed earlier in this paper, findings suggest that larger solar PV installations may provide a significant benefit to this community, despite the high capital investment required. Consequently, the matter of socioeconomic prioritisation should not necessarily preclude large-scale solar and storage installations in disadvantaged communities. It is crucial to explore various approaches to execute this project, including establishing a *community solar* in densely populated regions, which will be explored further in this research.

5.4 Procuring Land Rights for PV Installation

Deployment of large-scale solar farms and their associated infrastructure is frequently met with resistance at the community level, even though clean energy is generally perceived positively by many. There are also some restrictive regulations that may create hurdles ahead of land use for solar construction. These regulations can include restrictions on the size or height of solar installations or requirements for setbacks from property lines and roads, limiting the available space for Solarplus development. In the case of San Bernardino County, some stringent zoning restrictions exist in certain areas, such as historic districts, coastal zones, or wildlife habitats, which can limit solar development opportunities in those locations. For instance, based on the zoning restriction, large-scale solar development is even prohibited in some regions of the San Bernardino desert[10]. While there are limitations in solar and storage development near the residential areas, such as, ‘set back from the property line either pursuant to the Land Use Zoning District standards or 130 per cent of the mounted structure height, whichever is greater.”(San Bernardino Code or Ordinances, 2023)

Notwithstanding, one of the unique strengths of solar PV technology is its versatility and adaptability to different applications and locations: from centralised to decentralised rooftops, parking lots, and field-mounted arrays. While the land requirements for large-scale solar projects should not be underestimated, the flexibility of solar could potentially mitigate the likelihood of encountering significant “land-use” limitations in the regions under study. And its compatibility with multiple land-use can potentially eliminate the ecological footprint concerns.

5.5 Equity Dimension and Solar Plus Storage System Installation

The simulated microgrid projects demonstrate economies of scale advantages that significantly benefit communities in Redlands with substantial capital. Nevertheless, a truly resilient system necessitates a considerable upfront capital investment beyond the means of LMI communities, such as the residents of San Bernardino downtown. Moreover, Figure 23 reveals a dearth of installed solar PV in the region, indicating the demand for this technology in this region. Hence, alternative funding sources, such as subsidies or grants, may be explored to make the deployment of solar plus financially feasible in San Bernardino downtown.

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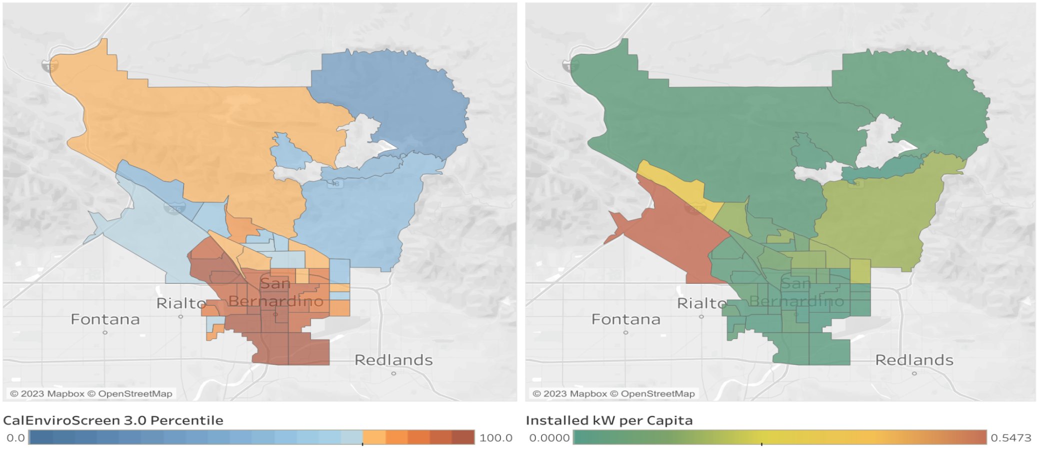
[10] “Muscoy, Bear Valley, Crest Forest, Hilltop, Lake Arrowhead, Lytle Creek, Oak Glen, Homestead Valley, Joshua Tree, Lucerne Valley, Morongo Valley, Oak Hills and Phelan/Phelan Hills.”(Resolution No. 2019-17, Amendment of the Renewable Energy and Conservation Element of the County General Plan)

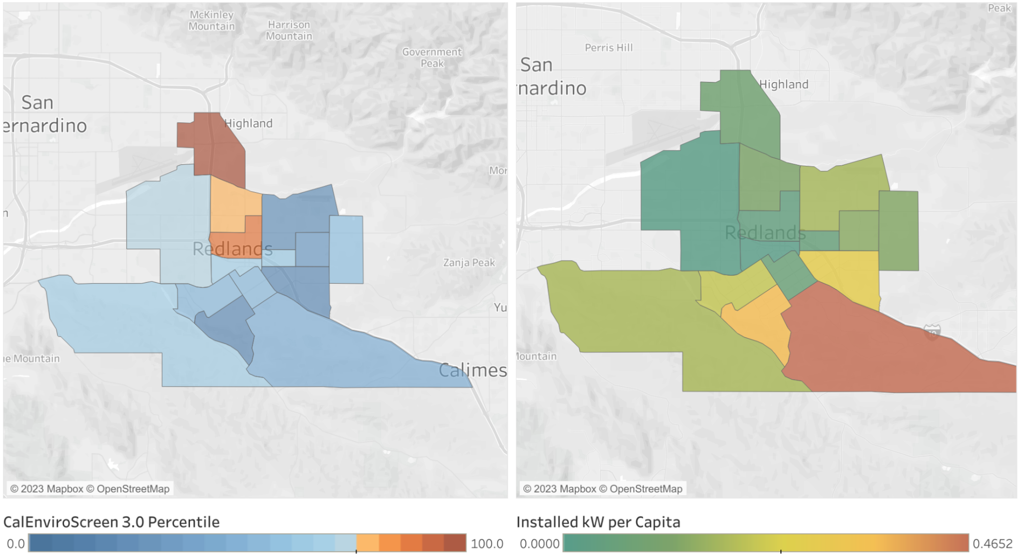
Figure 23: Distributed Solar (PV) Deployment Rates in the City of San Bernardino by Census Tract, Environmental Justice (EJ) Metrics, Utility Service Territory, and Year (1998-2017)



The newly enacted Inflation Reduction Act could enhance the progress of solar plus adoption in both communities. Apart from tax credits for solar and storage projects, the act sets aside $7 billion to assist community solar programmes. Hence, there is a unique opportunity for the county of San Bernardino to adopt these renewable technologies further. In addition, the California Public Utilities Commission's recent overhaul of the rooftop solar regulations provides incentives for more solar projects for low-income homes, which could benefit LMI communities in San Bernardino Downtown. However, it is essential to note that the new regulations reduce payments to homeowners for excess power they generate and sell back to the grid, which could make rooftop solar less financially attractive for some homeowners in the Redlands region who have higher incomes.

As shown in Figure 24, Redlands is one of the most prosperous cities in the county, and it does have a considerable amount of solar installation in the southeast. However, northwest Redlands and downtown are in the CES top percentile, but the solar PV adoption in these locations is the lowest. This could mean that there is a renewable adoption injustice here in which the more affluent the neighbourhood, the more adoption of solar and storage takes place.

Figure 24: Distributed Solar (PV) Deployment Rates in the City of Redlands by Census Tract, Environmental Justice (EJ) Metrics, Utility Service Territory, and Year (1998-2017)



Policymakers of Redlands can increase adoption equity through measures that address specific barriers to LMI adoption and shift PV deployment patterns into underserved areas. By shifting deployment into underserved parts of the city with more LMI households, they could catalyse peer effects and greater installer marketing in those neighbourhoods, which, as has been shown elsewhere, may generate self-sustaining increases in adoption in those areas(O'Shaughnessy et al., 2021).

In addition, in order to alleviate the cost burden of larger PV array sizes, the policymakers of the two regions can undertake these simulated projects as community solar projects; gathering more stakeholders and sharing the financial burden. However, executing community solar projects in LMI communities requires policy intervention to maximise community involvement.

5.6 Innovative Solutions for Advancing San Bernardino LMI Participation in Community Solar

In September 2022, California passed AB 2316, under which community solar is defined as a public project and requires “at least 51%” of the community solar programme capacity to serve LMI (State of California, 2022). Under this bill, the community solar generation in San Bernardino will be rewarded based on the avoided-cost calculation to incentivise battery storage. Also, the bill requires the project to be connected to the distribution grid to bolster the resilience of the local energy system. Notably, this aligns with the objectives of this research in advocating for the implementation of community solar and storage in San Bernardino County.

