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Microgrids as a Resiliency Measure to California Wildfires

by

Brendan Michael Cooke

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Abstract

As a result of the rapid increase in wildfire activity within the state of California, and the interaction between these fires and electrical infrastructure, the state is experiencing a lack of electrical reliability. This project offers an end-to-end review of the key factors impacting the integration of resilient residential microgrids to mitigate this loss of reliability. An in-depth review of wildfire trends, microgrid and DER technology, and their economic and environmental impacts was conducted to understand the interaction between these factors and electrical reliability. Several community scenarios were modelled using NREL's REopt Lite software to determine the specific impacts of microgrid integration in Napa County. Findings suggest that Napa presents an ideal location for microgrid investments, and projects have the potential to provide reliable revenue streams for investors depending on how operations are modelled.

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List of Abbreviations

BES – Battery Energy System

BTM – Behind the Meter

CAISO – California Independent System Operator

Cal Fire – California Department of Forestry and Fire Protection

CE – Common Era

CEC – California Energy Commission

CERTS – Consortium for Electric Reliability Technology Solutions

CO_2 – Carbon Dioxide

CPUC – California Public Utilities Commission

DC – Direct Current

DGEMS – Distributed Generation Enabled Microgrid Services

DOE – Department of Energy

DER – Distributed Energy Resource

EV – Electric Vehicle

GHG – Greenhouse Gas

Grid – Main electrical grid or macrogrid

GW – Gigawatt

III – Insurance Information Institute

IOU – Investor-Owned Utility

IRR – Internal Rate of Return

kW – Kilowatt

kWh – Kilowatt-hour

LCOE – Levelized Cost of Electricity

Li-ion – Lithium-Ion

MW – Megawatt

MWh – Megawatt-hour

NEM – Net Energy Metering

NG – Natural Gas

NPV – Net Present Value

NREL – National Renewable Energy Laboratory

NSC – Net Surplus Compensation Rate

O&M – Operations and Maintenance

PG&E – Pacific Gas and Electric Company

PHS – Pumped Hydro Storage

PPA – Power Purchase Agreement

PSPS – Public Safety Power Shutoff

PURPA – Public Utilities Regulatory Policy Act

PV – Photovoltaic

REopt – Renewable Energy Integration and Optimization software

TOU – Time of Use

USD – United States Dollars

W – Watt

WHO – World Health Organization

Chapter 1: Introduction

In recent years, the increasing rate of wildfire activity in the state of California has become a great concern, not only due to the physical devastation caused, but also due to the impact on the reliability of the California electrical grid.

Since the 1970s, annual wildfires in California have increased by 500%, and summer season fires have increased by nearly 800%, with some of the largest and most devastating fires on record occurring in the past few years alone (Williams, et al., 2019). Increasingly, high voltage transmission lines and electrical equipment have been found to have contributed to, or been solely responsible for, a number of these fires. The Pacific Gas and Electric Company (PG&E), one of the state’s primary electrical providers, has recently disclosed its involvement in over 1,500 fires since 2014 (Gold, Blunt, & Smith, 2019). While the majority of these were extinguished quickly and did not cause lasting damage, several of the largest fires in state history, including the Camp fire, have been linked to electrical equipment failures.

The increase in at-fault fires, and the related liability payments, have put utility companies on high alert. As a result, the state of California is seeing unprecedented blackouts while utilities are proactively shutting down their equipment during periods of high temperatures and high winds. These blackouts are known as Public Safety Power Shutoffs (PSPS) events. The result of increased PSPS events has been devastating to the reliability of the electrical supply throughout the state. During one of the worst periods, October 2019, over 1.8M residential customers, or an estimated 5.3M individuals, were without power, some for durations over five days (California Public Utility Commission [CPUC], 2020c) (United States Census Bureau, 2019). The average California citizen now experiences 7 blackouts per year, nearly double the national average (Hay, 2019).

The use of microgrid technology offers the ability for a community to break its connection to the grid and operate as a self-sustaining island in the event of a power outage or PSPS shutdown of the grid. Through the utilization of solar photovoltaic (PV) and battery storage, a residential community connected through a microgrid can support critical building functions, and keep key infrastructure energized. By doing so, the community can avoid negative impacts to safety, health, and community economics, which can otherwise result from a prolonged outage. In addition to local benefits, microgrid technology is proven to be a viable means of adding redundancy to the main grid, and thus increasing the resiliency of the electrical system.

Due to the increasing risk of wildfires throughout the state and the resulting degradation of grid reliability, along with access to the technology and capital needed to complete energy infrastructure projects, California represents an excellent region to act as a pilot for the use of residential microgrids. This is however not to say that issues of grid resiliency are specific to California. It is believed that natural disasters, many linked to climate change, will continue to increase in frequency in the coming years. Recently we have seen devastating hurricanes in the tropics, and unprecedented wildfires throughout Australia (BBC, 2020; Geophysical Fluid Dynamics Laboratory, 2020). All of these disasters bring with them a risk of damage to electrical infrastructure. While this research focuses on California, findings can be applied to many other locations around the world.

1.1. Purpose of Research

This research project seeks to answer the important question of “what are the key supporting and limiting factors when developing a resilient residential microgrid system in new California communities?” Through a review of pertinent literature, and the modelling of several microgrid systems using National Renewable Energy Laboratory’s (NREL) REopt Lite Software (NREL, n.d.), this research presents an end-to-end investigation into the myriad elements influencing fire-related grid reliability issues, and the ability for solar plus storage microgrids to alleviate them. The research addresses a range of topics including global and regional wildfire trends and their impacts on electrical reliability, an overview of microgrid research from its origins to modern applications, recent trends in the cost and deployment of solar PV and power storage technologies, details on the current California regulatory environment as it pertains to microgrid projects, and finally culminates in the economic and environmental analysis of several modelled microgrid scenarios.

While research is widely available on the economic, and environmental benefits of distributed energy resources (DER) and microgrid technology, most of this research focuses on utility-scale or commercial operations. Little information is available on residential specific microgrids. Moreover, there is a lack of information related to the trade-offs required in decision making when implementing a microgrid system. The information in this research project is intended to serve as a guiding document to better understand what the costs and benefits of a residential microgrid system may be, and how political and environmental factors may impact the success of a project.

1.2. Pillars of Sustainability

This research project is interdisciplinary in nature and focuses on 3 main pillars of sustainability; energy, environment, and economics.

Energy is the primary motivation of this research and impacts nearly every other factor studied. The main goal of the microgrid systems discussed throughout this research project is to positively impact the energy resiliency of residential communities. The progression of energy systems is studied through a literature review of past and present trends in microgrid technology, DERs, and energy storage systems. This review focuses on the rates of deployment, changes to costs, and rates of technological advancement in each sector, along with the resiliency of each technology. Finally, energy needs and outputs are calculated for each of the modelled microgrid systems to enable economic and environmental impact calculations.

The second pillar, environment, is touched on throughout the project. Research for this project began by looking to understand wildfire trends both within California and globally, and how the impacts of climate change on temperature, precipitation, and vegetation aridity impact them. These environmental factors are assessed in terms of their impact on the future fire risk within California, and their influence on the PSPS events which resulted in loss of power throughout the state. Environmental impacts of potential microgrid systems are also analyzed based on GHG emissions. This is completed by using the annual power production of each microgrid system, and emission factors for the California grid, to calculate the avoided emissions potential of switching from grid power to a solar plus storage microgrid.

The final pillar, economics, is also interwoven throughout this research project. Firstly, the annual costs of wildfire damage, and of PSPS events are reviewed for later comparison to the cost of microgrid implementation. Price trends across solar PV and energy storage systems are also investigated to provide a baseline of comparison for later modelled systems, as well as to understand how future research and development may impact the capital required for microgrid projects in the years to come. Finally, modelled systems are evaluated in terms of returns on investment, payback periods, and the ability to generate revenue to determine the economic attractiveness of a microgrid investment.

1.3. Key Definitions

Resiliency

Resiliency, as it pertains to energy infrastructure, is defined as “the capacity of an energy system to tolerate disturbance and to continue to deliver affordable energy services to consumers. A resilient energy system can speedily recover from shocks and can provide alternative means of satisfying energy service needs in the event of changed external circumstances” (Chaudry, et al., 2011, p. iv). Based on this definition it can be easily concluded that the current electrical grid in California does not meet the definition of resilient infrastructure. Microgrid infrastructure on the other hand, is shown to meet this definition in emergency situations such as during the 2011 tsunami in Japan. During this disaster, the Sendai Microgrid was able to supply Tohuku Fukushi University with power during a two-day blackout period (Berkeley Labs, 2020).

Microgrid

Several types of microgrids exist, however for the purposes of this research project “microgrid” refers to the technology type known as a “true microgrid”. This means it is a self-governed, self-sustaining system, completely downstream of a connection point to the main electrical grid. This allows for communication with the grid just as any other customer would have, but also allows for the connection to be broken in the case of an emergency, allowing the microgrid to function as an island. This also fits within the U.S. DOE MEG's microgrid definition, "*A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode.*" (Berkeley Labs, n.d.)

Distributed Energy Resource

"Distributed energy resources (DER) are small or medium-sized power sources that are mainly connected to the lower voltage levels of the system (distribution grid), near the end users" (IRENA, 2019b, p. 23). The DERs focused on throughout this research project utilize renewable resources, specifically solar PV. However, may other DER technologies exist which utilize fossil fuels such as diesel generators, micro natural gas turbines, or simple combustion engines.