Community solar plus deployment in San Bernardino necessitates active engagement with the community and may benefit from partnerships with community-based organisations. These collaborations could facilitate the creation of a *solar share gifting model* to distribute the initial capital expenditure between the SCE, the primary utility provider in the area, a non-profit organisation and a philanthropic partner. There are precedents for this type of agreement in other states, such as “Habitat for Humanity and Electric Utility Gift Community Solar Subscriptions to Kentucky Households.”(NREL, 2022)

Furthermore, the San Bernardino *Housing Authority* could serve as a *financial guarantor* for the community solar plus project, working closely with the developer to minimise their risk. This would involve the Housing Authority paying for the electricity consumed by the affordable housing units in downtown San Bernardino and the hospital paying its own share. At the same time, the life cycle savings from the project could be reinvested in the facilities to cover operation and maintenance(O&M) costs. This type of collaboration has been successfully implemented in the City of Pueblo, Colorado, where a 2 MW community solar garden was established through a partnership between the housing authority, a solar developer, and a non-profit organisation, providing solar job training for approximately 50 LMI individuals.

Despite being limited in space, the constraints in San Bernardino Downtown present an opportunity for collaboration with corporations such as FedEx and Amazon(both own a number of properties and lands in the city) to host the solar plus storage project at their facilities or buildings; in exchange for establishing the Solarplus system, the corporation can allocate a portion of the energy bill credits to offset its electricity costs.

5.7 Community Solar Plus Enabling Policies

California has implemented a number of policies to promote the development of community solar projects. One of the key policies is *Virtual Net Energy Metering (VNEM)* which is a tariff arrangement that allows the owners with multimeter properties to allocate their solar system's energy credits to tenants. In this model, the tenant and landlord receive the equivalent of generated electricity in kWh. Therefore, the tenants directly benefit from the solar and storage system. This mechanism is particularly beneficial to locations like downtown San Bernardino, with a relatively high number of renters with lower incomes. Other LMI-focused policies are mainly oriented around carve-out subsidies to incentivise community solar projects, as summarised in Table 4.

Table 4: Summary of Already in-place Carveout Incentives in California - Source: CPUC(n.d.)

State	Legislation	Rulemaking/ Proceeding	Programme	Carveout	Incentives	Notes
CA	Community Solar - Green Tariff program (CS-GT) and the DAC Green Tariff program (DAC-GT)	Rulemaking 14- 07-002	Community Solar Green Tariff Program (CS-GT) DAC Green Tariff Program (DAC-GT) Community Department of Community Services and Development Community Solar Pilot Program	Subscription to this programme is limited to eligible residents of DAC only.50% of a project's energy output must be subscribed by customers eligible for CARE or FERA.	Community sponsors that meet the eligibility criteria can receive a discount of 20% on their electricity rates for up to 25% of the energy produced by a CGST project. Additionally, eligible residential customers in DACs can receive a 20% discount on their electricity rates.	This initiative operates similarly to the DAC-GT scheme, but it mandates that each solar project be located close to the customers it serves. DAC-GT enables customers who cannot benefit from SOMAH or DAC-SASH through onsite solar to take advantage of solar energy still.

Nonetheless, subsidies may not be the most effective policy intervention, as O'Shaughnessy et al.(2023) posit that despite California's LMI solar energy programme being the largest programme of its kind in the US, it has resulted in only 4% cumulative LMI adoption in the state.

Another enabling policy has been used in other states that can potentially be leveraged in San Bernardino County to target LMI households in both the city of San Bernardino and the Redlands. This paper recommends policies like consolidating energy bills in order to streamline billing and facilitate LMI resident participation. The state government may provide direct financial support for LMI subscribers through electricity bill discounts or support in subscription payments, funded from savings from solar energy generated in either of the campuses designed in this paper.

Local governments can also act as "*anchor subscribers*", purchasing a significant share of the subscriptions and acting as a safety net for customers who may choose to opt out of the project, such as renters, households with financial difficulty, or students who move to other states post-graduation. Local governments or housing associations can lease or donate public property or any under-utilised land for solar and storage infrastructure. This approach may be particularly relevant for densely populated areas such as San Bernardino downtown, which is constrained by land availability. Perris Hill Park, located near San Bernardino Community Hospital, could be suitable for such initiatives or the recently demolished Carousel Mall[11] in downtown San Bernardino.

5.8 Community Solar Subscription Payment Assistance

LMI households in both San Bernardino Downtown and Redlands may encounter challenges in financing the subscription for community solar and storage projects. However, the local government can help ease the financial burden by *prepaying the subscription* on their behalf using external resources such as grants and state funds. This approach would enable LMI households to enrol in the plan for a predetermined period of time.

An alternative approach is for the San Bernardino Housing Authority to collaborate with the developer and finance the subscription. Although this approach would mitigate the issue of customer turnover, it would create an administrative burden for the local government. To hedge against the risk of default participants, a *flexible subscription* can be put in place, with *backup subscribers* such as churches, mosques, synagogues or any non-profit making organisations, as demonstrated by the solar community of "Interfaith Power & Light project" in Minnesota (Jossi, 2017).

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[11] Demolishing of this mall will free up 43 acres of land only 3 miles aways from the community hospital in San Bernardino Downtown https://abc7.com/san-bernardino-carousel-mall-demolition-downtown/13181508/

The local government can also incentivise businesses to pay the subscription on behalf of employees or become flexible subscribers. While this approach– "workplace subscription programmes"– would address the issue of turnover and credit risk for LMI, businesses would have the authority to set the period of the contract with consumers(O'Shaughnessy et al., 2018).

5.9 Developing Innovative Finance Models for solar plus Systems in Communities

In the context of San Bernardino downtown, it may not be practical to implement subscription models that involve an upfront payment and multi-year payback period for LMI customers. This is due to the fact that these households may not be able to obtain traditional loans from banks to cover the upfront cost and subscription. Therefore, programmes can be developed that are either entirely free or involve minimum ongoing payments that are offset by bill credits.

1- Lower Interest Loans: California can provide up-front financing for a loan loss reserve(LLR) to pay low-interest loans to LMI customers in San Bernardino. This has already been practised in Michigan and Massachusetts, but the risk is that the fund might not be sufficient if defaults occur frequently(DOE, n.d).

2- Tax Exempt Municipal and Green Bonds: Municipal and green bonds present a viable option for financing community solar and storage projects in the LMI communities of San Bernardino. The county can leverage green bonds to lower upfront costs and increase participation in such projects. The community hospital in San Bernardino or Redlands University can issue green bonds to fund solar power and storage projects and use the energy cost saving to repay the bonds. Furthermore, tax-exempt bonds can help LMI communities of the county to finance energy efficiency upgrades in multifamily housing and small businesses. For instance, California Statewide Communities Development Authority(CSCDA), provides tax-exempt bonds for financing affordable housing developments that include solar panels and energy-efficient appliances. These bonds have been used for several projects across California and can be utilised in San Bernardino too (EPA, n.d).

3- On-bill Financing

This approach can be used to enable customers to pay their community solar subscription fees through the regular payment on their utility bills, thereby reducing the burden of the upfront cost. This mechanism offers solutions for poor credit histories and less access to bank loans. However, the risk of subscriber default is on the utility[12].

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[12] Some established examples of on-bill financing are: Hawaii GEM$ On-Bill Program. gems.hawaii.gov/ and OPALCO's Switch It Up Program. energysavings.opalco.com/switch-it-up/

Chapter 6: Conclusion and Policy Implications

It is anticipated that the findings discussed in this study offer some valuable perspectives and potential guidance for policymakers at the county and state levels and developers interested in exploring DER investments in Southern California. While small-scale and geographically specific, the San Bernardino and Redlands simulations nonetheless offer helpful lessons for other local-level renewable energy generation programmes in other locations within the state or even country-wide.

Based on the findings of this project, through assessing 50 different inputs for San Bernardino and 63 different inputs for Redlands, it can be concluded that a larger PV array size and available land can significantly improve the financial viability of solar and storage deployment over a 25-year period. This allows the communities to derive more electricity off-the-grid, justifying the upfront capital costs with projected electricity savings. However, utilising more land can create some challenges for the developers, particularly in space-constrained locations like the city of San Bernardino. While space is likely more available outside the borders of San Bernardino, microgrids are specifically intended to generate and supply electricity locally, so developing solar projects elsewhere, preferably on a utility-scale, would return to the purview of the utility company itself.

It is more cost-prohibitive to develop a microgrid in a land-constrained space such as the existing hospital sites chosen. Instead, as the city government reclaim defunct shopping malls or develops under-utilised lots for urban renewal developments, the city policymakers could incentivise developers by tax breaks and land gifting to make solar PV space available and lower the upfront capital cost. In order to attract more LMI subscribers to the pool of solar plus consumers, the local government can act as an anchor subscriber to hedge the risk of default for developers or pre-pay the subscriptions to lower the cost of solar plus integration for the communities.