Chapter 2: Changes in Global Forest Fire Trends

Wildfires play an important role in regulating the long-term health and development of natural ecosystems. Fires remove old growth, allowing shade sensitive plants and organisms to thrive, they also contribute to natural carbon and chemical cycles, and can eliminate invasive pests from a devastated region (Pausas & Keeley, 2019). Although important to ecosystem health, wildfires can also cause massive devastation in the short-term to both natural and constructed environments. The devastation caused by wildfires to man-made environments includes the destruction of built structures, impacts to agriculture and forestry industries, disruption of transportation routes, and most important to this project the interruption of electrical and utility services.

As the next section reveals, global warming is having a massive impact on the changing trends of wildfire around the world. The impact forest fires have on the environment is also changing from a local phenomenon to a global concern as well. Guido van der Werf, a researcher working on the Global Fire Emissions Database, estimates the average annual emissions from forest fires between 1997 and 2016 to be roughly 2.2 billion tonnes of greenhouse gases (GHG) (van der Werf, et al., 2017). These emissions can have a serious impact on climate change. The loss of forest also results in a decrease in the available carbon sinks globally, further exacerbating the issue.

2.1 Primary Drivers of Change

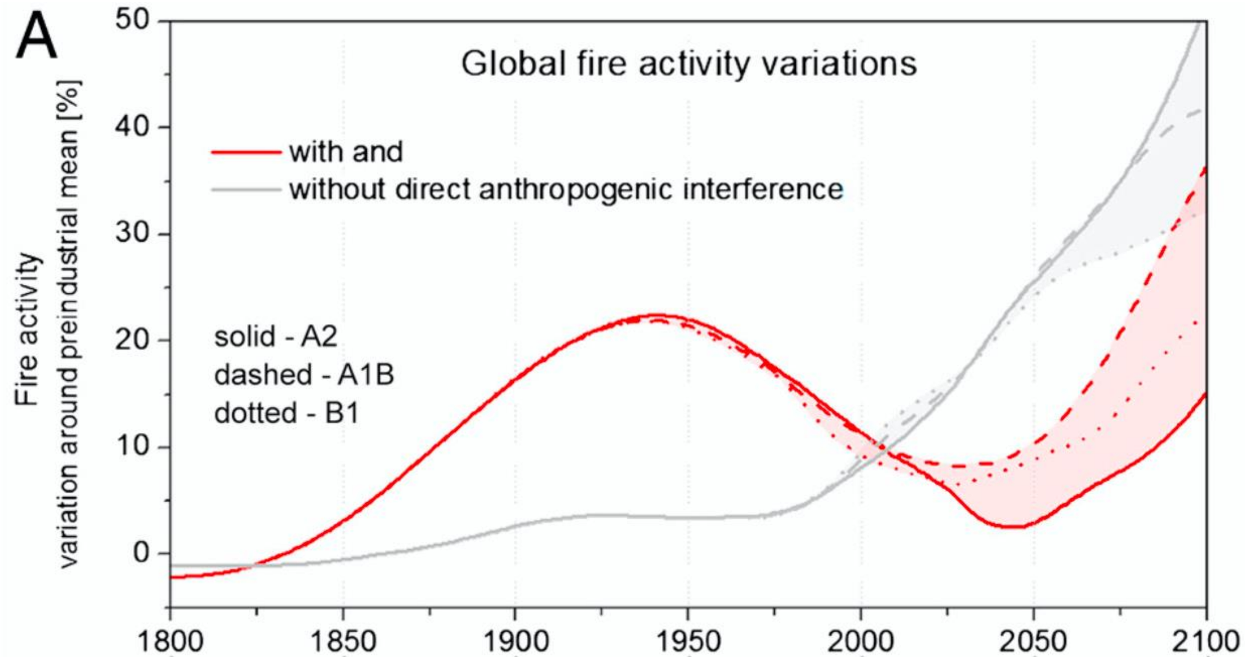
The primary drivers of wildfires can be summarized by three key factors, climate, vegetation density, and anthropogenic impacts. A study conducted by NASA in collaboration with Columbia University shows that each of these factors has played a key role in global fire activity throughout history, and maps global trends from 844 common era (CE) to present day, as well as predicts trends out to 2100 CE based on granular data points within the 3 main factors (Pechony & Shindell, 2010).

Climate-related impacts, which include temperature, precipitation, and relative humidity, affect fire activity primarily by reducing available moisture resulting in drying of biomass and thus increasing flammability. Throughout history the main climate-related driver of wildfires has shifted from precipitation to temperature (Pechony & Shindell, 2010). In the preindustrial era, pre 1700CE, precipitation was the main factor impacting global fire trends, and influenced approximately 70% of worldwide fire activity according to the NASA/Columbia study. This is shown by examining regions where temperature drops along with increased precipitation resulted in reduced fire activity, compared with regions in the same timeframe where similar drops in temperature along with decreases in precipitation resulted in increased fire. For much of history this was the case; however, in the current post-industrial era, climate change, and the large global temperature changes that accompany it, are beginning to overtake the impacts of precipitation leading temperature to be the primary driving factor. Historically, temperature variations were held far below the increases we are seeing present day, and so the resulting impact was overshadowed by changes in precipitation and humidity. As increases in temperature reach critical levels however, the exponential impact of temperature on fire activity is now overwhelming the impact of precipitation and becoming the dominant driver. If global temperature continues to rise in alignment with climate models these temperature increases could result in a corresponding exponential growth in global fire activity by 2050.

The regional change in fire activity will not be the same across the globe however. This is primarily due to an unequal distribution of precipitation across different regions. As global temperatures increase, global precipitation is expected to increase as well, however existing disparities in rainfall between regions are also expected to grow. This is consistent with the findings in most climate change research, showing that already arid regions will likely see more droughts and prolonged dry periods, while tropical and wet climates are expected to see greater rainfall during monsoon seasons, and increased storm activity (Meehl, et al., 2007).

Next to climate-related factors, anthropogenic factors have played the second largest role in affecting global fire activity (Pechony & Shindell, 2010). The impact of anthropogenic factors was seen most prominently in the industrial era (1700CE-1900s) where rapid population growth corresponded with an increase in global fire activity, followed by a large drop off around 1950CE (see Figure 1). This exponential increase and subsequent decrease are well understood to be the product of human influence. In the late 1700s early climate change as a result of increased fossil fuel use, along with increased industrial activity resulting in greater human-related ignitions, are thought to be the primary factors driving the increase in global fire activity. However, in the mid-1950s rapid development in human fire suppression efforts and the development of new technology to combat fires result in a steep decline in global fire activity. Fire suppression efforts have steadily reduced fire activity to date, but as we move into the 21st century, the exponential impacts of rising temperatures are expected to overwhelm human efforts, much like they did with precipitation changes.

Figure 1: Global Fire Activity Variations



Source: (Pechony & Shindell, 2010)

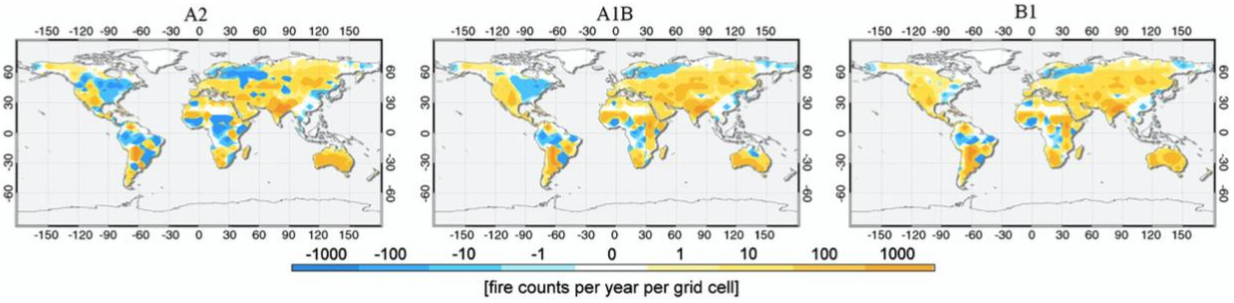
Finally, vegetation density is directly correlated to fire activity; as density increases, so does fire activity due to the increased availability of biomass (Pechony & Shindell, 2010). During the preindustrial era, regional vegetation density was predominantly a result of natural forces. However, corresponding to the exponential growth in the human population from ~1700CE to present day, we have seen a similarly exponential decrease in global vegetation density. This is the result of industrial activities and large-scale changes in land use; including clearing of forests for agricultural lands, pulp and paper and lumber industries, clearing of natural vegetation for city development, etc. This reduction in vegetation may be responsible in part for the reduced fire activity during the late 1900s, however its continued decrease is not expected to have a noticeable impact on reducing future activity driven by increased temperatures.

2.2 Current Trends

As mentioned, changes to fire risk are not equally distributed throughout the globe, and high-risk regions tend to be those which have historically had an arid or semi-arid climate. Regions of particular risk can be seen on the map created by Pechony and Shindell in Figure 2. The areas with the highest risk are Australia, the western portion of the United States and Canada including Alaska, Chile and western South America, Russia, India, and areas throughout Africa. It is therefore no surprise that many of these regions have seen increased wildfire activity over the past few decades.

Figure 2: Predicted Changes in Global Fire Activity Over the 21st Century

High Anthropogenic Influence　Moderate Influence　Low Influence



Source: (Pechony and Shindell, 2010)

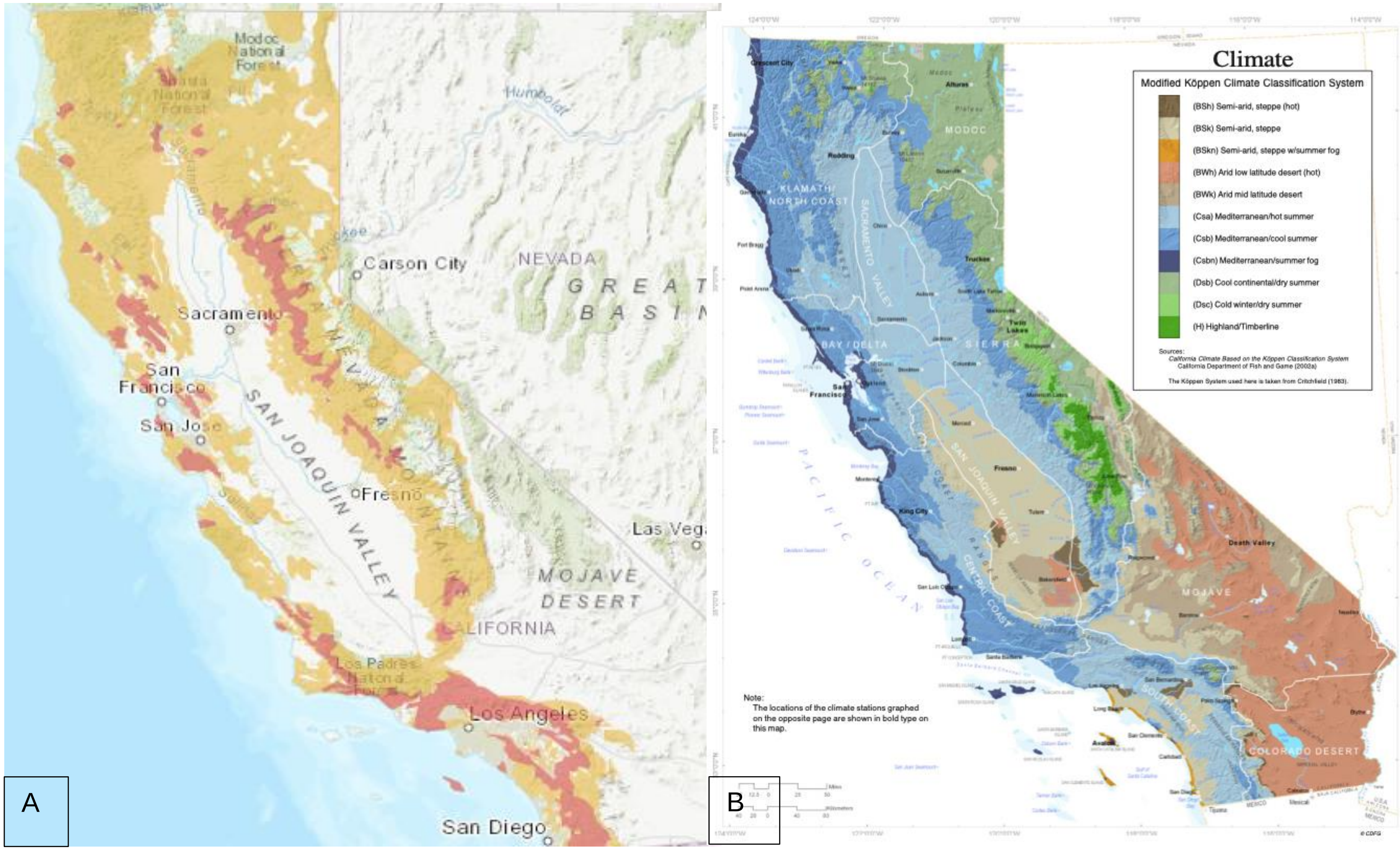
Chapter 3: California Wildfire Activity

3.1 California Climate and Its Impact on Fire Trends

California climate varies considerably based on geography, from the extreme dry heat of Death Valley, the hottest and driest place on earth, to snowy peaks, redwood forests, and subtropical coasts (Kauffman, 2003). In fact, California is a rare example of five different climates occurring within a relatively small geographic region; Cool Interior, Desert, Highland, Mediterranean, and Steppe climates. Understanding the nuances of these different climates is important in understanding how they will be impacted by global warming and how fire activity within them may respond. A study by Keely and Syphard shows that temperature increases do not affect all regions equally (Keeley & Syphard, 2016). Specifically, arid and desert regions of the state are less impacted by temperature increases, as existing high temperatures make the region already fire prone. Whereas cooler forested and more densely vegetated regions are far more impacted by temperature increases which result in the drying of both living and dead fuel sources. The study also finds however, that drought conditions negatively impact fire activity across all areas of the state, once again due to the drying of live and dead fuels. Desert regions are the one exception to this as the sparse vegetation results in a much lower risk of ignition, and a very low risk of fire spreading due to lack of fuel sources.

When looking at the different climate zones presented by Kauffman, it can be inferred that the areas most likely to be impacted by climate change and rising temperatures are the Cool Interior, Highland, and Mediterranean climate zones (Kauffman, 2003). These zones correspond to the Klamath/North Coast, the Bay Area, the South Coast, and the Sierra Nevada, which also correspond to the regions signalled by the California Public Utilities Commission (CPUC) as the areas of greatest fire risk in coming seasons, and the areas with the highest increase in fire activity in recent years (see Figure 3 for comparisons) (CPUC, n.d.a). Considering the primary fire activity drivers laid out by Pechony and Shindell, and by Keeley and Syphard, in conjunction with the fire history and climate in these regions, it is easy to see why California has seen such a rapid

Figure 3: Side-by-Side Comparison of California Wildfire Risk and Climate Zones



Sources: A) California wildfire risks (CPUC, n.d.a), B) California climate zones (Kauffman, 2003) increase in fires over the past several decades (Pechony & Shindell, 2010) (Keeley & Syphard, 2016). Pair this with the myriad global warming models predicting increased temperatures and it is clear California is at high risk for a continued increase in fire activity into the coming decades.

To further exacerbate the problem California is prone to drought conditions, and much of the state is still recovering from the 2011-2017 drought, one of the worst in the state's history. This 6 year period of extreme dry conditions, including several months in 2014 where over 60% of the state was classified as in exceptional drought (the highest classification of drought by the US Drought Monitor), has left many of the state's forests and woodlands with millions of dead trees and severely dried fuel (National Integrated Drought Information System, n.d.).

3.2 Current Trends in California Fire Activity

Since the 1970s, annual wildfires in California have increased by 500%, with some of the largest and most devastating fires occurring between 2017 and 2019 (Williams, et al., 2019). Much of this increase in fire activity is attributed to anthropogenic and climate impacts through global warming. Since the early 1970's the average warm season day saw an increase in temperature of ~1.4°C (Williams, et al., 2019). This is of particular importance to fire activity as the impact of warming during the summer season, the traditional the fire season in California, has a far greater correlation to fire activity, both during the summer and fall months, than increased annual temperature (Keeley & Syphard, 2016). Goss et al. maintains similar findings, showing that the states warmest 5 years on record occurred between 2014 and 2018 (Goss, et al., 2020).

An increase in fire activity should be expected even if the impacts of climate change and the warming of the current California climate are ignored. This is due to the heavy influence of anthropogenic activity and the growing population within the state, including land-use changes, human ignition, and fire suppression efforts (Williams, et al., 2019) (Goss, et al., 2020). The consistent application of fire suppression efforts, while limiting the number and frequency of small wildfires, has resulted in an unnatural build-up of dry fuels in many regions. This build-up can result in large scale, unmanageable fires in areas that would not historically see wildfire activity of this magnitude. That said, Williams, et al. still finds increasing atmospheric aridity, and the resultant drying of fuels, to be the primary driver of increased wildfires between 1972 and 2018 (Williams, et al., 2019).

The findings of Williams, et al. (2019), are consistent with the expected changes in wildfire trends presented in the last chapter. While California wildfire activity has increased exponentially in the past 50 years, the increase in activity has been almost entirely focused in the Sierra Nevada and Northern Coast regions of the state. While other regions saw insignificant increases, these regions alone increased by upwards of 765%, and the percent of fires in forested regions of the state increased from 51% of all fires in the 1970s, to 71% of all fires between 2010-2018 (Schoennagel, et al., 2017; Williams, et al., 2019). Due to the high correlation between warming, atmospheric aridity, and increased fire activity in forested regions, it is expected that the fire regime in the Sierra Nevada, and Northern Coasts will continue to increase in the future if the issue of global climate change is not addressed.

The steady increase in fire activity across the state culminated in the fire seasons of 2017, and 2018, both setting records for the worst wildfire years on record according to the California Department of Forestry and Fire Protection (Cal Fire) (2020b). 2017 set the record for the more destructive season on record and includes the Thomas Fire, the largest individual fire on record at the time (Cal Fire, 2019e). 2018 is now regarded as the most destructive and deadliest wildfire season on record, with several record-breaking blazes, including the Camp Fire, California’s most deadly and destructive fire, and the Mendocino Complex Fire, California’s largest wildfire on record, taking the title from the Thomas Fire the prior year (Cal Fire, 2019c; Cal Fire, 2019d; Cal Fire, 2019e). A national emergency was declared in the summer of 2018 due to the vast fires burning in the northern California forests (Cal Fire, 2020b).