This paper recommends exploring innovative financings like green bonds and tax-exempt bonds by San Bernardino Hospital and Redland University, and the county's Housing Association to finance the subscriptions to the community solar plus system. Undertaking all the stated approaches constitute a forward-looking policy for future development, as opposed to one trying to correct past shortcomings.

This study finds that serving high critical load factor during PSPSs requires a larger battery capacity, and there is a threshold where the deployment project becomes infeasible; when NPV starts declining due to an increase in expenditure. This trend is observed in both campuses in San Bernardino and Redlands.

Even with policy intervention, specific parameters would need to be satisfied: namely, a positive NPV lifecycle cost that exceeds the initial upfront capital cost in order to be attractive to investors. Otherwise, the long-term finances of a microgrid in a city with higher population density, and denied the economies of scale resulting from land resource constraints, make the city interior less attractive as a microgrid site.

With lower population density and more land available on the edges of the university campus, microgrid projects seem more financially viable in Redlands. With economies of scale, microgrid projects with more land resources yield higher NPV, presenting more feasible investment opportunities. A university campus also has a lower critical load factor than, for instance, a hospital. So the scale of battery resources needed to weather a power outage is less daunting.

In weighing the return period, stakeholders would need to consider the tradeoffs between life-cycle savings and upfront capital costs and whether residents would stay in the area long-term to reap the long-term benefits. A university that owns apartment buildings as residences for its students could see the long-term benefits of investing in a microgrid project, even if private homeowners anticipating moving houses every few years or so would not.

In conclusion, a Solarplus project in Redlands can be a private investment where the university can partner up with businesses and leverage its endowment to fund the project, especially considering the financial viability of microgrid projects in the area and the potential for long-term benefits.

6.1 Limitations of Research

This project first required a cursory selection of areas that would be feasible for constructing a PV solar array in the current cityscape using available land resources. In a genuinely optimal scenario, there would be feedback from multiple stakeholders to decide on a locale for the placement of the solar PV, and not just selecting an area based on an aerial map and the outputs of the PVWatt solar mapping tool.

The inputs for the ReOpt model are based on best estimates for how much land could be available for the microgrid and calculating the life cycle costs and other outputs based on an initial baseline estimate of the PV array size. Breaking ground on such an undertaking would require much more discussion and community engagement for sizing. Therefore, this project is only meant as a case study of the economics and financial viability of a given baseline microgrid project, with additional simulations stemming from variations of certain other parameters and variables. In addition, this analysis aims to broaden the consideration of equity values in microgrid design and investment decisions. However, the factors included in this analysis only scratch the surface of the broader energy justice realm.

6.2 Future Research Direction

The field of microgrid technology is still relatively new, and there is not too much research literature on how microgrids perform and how closely the finances and economics (of actual existing microgrids) of such projects match with simulations and calculations of their feasibility and viability. Again, this thesis was meant to present case studies of feasible or not-so-feasible microgrid projects based on aerial maps of available land resources. Further research might entail different sets of models to optimise the size and setting of solar PV, a broader investigation of the number of participants, and re-running the ReOPT model with retail or commercial stakeholders as well. An alternative research direction could be designing/simulating a network of neighbouring hospitals that form an integrated microgrid instead of the hospital partnering with residential buildings in the area.

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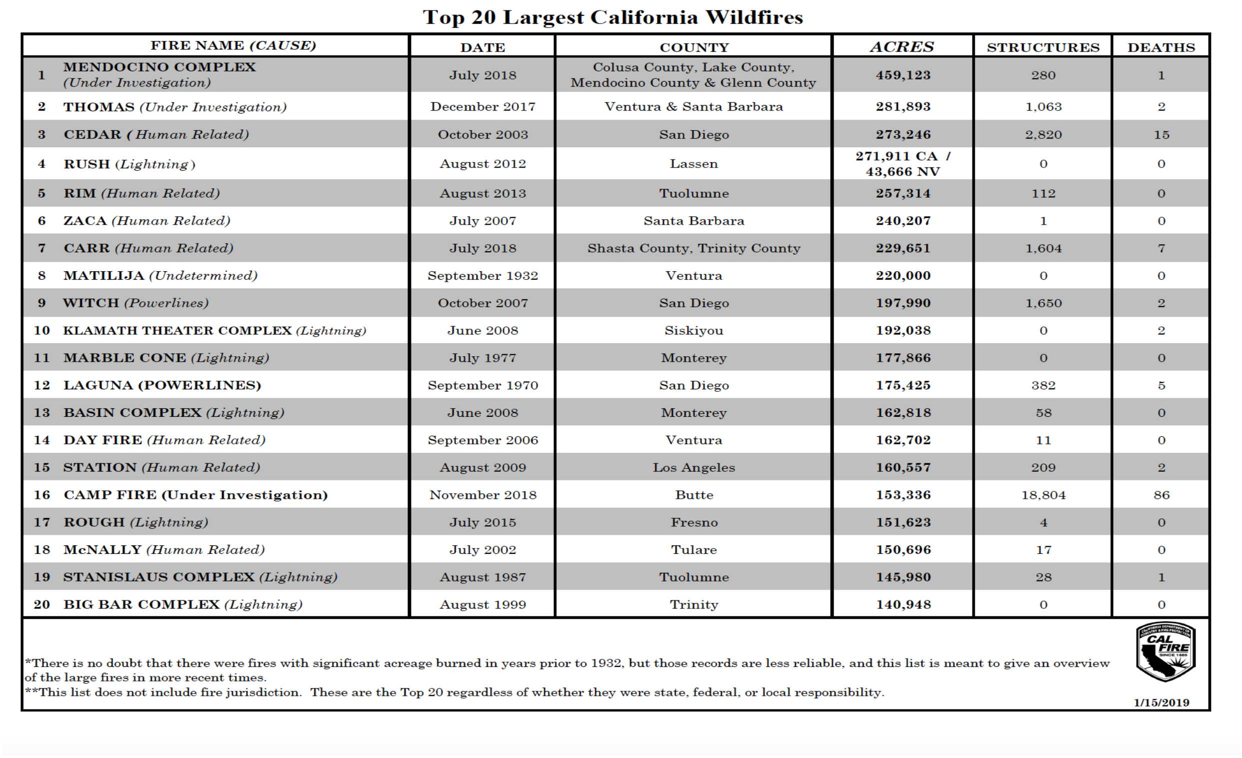
Appendix

Appendix A: Top 20 Largest Wildfires in California (Calfire, 2019)



Top 20 Largest California Wildfires

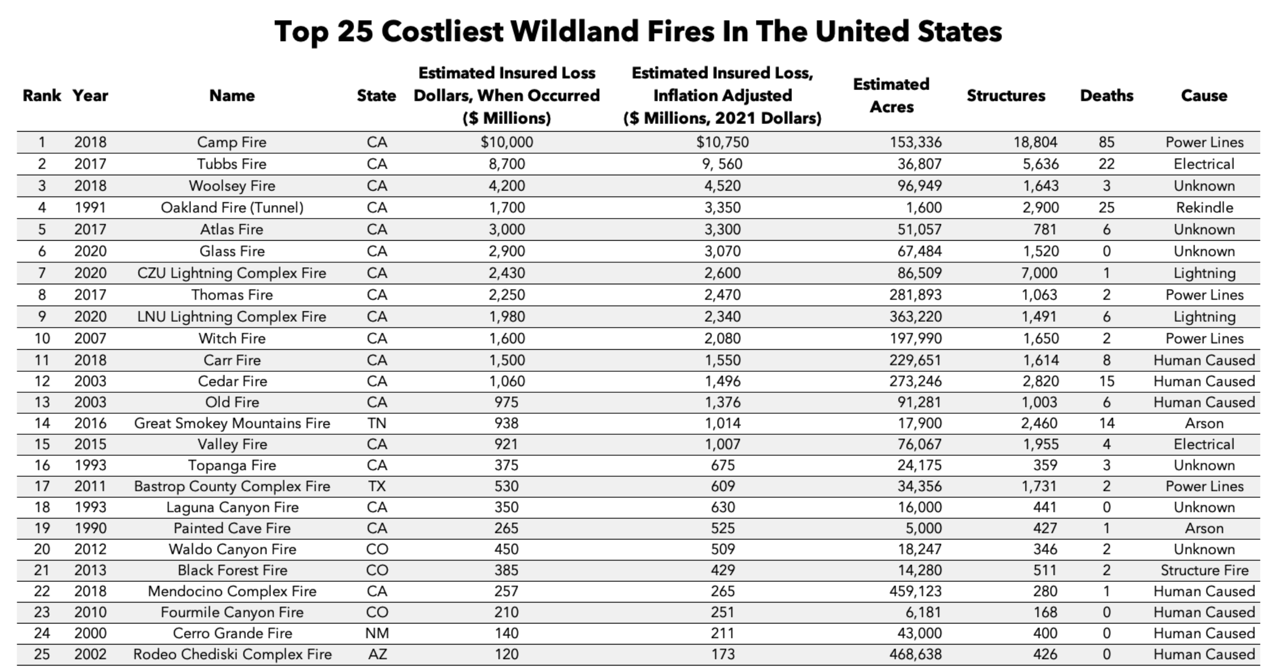
	FIRE NAME *(CAUSE)*	DATE	COUNTY	*ACRES*	STRUCTURES	DEATHS
1	**MENDOCINO COMPLEX** *(Under Investigation)*	July 2018	Colusa County, Lake County, Mendocino County & Glenn County	**459,123**	280	1
2	**THOMAS** *(Under Investigation)*	December 2017	Ventura & Santa Barbara	**281,893**	1,063	2
3	**CEDAR** *(Human Related)*	October 2003	San Diego	**273,246**	2,820	15
4	**RUSH** *(Lightning)*	August 2012	Lassen	**271,911 CA / 43,666 NV**	0	0
5	**RIM** *(Human Related)*	August 2013	Tuolumne	**257,314**	112	0
6	**ZACA** *(Human Related)*	July 2007	Santa Barbara	**240,207**	1	0
7	**CARR** *(Human Related)*	July 2018	Shasta County, Trinity County	**229,651**	1,604	7
8	**MATILIJA** *(Undetermined)*	September 1932	Ventura	**220,000**	0	0
9	**WITCH** *(Powerlines)*	October 2007	San Diego	**197,990**	1,650	2
10	**KLAMATH THEATER COMPLEX** *(Lightning)*	June 2008	Siskiyou	**192,038**	0	2
11	**MARBLE CONE** *(Lightning)*	July 1977	Monterey	**177,866**	0	0
12	**LAGUNA (POWERLINES)**	September 1970	San Diego	**175,425**	382	5
13	**BASIN COMPLEX** *(Lightning)*	June 2008	Monterey	**162,818**	58	0
14	**DAY FIRE** *(Human Related)*	September 2006	Ventura	**162,702**	11	0
15	**STATION** *(Human Related)*	August 2009	Los Angeles	**160,557**	209	2
16	**CAMP FIRE (Under Investigation)**	November 2018	Butte	**153,336**	18,804	86
17	**ROUGH** *(Lightning)*	July 2015	Fresno	**151,623**	4	0
18	**McNALLY** *(Human Related)*	July 2002	Tulare	**150,696**	17	0
19	**STANISLAUS COMPLEX** *(Lightning)*	August 1987	Tuolumne	**145,980**	28	1
20	**BIG BAR COMPLEX** *(Lightning)*	August 1999	Trinity	**140,948**	0	0

*There is no doubt that there were fires with significant acreage burned in years prior to 1932, but those records are less reliable, and this list is meant to give an overview of the large fires in more recent times.

**This list does not include fire jurisdiction. These are the Top 20 regardless of whether they were state, federal, or local responsibility.

1/15/2019

Appendix B: Top 25 Costliest Wildfires in the US



Top 25 Costliest Wildland Fires In The United States

Rank	Year	Name	State	Estimated Insured Loss Dollars, When Occurred ($ Millions)	Estimated Insured Loss, Inflation Adjusted ($ Millions, 2021 Dollars)	Estimated Acres	Structures	Deaths	Cause
1	2018	Camp Fire	CA	$10,000	$10,750	153,336	18,804	85	Power Lines
2	2017	Tubbs Fire	CA	8,700	9, 560	36,807	5,636	22	Electrical
3	2018	Woolsey Fire	CA	4,200	4,520	96,949	1,643	3	Unknown
4	1991	Oakland Fire (Tunnel)	CA	1,700	3,350	1,600	2,900	25	Rekindle
5	2017	Atlas Fire	CA	3,000	3,300	51,057	781	6	Unknown
6	2020	Glass Fire	CA	2,900	3,070	67,484	1,520	0	Unknown
7	2020	CZU Lightning Complex Fire	CA	2,430	2,600	86,509	7,000	1	Lightning
8	2017	Thomas Fire	CA	2,250	2,470	281,893	1,063	2	Power Lines
9	2020	LNU Lightning Complex Fire	CA	1,980	2,340	363,220	1,491	6	Lightning
10	2007	Witch Fire	CA	1,600	2,080	197,990	1,650	2	Power Lines
11	2018	Carr Fire	CA	1,500	1,550	229,651	1,614	8	Human Caused
12	2003	Cedar Fire	CA	1,060	1,496	273,246	2,820	15	Human Caused
13	2003	Old Fire	CA	975	1,376	91,281	1,003	6	Human Caused
14	2016	Great Smokey Mountains Fire	TN	938	1,014	17,900	2,460	14	Arson
15	2015	Valley Fire	CA	921	1,007	76,067	1,955	4	Electrical
16	1993	Topanga Fire	CA	375	675	24,175	359	3	Unknown
17	2011	Bastrop County Complex Fire	TX	530	609	34,356	1,731	2	Power Lines
18	1993	Laguna Canyon Fire	CA	350	630	16,000	441	0	Unknown
19	1990	Painted Cave Fire	CA	265	525	5,000	427	1	Arson
20	2012	Waldo Canyon Fire	CO	450	509	18,247	346	2	Unknown
21	2013	Black Forest Fire	CO	385	429	14,280	511	2	Structure Fire
22	2018	Mendocino Complex Fire	CA	257	265	459,123	280	1	Human Caused
23	2010	Fourmile Canyon Fire	CO	210	251	6,181	168	0	Human Caused
24	2000	Cerro Grande Fire	NM	140	211	43,000	400	0	Human Caused
25	2002	Rodeo Chediski Complex Fire	AZ	120	173	468,638	426	0	Human Caused

Appendix C: San Bernardino Downtown, CA Input Parameters

Input	Unit	Value	Source
Location	1805 Medical Center Dr San Bernardino CA 92411 USA		Assumption
Building Type	Number	Hospital (6 buildings) + Midrise Apartments(10-75)	Assumption
Estimated Residents per Mid-rise Apartment	Number	82.5	US Census
Electricity Rate	Southern California Edison Co - TOU General Service, Option C: GS-1 TOU A, 3-Phase (Under 2 kV)	(SCE, n.d.)	NREL, n.d.
Land Available	m2	22,532	NREL PVWatts
Resilience			
Outage Durations	Hrs	18	Assumption
Outage Start Date	15-Oct	N/A	Assumption
Outage Start Time	7:00 AM	N/A	Assumption
Type of Outage	Annual	N/A	N/A
Financial			
Discount Rate	%	5.64	NREL, n.d.
Electricity Cost Escalation	%	1.9	NREL, n.d.
PV System Capital Cost	$/kW	1592	NREL, n.d.
Battery Energy Capacity Cost	$/kWh	388	NREL, n.d.
Battery Power Capacity Cost	$/kWh	775	NREL, n.d.
PV O&M Fixed	$/kW	17	NREL, n.d.
Load Profile			
Hospital Building annual consumption	kWh	7752817	NREL, n.d.
Mid-rise Apartment Annual Consumption	kWh	248028	NREL, n.d.
Critical Load Factor	%	50 for SC 1 and 3 25-80 for SC2	Assumption
Max PV Size (Only for SC1&2)	kWdc	3379.8	NREL PVWatts