3.3 Increase in Late-Season Fire Activity

In addition to an overall increase in favourable fire conditions, and fire activity, California has seen a surge in late-season fires. Of the most devastating wildfires of the 2017 and 2018 season, the majority are concentrated in the fall and winter months (Cal Fire, 2020b). Goss et al. (2020) offers insights into a variety of factors that may be driving this trend, including early arrival of dry offshore downslope winds, increasing annual and summer warming trends, decrease in autumn precipitation, decreased snowpack, lack of late-season firefighting resources, and factors leading to the buildup of fuel sources, such as increased forest mortality and increased fire suppression efforts (Goss, et al., 2020). Increases in these factors has resulted in a doubling of autumn days with conditions associated with extreme fire risk between 1980 and 2020. Specific to this research, the most important factors in late season fire activity are offshore wind events, warming trends, and decreases in autumn precipitation and snowpack, as they coincide with increased potential of utility ignited fires, as will be discussed in Chapter 4.

As discussed, global warming and warming patterns across the state have contributed to an overall increase in fire activity. However, the timing and distribution of this warming plays a vital role in the occurrence of fall wildfires. Goss et al. finds that autumn temperatures are trending upwards at an average of 0.3°C per decade, and precipitation through the autumn season is trending downwards at approximately 12mm/decade further increasing the risk of fall wildfire activity (Goss, et al., 2020). This late season warming and delay of annual precipitation into the winter months, has led to an unprecedented abundancy of dry fuel sources after the traditional fire season has ended. The decline in snowpack caused by the now common summer heatwaves further exasperates the issue and increases the risk of high fuel aridity.

As mentioned, strong dry winds play a major role in late-season wildfire risk as well, as they further contribute to the drying of living vegetation, and provide excellent conditions for the rapid spread of wildfires once ignited. The Diablo winds, a weather event impacting northern California, results in highspeed downslope winds driving hot, dry air from the Great Basin over the Bay area (Bowers, 2018). These winds can occur year-round, however, when they occur in autumn months, and thus coincide with the lowest moisture contents in live vegetation, they can present a massive increase in fire risk. The Santa Ana winds which behave in much the same manner as the Diablo winds, downslope offshore winds originating over inland mountain ranges, produce the same strong, hot, dry, winds over the southern portion of the state (Jin, et al., 2014). Much like the Diablo winds to the north, these wind events are highly concentrated in the fall and winter months, and is connected to some of the most devastating fires in California history.

The majority of California fires still occur in the summer months during the traditional fire season, June-August, and natural events still make up the majority of fire ignitions, with most of these attributed to lightning strikes (Cal Fire, 2017; Cal Fire, 2018; Cal Fire, 2019a; Cal Fire, 2020a). However, based on a review of Cal Fires Redbook data, there is a noticeable change in ignition source between summer and fall fires. As the summer season ends, human ignitions begin to play a much larger role in fall season fire activity. The impacts of global warming along with fall and winter wind events, paired with anthropogenic late-season ignition sources including power lines, creates a perfect recipe for the large scale, devastating blazes that have been witnessed over the past decade.

Chapter 4: Interplay of Wildfires and Electric Utilities

4.1 Impact of Electrical Utility on Wildfires

While lightning strikes still make up the majority of fire ignitions within the Sierra Nevada and northern coastal regions, human ignitions now make up the majority of ignitions across the full state, and have tripled the wildfire season from an average of 46 days for lightning-ignited fires, to 156 days for human ignited fires (Balch, et al., 2017). In addition, Balch et al. also observes a concentration of natural ignition sources in summer months, while human ignitions are evenly distributed throughout all fire season months. However even within the Sierra Nevada and northern coastal regions the impacts of human ignition can be easily observed. A growing number of human ignitions are also being directly linked to high voltage powerlines and electrical equipment. PG&E, one of the state’s primary electrical providers, has disclosed its involvement in over 1,500 fires since 2014 (Gold, Blunt, & Smith, 2019). While the majority of these were extinguished quickly and did not cause lasting damage, several of the largest fires in state history including the Camp fire have been linked to electrical equipment failures. Cal Fire statistics from prior years highlight the impact of these utility-related fire trends. Of the 20 largest wildfires in the state’s history, measured by acres burned, 11 are attributed to human ignitions, and 4 are directly attributed to electrical equipment/powerlines (Cal Fire, 2019d). Of the 20 most destructive wildfires, measured by financial cost, 15 are attributed to human ignitions, and 10 are directly attributed to electrical equipment/powerlines (Cal Fire, 2019e). Of the 20 deadliest wildfires, 13 are attributed to human ignitions, and 5 are directly attributed to electrical equipment/powerlines (Cal Fire, 2019c).

The CPUC has also collected data on the direct causes of utility ignited wildfires. Its data suggests the vast majority of ignitions are caused by vegetation contact with power equipment, this accounts for roughly two-thirds of PG&E’s at fault ignitions across 2014, 2015, and 2016 (CPUC, 2017). Based on these same 3 years, CPUC has reported that 33.5% of PG&E’s fires were caused by a failure of, or contact with, the conductor, 22% from the splice location, and nearly 9% from the transformer. This information has led to initiatives from PG&E and other power companies to better clear vegetation from around power equipment in recent years (PG&E, 2020g). These programs will prove extremely important as the percentage of PG&E's territory impacted by wildfires continues to grow. In 2012 approximately 15% of PG&E's territory was considered to be within a wildfire risk zone as indicated by Cal Fire, however as of 2019 that number has grown to 50% (Johnson, 2019).

4.2 Disruption to California Utilities

Due to the growing evidence of utility ignited wildfires, the California wildfire season is beginning to have a dramatic impact on power reliability across the state. Under California law, specifically Article 15 of the Public Utilities Code, California utilities may de-energize their electrical grids if it is deemed in the interest of public safety. These de-energization events are referred to as Public Safety Power Shutdowns (PSPS) (Reliable Electric Service Investments Act PUC § 339.2, 2000). On July 16, 2018, the definition of reasonableness, along with reporting requirements following a PSPS event, was amended when CPUC passed Resolution ESRB-8 which extended the de-energization reasonableness, previously only applicable to San Diego Electric, to all investor-owned utilities in the state of California (CPUC, 2018). Resolution ESRB-8 supports the decision of utilities to utilize PSPS events to reduce the public safety risk of wildfires that could be ignited due to power equipment. However, it is the opinion of many people that this right to de-energize was abused during the 2019 wildfire season, which saw the first multiday outages across the state. Unfortunately, according to executives from each utility, these outages could become the new normal for the next one to three decades (Murkowski, 2019).

This implementation of widespread PSPS events in 2019 is largely a result of the now overly cautious operations of PG&E. This cautious approach is not without reason. After a record-breaking 2015 fire in Butte, and the most damaging wildfire seasons on record in 2017 and 2018, including the Tubbs and Camp fires, PG&E was forced to file for chapter 11 bankruptcy in January 2019 due to the value of victim claims against the company (CPUC, n.d.c). The value of these claims, as outlined by PG&E in the summer of 2020, after receiving court approval for its reorganization plan, is $25.5 billion USD (PG&E, 2020i). This includes $13.5 billion in claims to individual victims of the aforementioned fire seasons, $1 billion in claims to municipalities, counties, and other public entities, and $11 billion to insurance companies who have previously covered claims.

Although they were unprecedented, the PSPS blackouts of fall 2019 were likely a wise decision for PG&E, as they avoided potential points of ignition from the company's power equipment; PGE found 554 instances of damage and hazards after the October 26th PSPS event, 315 of which included contact between vegetation and power equipment (PG&E, 2020c). The PG&E 2019 PSPS events took place between June 7th and November 21st, and are separated into 7 individual events; June 7-9, September 23-26, October 5-6, October 9-12, October 23-25, October 26-November 1, and November 20-21 (PG&E, 2020a; PG&E, 2020b; PG&E, 2020c; PG&E, 2020d; PG&E, 2020f; PG&E, 2020h). The customer outages in these events lasted from a few hours to over 5 days, and impacted an estimated 2,036,000 distribution customers (CPUC, 2020c). Although Resolution ESRB-8 mandates community communication of pending PSPS, several thousand customers lost power without notice during 2019. These instances of power loss without notice are especially dangerous as they remove the opportunity for customers to prepare for the event. This can also limit the effectiveness of microgrid systems, as will be explored in-depth in Chapter 6, as it eliminates the ability of grid charging for energy storage systems.

It should also be noted that while PG&E is the focus of this analysis, PSPS events were issued by all investor-owned utilities (IOU) in California in fall 2019. These conditions of extreme unreliability are wholly unexpected from one of the most prosperous states in the USA, a region on the cutting edge of tech development, and with one of the highest costs of electricity in North America.

4.3 Conditions for PSPS Events

To this point in time, PSPS events have been largely concentrated in the fall months; September and October. This trend is due to a variety of factors that impact the fire risk in the region, as well as the specific risks associated with power equipment ignited fires. PG&E has provided a list of factors used to determine the need for a PSPS event.