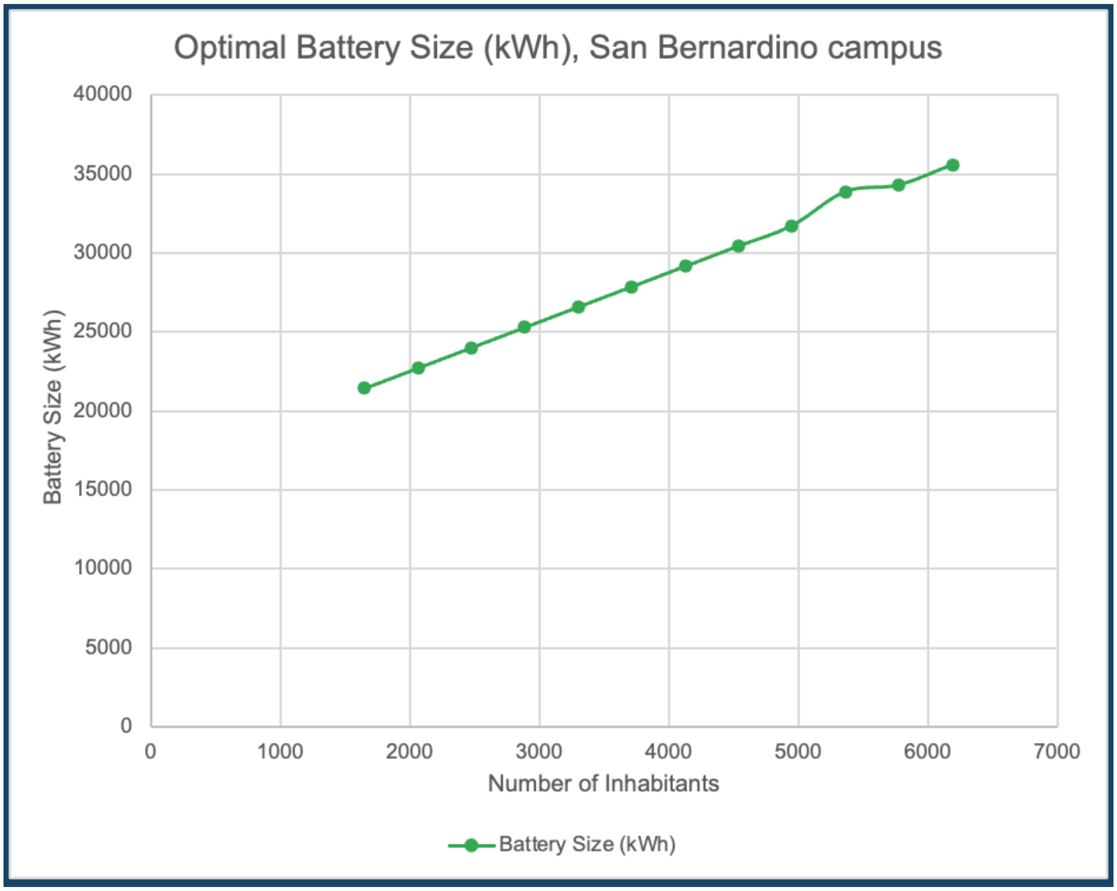
Appendix D: Redlands, CA Case Study Input Parameters

Input	**Unit**	**Value**	**Source**
Location	E Park Ave, Redlands, CA 92374		Assumption
Electricity Rate	Southern California Edison Co - TOU General Service, Option C: GS-1 TOU A, 3-Phase (Under 2 kV)	(SCE, n.d.)	NREL, n.d.
Building Type	Number	Univerity (30 buildings) + Midrise Apartments(40)	Assumption
Estimated Residents per Mid-rise Apartment	Number	82.5	US Census
Estimated Residents per Mid-rise Apartment	Number	82.5	US Census
Land Available	m2	132,025	NREL PVWatts
	Resilience		
Outage Durations	Hrs	12	Assumption
Outage Start Date	15-Oct		Assumption
Outage Start Time	7:00 AM		Assumption
Type of Outage	Annual		
	Financial		
Discount Rate	%	5.64	NREL, n.d.
Electricity Cost Escalation	%	1.9	NREL, n.d.
PV System Capital Cost	$/kW	1592	NREL, n.d.
Battery Energy Capacity Cost	$/kWh	388	NREL, n.d.
Battery Power Capacity Cost	$/kWh	775	NREL, n.d.
PV O&M Fixed	$/kW	17	NREL, n.d.
	Load Profile		
Hospital Building annual consumption	kWh	2584380	NREL, n.d.
Mid-rise Apartment Annual Consumption	kWh	248028	NREL, n.d.
Critical Load Factor	%	50 for SC 1 and 3 20-80 for SC2	Assumption
Max PV Size (Only for SC1&2)	kWdc	19803	NREL PVWatts

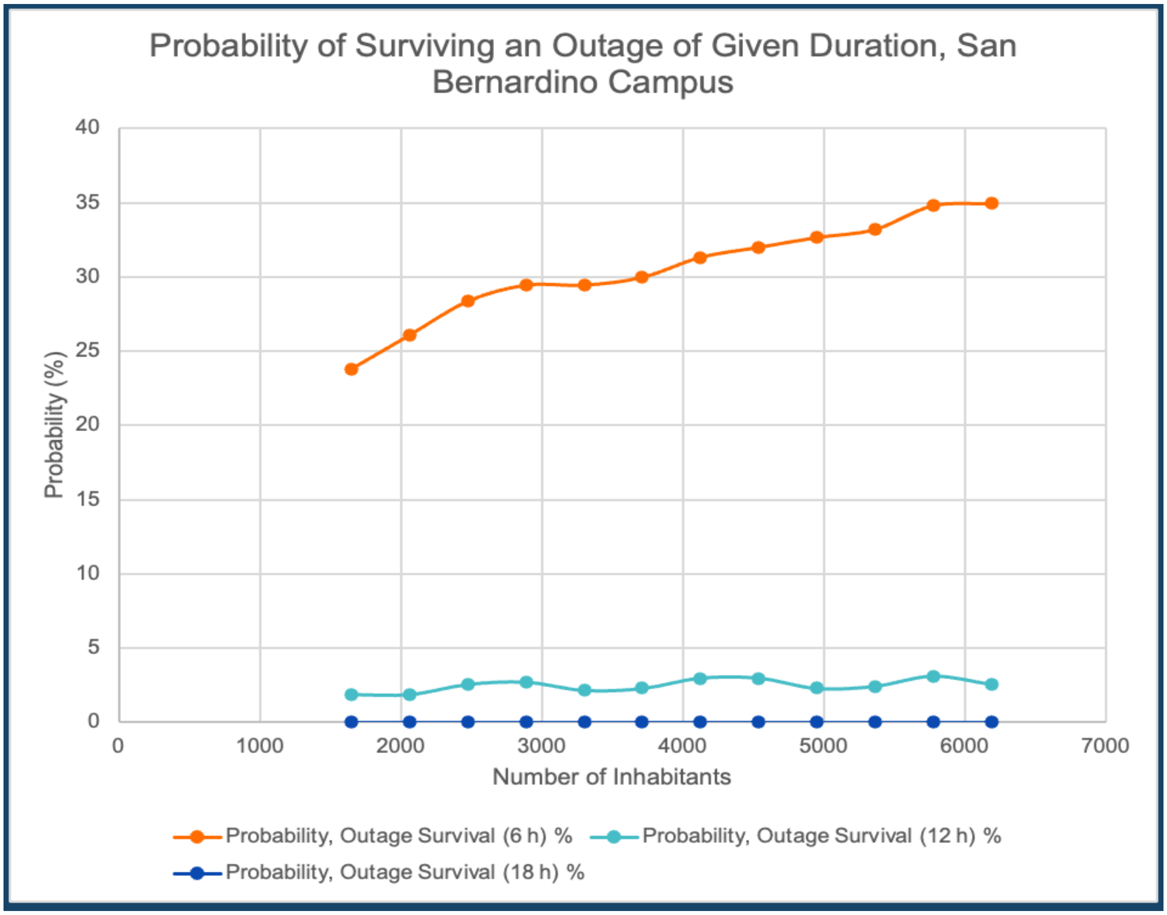
Appendix E: Average Survival Rate During 12 hours Pre-Determined Outage

Average Outage Survival Rate(%)	Scenario 1		Scenario2		Scenario 3	
REopt Outputs	6h	12h	6h	12h	6h	12h
San Bernardino Case study	29.65	2.31	33.79	4.24	42.69	16.86
Redlands Case Study	16.97	5.79	18.5	5.47	26.56	11.54