> These factors generally include, but are not limited to:
>
> - A Red Flag Warning declared by the National Weather Service
> - Low humidity levels, generally 20 percent and below
> - Forecasted sustained winds generally above 25 mph and wind gusts in excess of approximately 45 mph, depending on location and site-specific conditions such as temperature, terrain and local climate
> - Condition of dry material on the ground and live vegetation (moisture content)
>
> On-the-ground, real-time observations from PG&E's Wildfire Safety Operations Center and field crews. (PG&E, n.d., para.7).

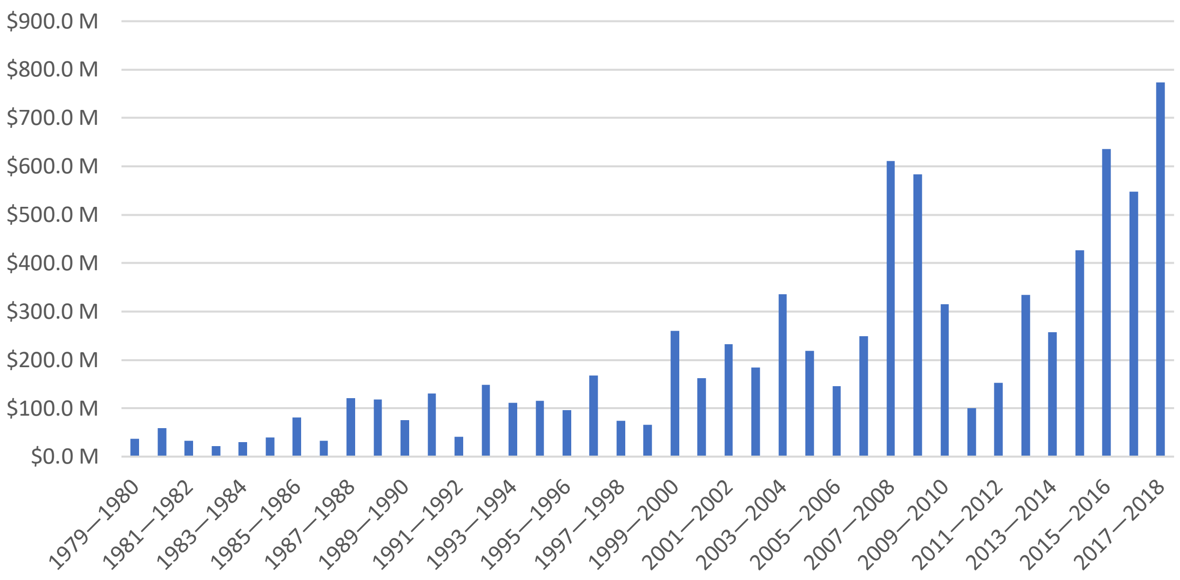
While these factors offer some specificity, they are vague in that all factors are reviewed in combination with each other, and the exact criteria for a PSPS remains unclear.

It can be observed that the factors driving an increase in fall fire activity throughout the state, namely offshore down-slope wind patterns such as the Santa Ana and Diablo winds, along with patterns of delayed fall precipitation and aridification of vegetation fuels, coincide with the specific factors and causes of ignition for power line related wildfires. These high winds and dry vegetation greatly increase the likelihood of the leading cause of powerline ignited fires, i.e., vegetation contact with power equipment. As such PSPS events can be expected to continue to concentrate in fall months so long as warming and climate change related patterns persist.

Chapter 5: Economic Costs of Wildfire Season in California

As the frequency and severity of wildfire activity increases across the state, so too does the cost of fire suppression. Cal Fire's Fire Suppression Expenditures document shows an exponential increase in annual expenditure from 1980-2018. After adjusting for inflation to 2018 USD the lowest annual cost recorded is $21.7 million during the period 1982—1983, and the largest is $773 million during 2017-2018, representing an increase of nearly 3500% (Cal Fire, 2019b). After averaging the adjusted values by decade to lessen the impact of outliers, a massive increase can still be seen. The 1980's average an annual cost of $61 million, while the period from 2010-2018 average $403 million, a 561% increase (see Figure 4 for annual values). This exponential increase is a result of the increase in wildfire activity paired with changing land use throughout California, and the increase in population density within close proximity to natural wildlands (Jin, et al., 2014).

Figure 4: Annual Fire Suppression Costs Adjusted to 2018 USD



Source: Author and (Cal Fire, 2019)

The increase in wildfire suppression costs is only a small piece of the puzzle, wildfires have a much further reaching impact including property damage, interruptions to economic activity, and hard to measure externalities such as crop devastation, healthcare costs, emergency services, property devaluation, lost wages, spoiled food, and social impacts such as missed school for children. A paper published by the Association for Fire Ecology in 2015 suggests that these additional costs could be up to 30 times the cost of fire suppression (Association for Fire Ecology, International Association of Wildland Fire, & The Nature Conservancy, 2015). This impact is easily observed when you consider the $25.5 billion owed by PG&E for at-fault fires in the past several years alone. The Insurance Information Institute (III) estimates the insurable losses for the 2018 Camp Fire to be up to $10.5 billion, and places several of the other 2017-2018 fires in the multi-billion dollar range as well; Medicino Complex Fire $1-1.5 billion; Woolsey Fire $3-5 billion; Tubbs Fire $7.5-9.7 billion; Atlas Fire $2.5-4.5 billion; Thomas Fire $1.5-3.5 billion (Insurance Information Institute, 2019). Data from the III also shows that of the top ten most costly fires in the US, all are in California and all carry over a billion dollars in insurable losses in 2019 adjusted USD. While these numbers are far larger than the cost of fire suppression alone they still do not capture the full cost of the external impacts of wildfires, RMI has placed the high-end estimate for the true cost of the record-breaking 2018 fire season at 400 billion USD (Tyson & Navavatty, 2020).

To further complicate the cost analysis, the cost of PSPS events must now be factored in as well. The factors impacting the cost of these events much resemble the factors impacting the costs of wildfires in general; interruptions to economy, school and business closures, lost wages, and spoiled food due to lack of refrigeration. For example, the Kincade Fire in 2019 resulted in school closures impacting roughly 500,000 students (Tyson & Navavatty, 2020). The estimated cost of these closures is $14 million per day. Michael Wara, the Director for Climate and Energy Policy at Stanford, estimates that the true cost to customers of the 2019 PSPS events of PG&E alone is more than $10 billion (Wara, 2019). Unfortunately, the costs of these events are most likely to hit already vulnerable groups who are not prepared for such outages, such as the very young, the elderly, the impoverished, and those reliant on power for medical devices.

Chapter 6: Microgrids

With the reliability of power supply becoming an increasingly real concern for many California citizens, microgrids may serve a role in mitigating this risk and increasing the resiliency of the grid. Several types of microgrids exist, however for the purposes of this research, the use of the term microgrid will be consistent with the definition established in section 1.3.

6.1 History of Microgrids

Microgrids in their basic form are by no means a new technology. In fact, many people point to Thomas Edison’s consumer grid at Pearl Station in 1882 as the first use of microgrid technology (Hirsch, Parag, & Guerrero, 2018). This means, as this was one of the first uses of grid technology in general, that microgrids predate macro grid systems. While Edison’s system does not meet the definition of a microgrid as outlined in this research project due to the lack of connection to a bulk grid, it is important to note that the use of DER for commercial power generation has been around for nearly 150 years.

These small-scale isolated power stations continued to supply up to 50% of customers in the U.S. well into the second and third decades of the 20th century. Once again, the lack of interconnectedness between these isolated grids disqualifies them from the modern definition of microgrids, however this is the only limiting factor. The size and scope of many of the systems, less than 10MW and serving homes and businesses within several miles of each other, are very similar to that of microgrid systems in use today (Herman, Barker, Johnson, & Maitra, 2001).

Ironically, a major issue with these early systems was reliability and resiliency, as they were only powered by a single DER. This meant that if the power source went down, there was no backup for customers. This lack of redundancy resulted in a push towards integrating multiple areas and municipalities into an interconnected grid, offering a layer of redundancy where one municipality could pick up the load from another, and vice versa (Herman, Barker, Johnson, & Maitra, 2001). As technologies in transmission and large-scale generation such as hydroelectric dams advanced, economies of scale began to become obvious and there was a rapid increase in the size of both generating resources and grid size. Government funding initiatives through the Rural Electrification Administration for larger dams, such as the Hoover Dam, large nuclear plants, and increased transmission lines, further spurred on development. As explained in a book by Amory Lovins, this race to be the biggest came to a halt in the 1970s with plants at ~1,400MW (Lovins, 2003). At this point the financial and engineering risks became too large for further exponential growth, and a new issue was emerging; once again the resilience of the grid was a major concern. With so much generating capacity confined to single units the risk of failure was once again too high and the evolution of the microgrid had come full circle. This culminated in the energy crisis of the 1970s, and the formation of the Public Utilities Regulatory Policy Act (PURPA) in 1978 (American Public Power Association, 2020).