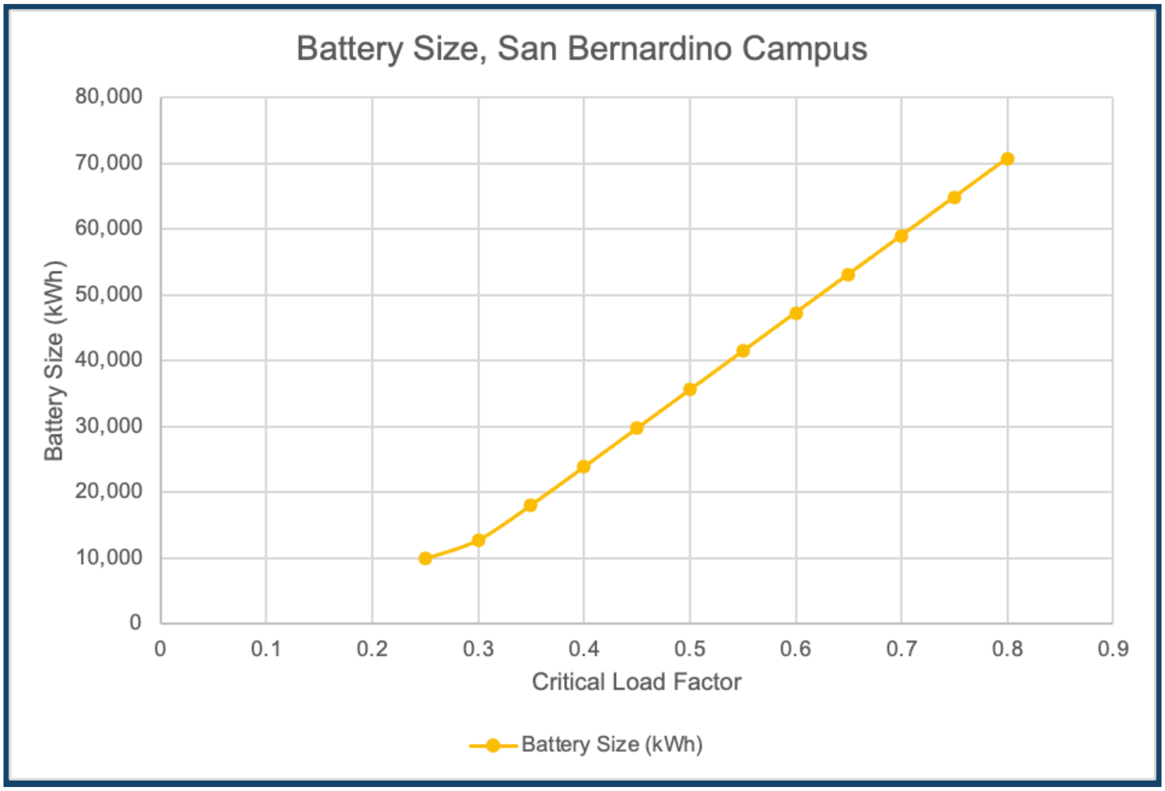
Appendix F: Optimal Battery Size with Increasing Number of Inhabitants- San Bernardino Campus



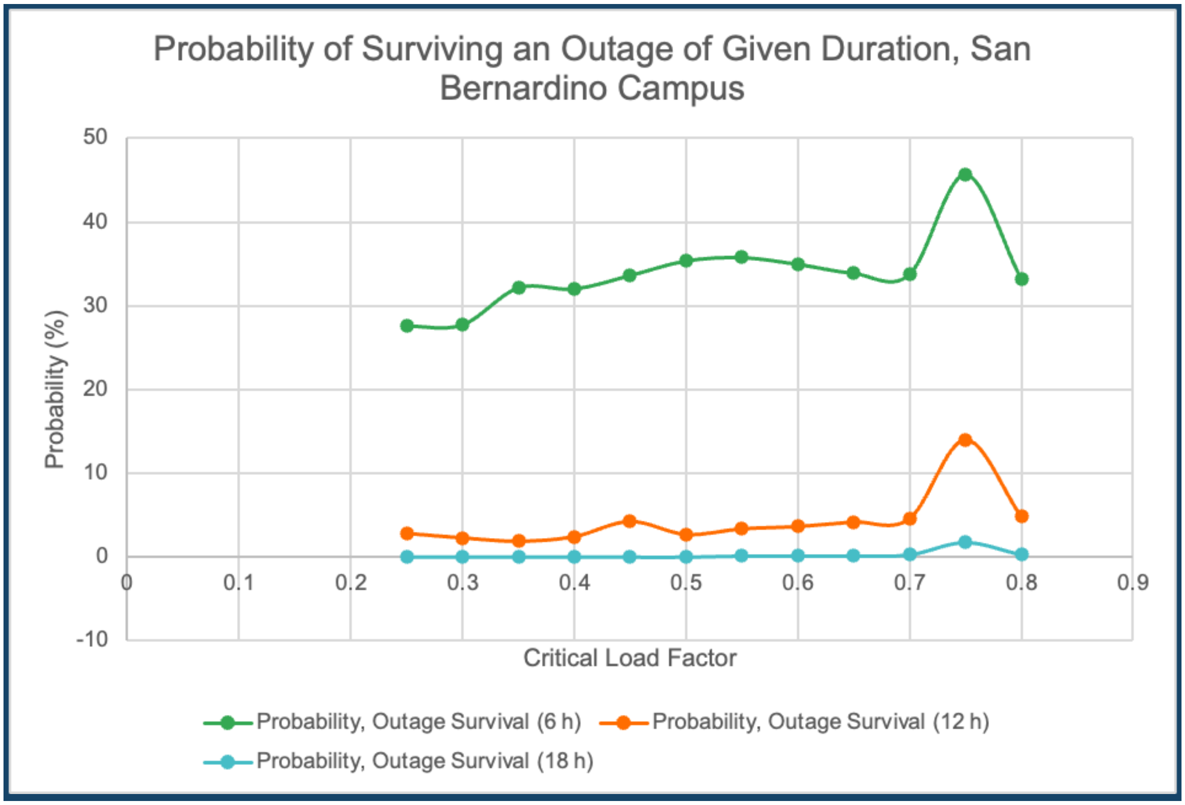
Appendix G: Outage Survival Rate with Increasing Number of Inhabitants– San Bernardino Campus



Appendix H: Optimal Battery Size with Increasing Critical Load Factor– San Bernardino Factor



Appendix I: Probability of Outage Survival Trends with Channing Critical Load Factor



Appendix K: San Bernardino Scenario 1

Number of Buildings	Number Mid-rise Apartment	Hospital Buildings, Annual Consumption	Apartments, Annual Consumption (kWh)	Annual Total (kWh)	Fraction Hospital Buildings	Fraction Residential	Number of Inhabitants:	Critical Load Percentage	Potential Life Cycle savings, San Bernardino ($)	PV solar installation size (kW)	Battery Size (kWh)	Probability, Outage Survival (6h) %	Probability, Outage Survival (12h) %	Probability, Outage Survival (18h) %	Lifecycle Reductions in Cost of Climate Emissions (cost compared to BAU)	Lifecycle Reductions in Cost of Health Emissions (cost compared to BAU)	Total Upfront Capital Cost Before Incentives, San Bernardino ($)
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	0.50	-480825.00	3379.80	35564.00	34.95	2.55	0.00	3172195.00	1010031.00	22060734.00
6.00	70.00	46516902.00	17361960.00	63878862.00	72.82	27.18	5775.00	0.50	-104817.00	3379.80	34281.00	34.81	3.09	0.00	3152260.00	989637.00	21477400.00
6.00	65.00	46516902.00	16121820.00	62638722.00	74.26	25.74	5363.00	0.50	270825.00	3379.80	33864.00	33.20	2.42	0.00	3132262.00	969181.00	20894405.00
6.00	60.00	46516902.00	14881680.00	61398582.00	75.76	24.24	4950.00	0.50	646249.00	3379.80	31714.00	32.66	2.28	0.00	3112200.00	948685.00	20311290.00
6.00	55.00	46516902.00	13641540.00	60158442.00	77.32	22.68	4538.00	0.50	1021879.00	3379.80	30431.00	31.99	2.96	0.00	3092096.00	928153.00	19728295.00
6.00	50.00	46516902.00	12401400.00	58918302.00	78.95	21.05	4125.00	0.50	1397231.00	3379.80	29147.00	31.32	2.96	0.00	3072058.00	907643.00	19145025.00
6.00	45.00	46516902.00	11161260.00	57678162.00	80.65	19.35	3713.00	0.50	1772141.00	3379.80	27863.00	29.97	2.28	0.00	3052141.00	887270.00	18561760.00
6.00	40.00	46516902.00	9921120.00	56438022.00	82.42	17.58	3300.00	0.50	2146890.00	3379.80	26580.00	29.44	2.15	0.00	3032232.00	866920.00	17978782.00
6.00	35.00	46516902.00	8680980.00	55197882.00	84.27	15.73	2888.00	0.50	2521651.00	3379.80	25297.00	29.44	2.69	0.00	3012317.00	847023.00	17395776.00
6.00	30.00	46516902.00	7440840.00	53957742.00	86.21	13.79	2475.00	0.50	2896568.00	3379.80	24013.00	28.36	2.55	0.00	2992352.00	826205.00	16812482.00
6.00	25.00	46516902.00	6200700.00	52717602.00	88.24	11.76	2063.00	0.50	3271434.00	3379.80	22730.00	26.08	1.88	0.00	2972335.00	805803.00	16229260.00
6.00	20.00	46516902.00	4960560.00	51477462.00	90.36	9.64	1650.00	0.50	3646058.00	3379.80	21447.00	23.79	1.88	0.00	2952344.00	785393.00	15646471.00
6.00	10.00	46516902.00	2480280.00	48997182.00	94.94	5.06	825.00	0.50	4395539.00	3379.80	18879.00	19.49	0.40	0.00	2912326.00	744498.00	14479941.00

Appendix L: San Bernardino Scenario 2

Number of Buildings	Number of Mid-rise Apartments	Hospital Buildings, Annual Consumption	Apartments, Annual Consumption (kWh)	Annual Total (kWh)	Fraction Hospital Buildings	Fraction Residential	Number of Inhabitants:	Critical Load Percentage	Potential Life Cycle savings, San Bernardino ($)	PV solar installation size (kW)	Battery Size (kWh)	Probability, Outage Survival (6 h)	Probability, Outage Survival (12 h)	Probability, Outage Survival (18 h)	Lifecycle Reductions in Cost of Climate Emissions (cost compared to business-as-usual scenario)	Lifecycle Reductions in Cost of Health Emissions (cost compared to business-as-usual scenario)	Total Upfront Capital Cost Before Incentives, San Bernardino ($)
6	75	46516902	18602100	65119002	71.43	28.57	6188	0.8	-10,707,982.00	3380	70,705	33.2	4.84	0.27	3,583,123.00	1,426,726.00	37,424,363.00
6	75	46516902	18602100	65119002	71.43	28.57	6188	0.75	-8,988,279.00	3380	64,848	45.7	13.98	1.75	3,520,940.00	1,363,727.00	34,863,588.00
6	75	46516902	18602100	65119002	71.43	28.57	6188	0.7	-7,272,276.00	3380	58,990	33.74	4.57	0.27	3,455,200.00	1,297,471.00	32,302,812.00
6	75	46516902	18602100	65119002	71.43	28.57	6188	0.65	-5,559,928.00	3380	53,133	33.87	4.17	0.13	3,386,041.00	1,227,416.00	29,742,036.00
6	75	46516902	18602100	65119002	71.43	28.57	6188	0.6	-3,850,343.00	3380	47,276	34.95	3.63	0.1	3,315,917.00	1,155,089.00	27,181,260.00
6	75	46516902	18602100	65119002	71.43	28.57	6188	0.55	-2,144,911.00	3380	41,418	35.75	3.36	0.13	3,246,985.00	1,083,564.00	24,620,485.00
6	75	46516902	18602100	65119002	71.43	28.57	6188	0.5	-440,084.00	3380	35,561	35.35	2.69	0	3,178,740.00	1,012,130.00	22,059,709.00
6	75	46516902	18602100	65119002	71.43	28.57	6188	0.45	1,258,530.00	3380	29,704	33.6	4.24	0	3,109,718.00	939,640.00	19,498,933.00
6	75	46516902	18602100	65119002	71.43	28.57	6188	0.4	2,950,913.00	3380	23,846	31.99	2.42	0	3,040,358.00	867,035.00	16,938,158.00
6	75	46516902	18602100	65119002	71.43	28.57	6188	0.35	4,579,152.00	3380	18,045	32.12	1.88	0	2,993,390.00	810,783.00	14,399,354.00
6	75	46516902	18602100	65119002	71.43	28.57	6188	0.3	6,055,348.00	3380	12,743	27.69	2.28	0	2,936,994.00	746,292.00	12,053,725.00
6	75	69775353	18602100	88377453	78.95	21.05	6188	0.25	6,896,706.00	3380	9,931	27.55	2.82	0	2,868,706.00	677,715.00	10,674,692.00

Appendix M: San Bernardino Scenario 3

Number of Buildings	Number of Mid-rise Apartments	Hospital Buildings, Annual Consumption	Apartments, Annual Consumption (kWh)	Annual Total (kWh)	Fraction Hospital Buildings	Fraction Residential	Number of Inhabitants:	Critical Load Percentage	Potential Life Cycle savings, San Bernardino ($)	PV solar installation size (kW)	Battery Size (kWh)	Probability, Outage Survival (6 h)	Probability, Outage Survival (12 h)	Probability, Outage Survival (18 h)	Lifecycle Reductions in Cost of Climate Emissions (cost compared to business-as-usual scenario)	Lifecycle Reductions in Cost of Health Emissions (cost compared to business-as-usual scenario)	Total Upfront Capital Cost Before Incentives, San Bernardino ($)
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	-9704101.00	1500.00	48361.00	32.80	4.84	0.40	1800525.00	850992.00	24033180.00
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	-4769377.00	2500.00	41552.00	33.47	4.30	0.27	2532132.00	936369.00	22983461.00
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	148844.00	3500.00	34744.00	34.68	2.55	0.00	3266996.00	1022174.00	21933743.00
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	5000900.00	4500.00	27939.00	32.66	2.02	0.00	4015296.00	1116410.00	20885629.00
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	9639277.00	5500.00	21458.00	27.96	2.28	0.00	4793800.00	1229172.00	19962746.00
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	12954388.00	6500.00	20114.00	27.69	2.69	0.00	5540999.00	1327209.00	21033496.00
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	16106680.00	7500.00	19412.00	28.09	2.69	0.00	6283629.00	1423275.00	22353085.00
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	19231587.00	8500.00	18805.00	27.55	2.28	0.00	7024287.00	1518944.00	23709439.00
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	22343380.00	9500.00	18198.00	27.02	2.69	0.00	7761141.00	1612302.00	25065793.00
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	25442116.00	10500.00	17590.00	27.28	2.96	0.00	8492563.00	1703436.00	26422146.00
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	28433263.00	11500.00	17353.00	27.02	2.69	0.00	9217051.00	1792264.00	27921949.00
6.00	75.00	69775353.00	18602100.00	88377453.00	78.95	21.05	6188.00	50.00	31367840.00	12500.00	17194.00	27.96	3.23	0.00	9933951.00	1879655.00	29452579.00
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	34205369.00	13500.00	17036.00	28.09	3.23	0.00	10631994.00	1963607.00	30983208.00
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	36896191.00	14500.00	16878.00	28.23	3.36	0.00	11302569.00	2044335.00	32513838.00
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	39302177.00	15500.00	16720.00	29.30	3.76	0.00	11920183.00	2116002.00	34044468.00
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	41410528.00	16500.00	16562.00	29.44	3.76	0.00	12484680.00	2182806.00	35575098.00
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	43176233.00	17500.00	16404.00	29.57	3.76	0.00	12986219.00	2238731.00	37105727.00
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	44572443.00	18500.00	17528.00	31.18	3.90	0.00	13495929.00	2305747.00	39134092.00
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	45740326.00	19500.00	19758.00	34.27	4.17	0.00	14038452.00	2384189.00	41591152.00
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	46720811.00	20500.00	23488.00	52.82	15.73	3.36	14727724.00	2533148.00	44988865.00

6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	47632047.00	21500.00	28047.00	76.21	38.71	15.19	15492624.00	2714862.00	48865883.00
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	48488698.00	22500.00	32457.00	83.60	50.00	25.27	16215521.00	2871905.00	52622205.00
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	50371954.00	25000.00	43715.00	94.62	75.67	56.85	17936376.00	3202528.00	62071633.00
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	51626994.00	27000.00	52454.00	97.04	87.01	74.87	19194812.00	3403793.00	69447464.00
6.00	75.00	46516902.00	18602100.00	65119002.00	71.43	28.57	6188.00	50.00	53121887.00	30000.00	65387.00	98.92	93.15	89.65	20967647.00	3628715.00	80444296.00