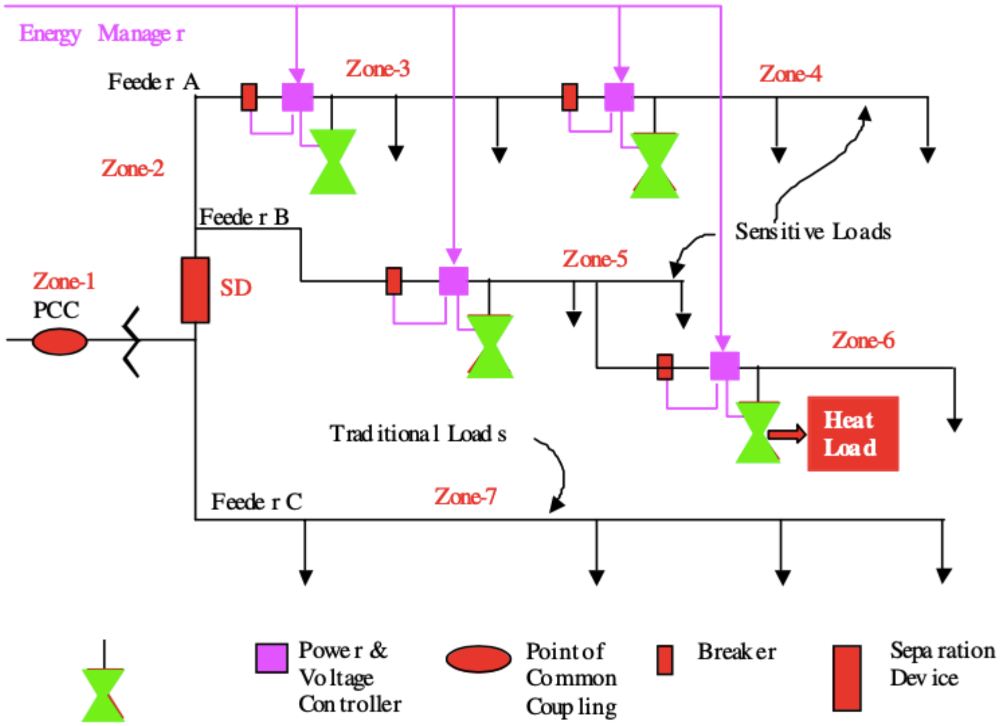
PURPA was an action by Congress and the DOE to reduce US dependence on foreign energy sources, and to clean up the US power grid by promoting power resource diversification and the use of renewable energy sources (UCS USA, 2002). One method taken to promote grid diversification was the allowance of non-utilities to own and operate power generating assets, and to mandate that utilities purchase power produced by these new entities, when the cost to generate was less than that of the utility. Prior to PURPA the utilities held a monopoly on electricity production, however the regulation opened the doors for much smaller entities, and without PURPA the modern microgrid would not be possible.

These initial ideas put forward in the early 1990s as a means to increase the reliability of the US power grid ultimately lead to the implementation of many DER systems. These systems were in essence small microgrids similar to the first power systems implemented by Edison in the late 1800s; although just like Edison’s they lacked the ability to island, disqualifying them from the modern definition adhered to in this research. These DER systems, along with other research conducted by the DOE, ultimately led to the establishment of the first microgrid research organization in 1999 (UCS USA, 2002). This organization was named the Consortium for Electric Reliability Technology Solutions (CERTS).

6.2 Modern Microgrid Technology

The beginning of what will be dubbed “Modern Microgrid” research can be traced to a 2002 publication by Lasseter et al. titled “The CERTS MicroGrid Concept” (Lasseter, et al., 2002). In this white paper Robert Lasseter proposes, for the first time, the concept of an islandable microgrid and a definition of microgrids which is consistent with the one used throughout this paper, with the exception that Lasseter’s definition is also focused on combined heat and power (CHP) to further increase efficiencies. The CERTS system consists of multiple loads and generating assets behind a point of common coupling with a separation device to allow for islanding, and power controllers throughout the system to manage the flow of electricity (see Figure 5).

Figure 5: Micro Grid Architecture from CERTS Microgrid Concept



Source: (Lasseter, et al., 2002)

The work by CERTS took a step back from the common approach to DER integration which focused on inserting small numbers of DERs into the electrical grid with mitigation of grid impacts as the primary concern (Lasseter, et al., 2002). Because of the focus on minimizing impacts, the systems were designed such that generation of power at these DER locations would be halted if grid issues were identified. This system of integration meant that even with onsite generating capacity, facilities would experience blackout events just the same as any other power customer. These early DER systems offered no additional resilience above what the grid offered. The CERTS design offers a solution to this by presenting the first islandable system which can separate from the grid and reconnect when it is once again safe to do so. The system CERTS designed manages this by acting as a single entity to the main grid, technically it is no different from any other power customer, except for its ability to disconnect from the grid at the location of the separation device. This treatment of the entire microgrid as a single entity also opens up business models for long-term power contracts with utilities, many of which we are just now starting to see in the market.

The 2002 CERTS Microgrid paper predicts future technological advancements and DER sources which were impossible or uneconomical at the time it was written (Lasseter, et al., 2002). The first of these is the ability of the microgrid to supply power back to the main grid as an ancillary service, and suggesting the future possibility of assisting in managing load changes and relief of grid congestion. While the paper notes that, at the time, there were major technological barriers to this, this is now considered to be one of the primary benefits microgrids can offer. Lasseter refers to this ability as making the microgrid a “Model Citizen”, and states the initial goal is to simply be seen as a “Good Citizen” by causing no adverse effects to the main grid; a common problem with many of the early DER generators. The second notable prediction by the CERTS team is regarding the attractive fit between microgrids and new renewable energy technology. Renewables at the time were very expensive and were regarded as uneconomical in most applications. However, the future use of renewable technology, specifically PV and storage, play a prominent role throughout the paper, both for its ease of integration through electronic devices which allows for better system control, as well as for environmental benefits.

Since this initial paper was written, research on modern microgrid technology and DERs has taken many forms. Papers have been published on system designs, specialized equipment developments, integration of renewable energy sources, and power reliability. The authors of these papers also cover a wide range of experts, from business-minded authors of white papers, to technical experts at leading universities. A few institutions that appear repeatedly in citations on the subject of microgrids include Berkeley Labs who have been publishing on the topic since 1989, RMI a not for profit organization focused on transitioning to clean energy, and CERTS who is still very active in the research of microgrid technology.

Berkeley Labs in conjunction with CERTS has provided vast insights into the favourable economics of Microgrid technology. As stated in a paper published by Berkeley researchers in 2015, microgrid technology can contribute positive economic benefits to a project through load shifting, power exports, demand response programs which pay consumers for control of their power consumption during peak hours, and value of lost load (VOLL) among others (Stadler, et al., 2015). Berkeley Labs has also been in the development of a tool they call DER-CAM since 2000 which optimizes DER resources based on project economics and can assist in selecting and sizing DERs (Berkeley Lab Grid Integration Group, n.d.).

Important to the purpose of this research is the potential environmental benefits of microgrids. To a large degree these benefits are seen due to the ease of deploying renewable DERs. As explained by Yael Parag and Malcolm Ainspan (2019), microgrids have a distinct advantage over large bulk grid systems in utilizing renewables as their small scale allows for economical deployment of integrated storage and demand-side management not feasible in larger networks.

Chapter 7: Distributed Energy Resources and Energy Storage

The DERs utilized in a microgrid system are traditionally smaller in scale than utility-scale power plants, however, as the variety of applications continues to grow so do the generators installed. The first microgrids typically made use of traditional fossil fuel generation methods such as reciprocating engines and diesel generators which, due to their small size and wide availability, made them a good option. Today the DERs range from these same traditional generators to renewable sources such as small-scale wind turbines, PV modules, biogas turbines, and some new micro applications of natural gas turbines. Many systems are now paired with energy storage as well to increase reliability, especially in the case of solar and wind based microgrids. These storage solutions are also rapidly developing, common technologies being paired with small scale DERs include Lithium-ion (Li-ion) batteries, flow batteries, lead-acid batteries, and high-temperature batteries.

DERs are beginning to gain traction for their ability to decentralize the existing electrical grid. New regulations are enabling the use of DERs to participate in market services, demand response, and ancillary services (IRENA, 2019b). As minimum capacity regulations begin to decrease, the number of DERs able to participate in the market continues to grow, and with it so does the flexibility of the existing grid.

For the purposes of this research, I will be focusing on the application of monocrystalline PV panels paired with Lithium-ion (Li-ion) battery storage. However other types of PV and battery technology will be briefly discussed as well.

7.1 Photovoltaic Technology

PV technology, invented in the 1950s at Bell Telephone laboratories, experienced its first public applications in the U.S space program to power satellites (EIA, 2020e). Since then PV technology has become one of the fastest growing renewable energy sectors (IRENA, n.d.). This surge in growth can be attributed to several factors, first, the ability to produce zero emissions power in a time of growing awareness regarding carbon emissions and climate change. Second, the ability to easily scale the technology from multi MW utility-scale installations to 100W portable charging stations and everything in between. And lastly, the rapidly falling cost of the technology as research and innovation booms.

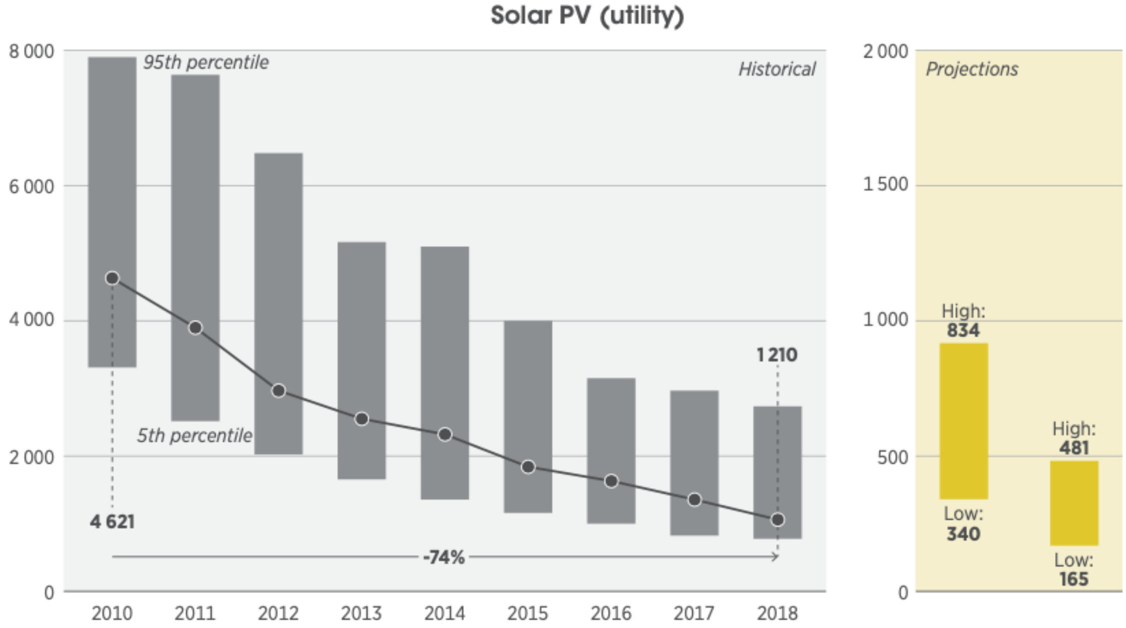
PV technology today can take many forms, IRENA breaks these technologies down into 3 categories; first, second, and third-generation PV systems (IRENA, 2012). First-generation PV systems utilize wafer based crystalline silicon panels. These technologies are mature, and are widely deployed in both utility and DER applications today. These can be further divided into poly-crystalline and mono-crystalline technology. The main difference between the two is in the way the silicon crystals are used. Mono-crystalline wafers use a single silicon crystal which is then thinly sliced, while poly-crystalline uses small portions of many crystals that are melted together to form the wafer (EnergySage, 2020). When compared to polycrystalline panels, monocrystalline technology has a slightly higher capacity factor, about +1%; capacity factors in 2019 averaged 17% and 18% respectively (IRENA, 2019b).

Second-generation PV systems consist of thin-film PV technologies. These technologies require far less material than first generation systems, and rely on many thin layers of semiconductor material to absorb solar radiation (IRENA, 2012). These systems do not yet have the same level of market penetration as first-generation systems, and are substantially more expensive (IRENA, 2020b). However, they have many promising applications where lightweight panels are required. Thin-film technology allows for integration of solar resources into building materials such as windows or structural facades, and offers far greater flexibility of design than first generation systems (IRENA, 2019b).

Third-generation systems are those which are still in trial stage (IRENA, 2012). A few promising technologies include Concentrating PV, which makes use of mirrors to concentrate solar radiation onto specially designed PV panels, and Organic Solar Cells, which are looking to use inexpensive organic polymers in the place of silicon crystals.

Today the majority of the market is held by crystalline silicon modules, more specifically mono-crystalline panels (IRENA, 2019b). This is due to falling prices of input materials, as well as market maturity driving higher efficiencies and lower costs compared to other technologies. As of 2019 crystalline PV modules made up 95% of global PV production. Due to the use of mono-crystalline technology, and the expected continued growth of these systems, they will be the basis for all PV discussions throughout this research project, and in modelled systems.

Figure 6: Cost of Utility-Scale Solar PV 2010-2018 (Projections for 2035-2050)



Source: (IRENA, 2019b)

The growth of grid-connected PV has been exponential over the recent decade. In 2019 global capacity surpassed 580 GW, a year over year growth of 20%, slightly down from the 26% growth in 2018 (IRENA, 2020a). This exponential growth is expected to increase over the next several decades, with a forecasted global capacity of 8,519GW by the year 2050. While the majority of this capacity is expected to be utility-scale power plants, ~40% is forecasted to be DER based on the surge of policies, funding, and research aimed at increasing DER globally (IRENA, 2019b).

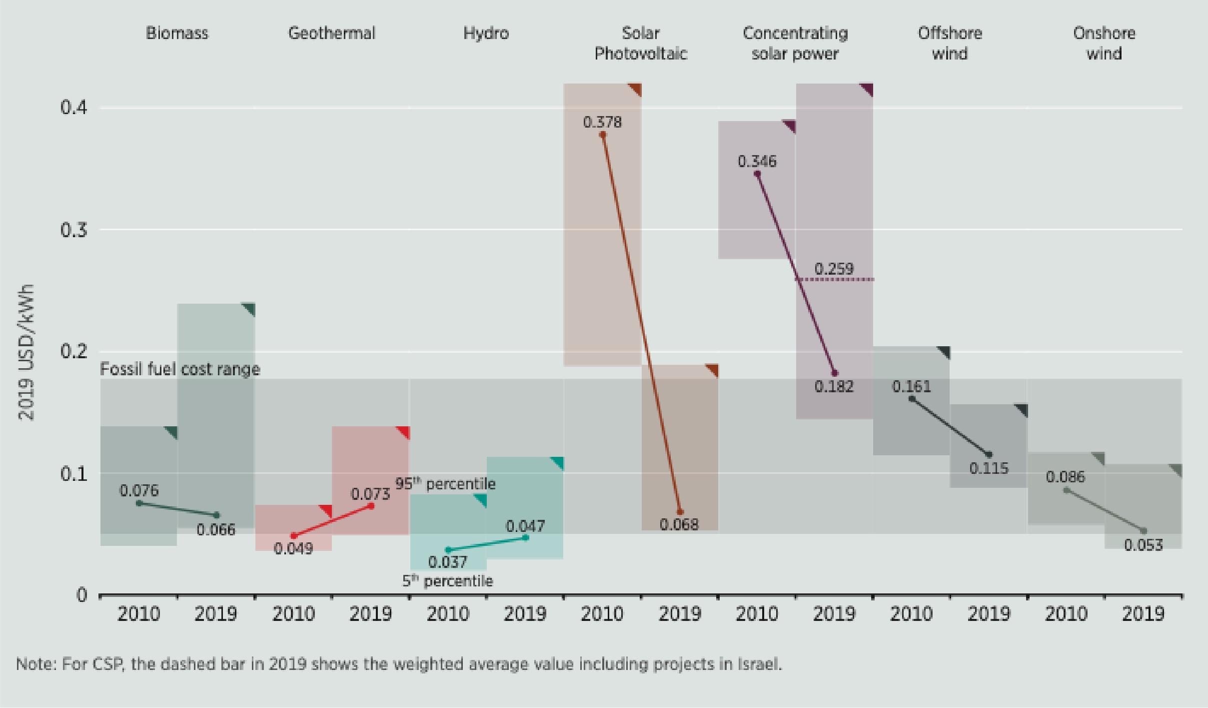
This rapid growth in recent years, along with global research and development efforts, has substantially driven down the cost of PV technology. Since 2010 the average total installed cost of utility PV systems has fallen from $4,621/kW to $1,210/kW in 2018

(IRENA, 2019b). IRENA has forecasted further exponential decreases to prices between $340-$830/kW by 2030 and between $165-480/kW by 2050 (See Figure 6).

When comparing systems, in addition to total installed cost, levelized cost of electricity (LCOE) is also often used. LCOE examines the average cost per kWh of power output, by taking into account interest rates, power production, up-front capital, fixed and variable operating costs, and the installed capacity of the system. The LCOE for utility-scale PV systems has dropped by 82% since 2010, primarily driven by the aforementioned reduction in panel and total installed cost (IRENA, 2020b). During this time LCOE for utility-scale solar dropped from a mean price of $0.378/kWh in 2010 to $0.068/kWh in 2019. This is the most significant drop of all power generation technologies, renewable and otherwise over the same period (See Figure 7). IRENA also reports that 40% of utility-scale solar installations in 2019 will produce power at a lower cost than available fossil fuel alternatives, an incredible achievement compared to 10 years ago when the average solar installation produced power that was nearly 8 times as expensive as fossil fuel generation methods. Preliminary evidence from early auctions for 2021 solar PV projects suggest that average prices from some projects could be as low as 0.039/kWh, a further 42% reduction from 2019 pricing, and 20% less than some coal-fired alternatives. Longer term changes in LCOE are forecasted by IRENA at $0.08/kWh by 2030 and $0.05/kWh by 2050 (IRENA, 2019b).

Residential and roof-mounted PV systems typically have higher LCOEs than utility-scale systems, mainly due to the distributed nature, lower capacity factors due to placement and lack of tracking, along with some economies of scale. LCOE for residential and rooftop installations in California decreased from $0.306/kWh in 2010 to $0.171 in 2019, while commercial installations saw a reduction from $0.259/kWh to $0.134/kWh over the same period (IRENA, 2020b).