Appendix N: Redlands Scenario 1

No, School Build.	No Mid-rise apartment	School Buildings, Annual Consumption	Apartments, Annual Consumption (kWh)	Annual Total (kWh)	Fraction School Buildings	Fraction Residential	No of Inhabitants	Critical Load %	Potential Life Cycle savings, Redlands ($)	PV solar installation size (kW)	Battery Size (kWh)	Probability, Outage Survival(6 h) (%)	Probability, Outage Survival (12 h) (%)	Probability, Outage Survival (18 h) (%)	Lifecycle Reductions in Cost of Climate Emissions (cost compared to BAU)	Lifecycle Reductions in Cost of Health Emissions (cost compared to BAU)	Total Upfront Capital Cost Before Incentives, Redlands ($)
40	75	103375200	18602100	121977300	84.75	15.25	6187.5	0.5	26,780,513.00	11304	21952	16.94	6.05	0.54	9,182,232.00	2,496,238.00	29,849,303.00
40	70	103375200	17361960	120737160	85.62	14.38	5775	0.5	26,974,799.00	11304	21287	16.8	6.05	0.54	9,158,624.00	2,468,154.00	29,506,207.00
40	65	103375200	16121820	119497020	86.51	13.49	5362.5	0.5	27,169,130.00	11304	20621	16.13	5.38	0.4	9,134,872.00	2,440,018.00	29,162,678.00
40	60	103375200	14881680	118256880	87.42	12.58	4950	0.5	27,363,174.00	11304	19955	16.13	5.91	0.4	9,111,046.00	2,411,834.00	28,818,855.00
40	55	103375200	13641540	117016740	88.34	11.66	4537.5	0.5	27,555,773.00	11304	19292	15.99	5.91	0.4	9,087,497.00	2,383,796.00	28,477,059.00
40	50	103375200	12401400	115776600	89.29	10.71	4125	0.5	27,747,563.00	11304	18626	15.73	5.78	0.4	9,063,268.00	2,355,466.00	28,133,041.00
40	45	103375200	11161260	114536460	90.26	9.74	3712.5	0.5	27,936,696.00	11304	17959	15.32	5.11	0.4	9,038,683.00	2,327,124.00	27,789,146.00
40	40	103375200	9921120	113296320	91.24	8.76	3300	0.5	28,121,739.00	11304	17297	15.05	5.11	0.4	9,013,610.00	2,298,895.00	27,447,624.00
40	35	103375200	8680980	112056180	92.25	7.75	2887.5	0.5	28,304,951.00	11304	16632	15.46	5.65	0.4	8,987,875.00	2,270,756.00	27,104,366.00
40	30	103375200	7440840	110816040	93.29	6.71	2475	0.5	28,466,234.00	11304	16028	16.13	6.59	0.4	8,960,692.00	2,242,824.00	26,784,405.00
40	25	103375200	6200700	109575900	94.34	5.66	2062.5	0.5	28,601,732.00	11304	15478	15.32	5.91	0.4	8,931,192.00	2,214,528.00	26,486,076.00
40	20	103375200	4960560	108335760	95.42	4.58	1650	0.5	28,721,782.00	11304	14926	15.19	5.91	0.4	8,898,201.00	2,185,108.00	26,186,667.00
35	55	90453300	13641540	104094840	86.90	13.10	4537.5	0.5	28,163,708.00	11304	16981	18.55	7.12	1.34	9,002,761.00	2,294,233.00	27,322,455.00
30	55	77531400	13641540	91172940	85.04	14.96	4537.5	0.5	28,432,512.00	11304	15174	16.67	5.24	0.4	8,873,795.00	2,197,249.00	26,364,042.00
25	55	64609500	13641540	78251040	82.57	17.43	4537.5	0.5	28,354,588.00	11304	13365	18.28	5.11	0.4	8,676,068.00	2,088,862.00	25,405,066.00
20	55	51687600	13641540	65329140	79.12	20.88	4537.5	0.5	27,959,102.00	11304	11558	22.98	6.05	0.54	8,416,906.00	1,973,512.00	24,446,405.00
35	45	90453300	11161260	101614560	89.02	10.98	3712.5	0.5	28,431,469.00	11304	15877	15.86	5.65	0.4	8,942,471.00	2,236,791.00	26,723,853.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	28,548,026.00	11304	14069	16.13	5.78	0.4	8,783,112.00	2,134,141.00	25,764,974.00
25	45	64609500	11161260	75770760	85.27	14.73	3712.5	0.5	28,338,194.00	11304	12262	18.28	5.65	0.4	8,559,714.00	2,022,739.00	24,806,635.00
20	45	51687600	11161260	62848860	82.24	17.76	3712.5	0.5	27,815,140.00	11304	10454	22.45	5.91	0.54	8,277,151.00	1,905,130.00	23,847,867.00

Appendix O: Redlands Scenario 2

Num, School Build.	Num Mid-rise apartment	School Buildings, Annual Consumption	Apartments, Annual Consumption (kWh)	Annual Total (kWh)	Fraction School Buildings	Fraction Residential	Number of Inhabitants	Critical Load %	Potential Life Cycle savings, Redlands ($)	PV solar installation size (kW)	Battery Size (kWh)	Probability, Outage Survival (6 h)	Probability, Outage Survival (12 h)	Probability, Outage Survival (18 h)	Lifecycle Reductions in Cost of Climate Emissions (cost compared to business-as-usual scenario)	Lifecycle Reductions in Cost of Health Emissions (cost compared to business-as-usual scenario)	Total Upfront Capital Cost Before Incentives, Redlands ($)
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.8	25,666,807.00	11304	25301	19.49	5.91	0.13	9,221,697.00	2,577,749.00	31,509,316.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.75	26,244,999.00	11304	23296	18.55	5.78	0.27	9,163,198.00	2,507,741.00	30,500,393.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.7	26,797,902.00	11304	21291	17.61	5.11	0.4	9,097,969.00	2,435,021.00	29,491,470.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.65	27,320,117.00	11304	19287	16.67	5.11	0.4	9,025,698.00	2,360,128.00	28,482,548.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.6	27,802,116.00	11304	17282	17.07	5.65	0.4	8,945,581.00	2,283,624.00	27,473,625.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.55	28,186,691.00	11304	15651	16.26	5.11	0.4	8,865,337.00	2,208,894.00	26,609,721.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	28,548,026.00	11304	14069	16.13	5.78	0.4	8,783,112.00	2,134,141.00	25,764,974.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.45	28,891,691.00	11304	12487	15.99	5.11	0.27	8,697,187.00	2,058,617.00	24,920,226.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.4	29,219,131.00	11304	10905	17.74	5.24	0.4	8,608,104.00	1,982,554.00	24,075,478.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.35	29,529,116.00	11304	9324	18.28	5.11	0.4	8,515,526.00	1,905,894.00	23,230,731.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.3	29,822,637.00	11304	7742	20.3	5.24	0.54	8,419,764.00	1,828,752.00	22,385,983.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.25	30,102,516.00	11304	6160	22.58	5.91	0.54	8,321,450.00	1,751,117.00	21,541,235.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.2	30,359,687.00	11304	4657	23.52	6.05	0.54	8,222,415.00	1,673,393.00	20,726,825.00

Appendix P: Redlands Scenario 3

Num, School Build.	Num Mid-rise apartment	School Buildings, Annual Consumption	Apartments, Annual Consumption (kWh)	Annual Total (kWh)	Fraction School Buildings	Fraction Residential	Number of Inhabitants	Critical Load Percentage	Potential Life Cycle savings, Redlands ($)	PV solar installation size (kW)	Battery Size (kWh)	Probability, Outage Survival (6 h)	Probability, Outage Survival (12 h)	Probability, Outage Survival (18 h)	Lifecycle Reductions in Cost of Climate Emissions (cost compared to business-as-usual scenario)	Lifecycle Reductions in Cost of Health Emissions (cost compared to business-as-usual scenario)	Total Upfront Capital Cost Before Incentives, Redlands ($)
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	79,406,181.00	45000	67712	97.04	85.22	74.6	28329448	6159818	105,923,190.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	75,850,794.00	40000	46927	73.12	48.12	32.66	25225906	5527240	87,750,328.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	71,279,469.00	35000	28427	54.84	31.85	14.65	22024461	4769989	70,610,197.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	65,335,248.00	30000	14129	29.57	7.12	0.81	18839170	3878293	55,552,380.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	57,102,364.00	25000	11950	22.85	5.78	0.4	16330648	3440433	46,746,966.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	47,399,668.00	20000	12724	22.98	5.78	0.4	13714064	2986836	39,087,068.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	45,399,715.00	19000	12878	22.18	5.65	0.4	13179183	2893267	37,555,088.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	43,379,688.00	18000	13033	21.37	5.65	0.4	12639814	2798668	36,023,109.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	41,343,333.00	17000	13188	20.83	5.65	0.4	12097283	2703650	34,491,129.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	39,265,634.00	16000	13342	20.83	5.65	0.4	11546977	2608088	32,959,150.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	37,132,413.00	15000	13497	19.89	5.65	0.4	10986920	2510665	31,427,170.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	34,936,809.00	14000	13652	19.09	5.65	0.4	10414352	2411357	29,895,190.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	32,654,627.00	13000	13806	17.07	5.51	0.27	9825803	2310059	28,363,211.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	30,278,435.00	12000	13961	16.13	5.51	0.27	9220063	2207686	26,831,231.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	29,041,504.00	11500	14038	16.13	5.51	0.27	8907397	2155107	26,065,242.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	28,548,026.00	11304	14069	16.13	5.78	0.4	8783112	2134141	25,764,974.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	27,770,572.00	11000	14116	16.4	5.78	0.4	8588190	2101601	25,299,252.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	25,086,596.00	10000	14271	16.53	5.78	0.4	7921900	1990919	23,767,272.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	22,129,363.00	9000	14653	16.26	5.91	0.4	7211510	1871522	22,323,743.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	19,044,440.00	8000	15253	16.4	5.91	0.4	6485953	1751165	20,964,353.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	15,942,668.00	7000	15852	17.2	6.05	0.13	5755570	1629020	19,604,962.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	12,797,243.00	6000	16547	18.15	5.24	0	5018827	1503798	18,282,548.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	9,461,902.00	5000	17963	20.03	4.57	0	4277677	1377562	17,240,051.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	5,727,969.00	4000	20908	23.79	4.03	0	3528267	1248682	16,790,618.00
30	45	77531400	11161260	88692660	87.42	12.58	3712.5	0.5	979,787.00	3000	27416	29.3	4.84	0	2777518	1120699	17,723,608.00