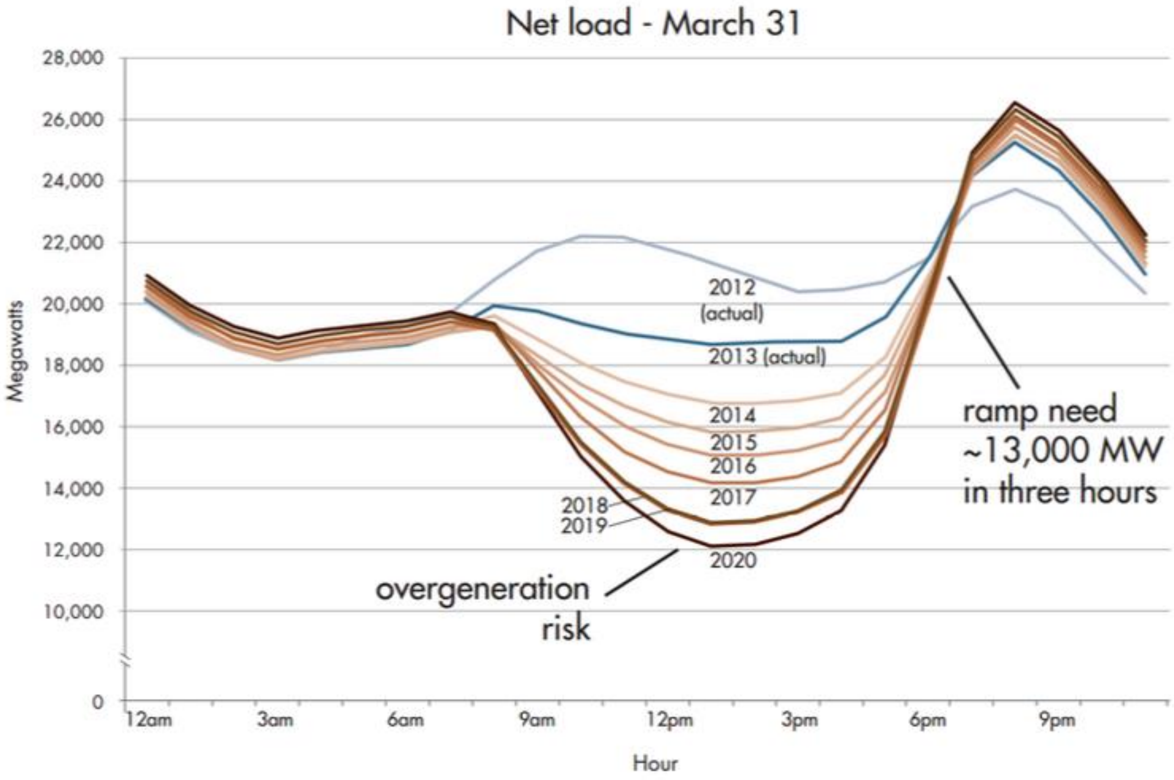
Figure 7: Change in Global Weighted Average LCOE from Utility-Scale Renewables



Source: (IRENA, 2020b)

Despite Solar PV's rise as the fastest growing power resource, and its nearly emissionless power generation, it is not without its challenges. One of the greatest barriers to solar power generation is intermittency (Headley & Copp, 2020). The issue stems from the reliance on high levels of solar radiation to maintain rated efficiencies. Power production and operating efficiency are therefore impacted by time of day, inclement weather, and a variety of other factors that can impact radiation penetration. This intermittency can impact the grid in two important ways. Firstly, the use of intermittent resources such as solar require other supporting generation methods to account for electrical demand during the hours when solar energy is not available. Secondly the rapid growth of solar resources, including rooftop installations, can result in large swings in power supply when these resources come on and offline. This volatility is not easily managed by existing baseload power sources such as coal and nuclear which require long durations to ramp up and down production. The impact of this can already be seen in what is referred to as the California Duck Chart (Denholm, O'Connell, Brinkman, & Jorgenson, 2015). The Duck Chart (see Figure 8) shows the impact of large quantities of solar generation coming online midday during sunny months, thus reducing the load on the grid substantially. This can result in over generation by other power assets, requiring them to be ramped down. However, once solar resources begin to decline in the evening there is a rapid need for other generation sources to come back online. This rapid ramp-up is at risk of being unable to be supported by baseload plants and could result in a mandatory curtailment of solar power generation during peak hours, thus limiting the effectiveness of the solar systems to both produce power as well as offset emissions from other sources.

Figure 8: The CAISO Duck Chart



Source: (CAISO, 2016)

DER systems can offer a solution to the first of these two intermittency related problems. By integrating DER with the main grid, this issue can be mitigated by decentralizing the production of solar energy so as to lessen the effect of negative influences in one area by taking advantage of simultaneous production in another. In this manner interconnection with the grid can help to stabilize power production at a specific DER site, while the use of multiple DERs can stabilize power production for the grid as a whole. The economic scalability of solar PV technology makes it a perfect candidate for this application. The integration of many smaller sites is not accompanied by substantially higher costs as it is with other technologies, namely fossil fuel generators, and hydro assets. Furthermore, depending on location type, integrating residential or commercial DER into the grid can reduce real-estate and land acquisition costs for utilities by utilizing a variety of modern business models. For off-grid use of DERs, or use in a microgrid in island mode, the pairing of DER with storage is fundamental to the ability for the grid to maintain power during periods of reduced solar radiation.

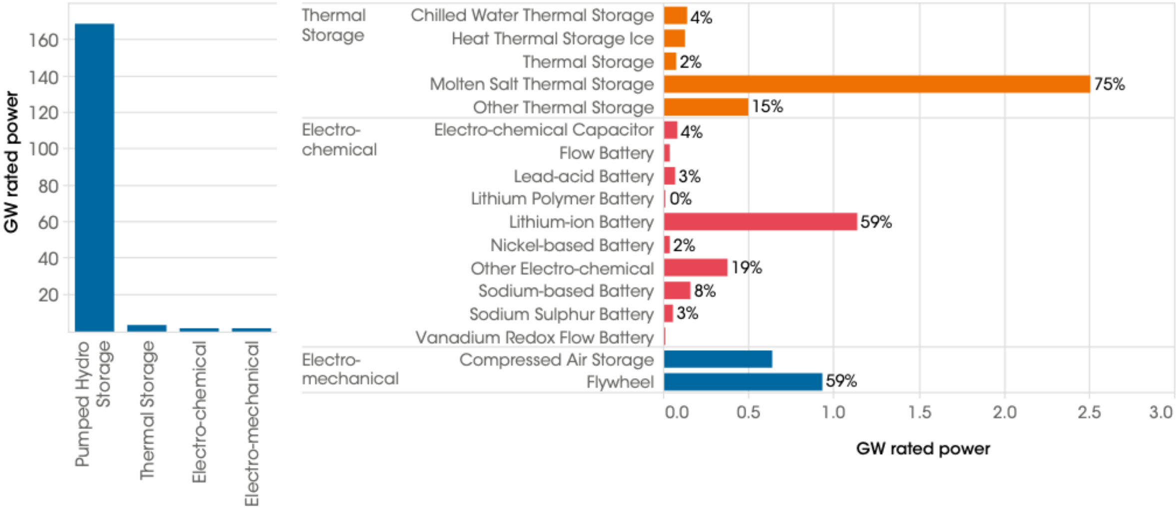
The inherent issues related to the Duck Chart can also be offset by the integration of energy storage solutions. Falling prices and advancements in battery storage technology are making the wide use of solar power much more feasible. Other advancements in demand-side monitoring, smart metering, and system operations and controls are promoting novel business models for DER further (IRENA, 2019b).

Chapter 8: Energy Storage Systems

As outlined above, energy storage represents a solution to many of the problems associated with the operation of a grid that is heavily reliant on solar power. Today there are many options for energy storage that vary widely in their market maturity and ideal applications. Pumped Hydro Storage (PHS), which as of 2017 made up an estimated 96% of global energy storage capacity, and 97% of US large storage projects, takes advantage of gravitational potential by utilizing excess power to pump water to a higher elevation where the potential energy can be stored until it is needed (IRENA, 2017) (EIA, 2020a). When electricity is needed the water is released and turns a turbine which converts the gravitational energy back into electrical power. PHS is an ideal technology for long-term power storage where steady dispatch rates are expected. These systems do have their disadvantages though, particularly when it comes to microgrid or small-scale applications. The land requirements for PHS systems are very large, and the permitting and construction phases make project timelines very lengthy. For these reasons nearly all new high energy capacity storage projects since 2003 have been focused on electrochemical and battery storage vs new PHS assets (EIA, 2020a).

On the other end of the spectrum from PHS is the use of flywheels for short term storage. Rather than storing energy as gravitational potential, flywheels utilize kinetic energy by driving a spinning mass at high speeds using electrical input. The power is stored in the rotational energy of the spinning mass, and when power output is required, the motor can function as a generator to generate power from the rotational energy. Due to the mechanics of these systems they are only suited for very short duration storage, however they are capable of very high-power outputs for these shorter periods. Between the two extremes of long term PHS and very short-term flywheel storage, are a range of other storage systems, including thermal storage systems, compressed air storage, and a variety of battery technologies (See Figure 9)

Figure 9: Global Electrical Storage Power Capacity by Technology (2017)



Source: (IRENA, 2017)

The primary use of energy storage systems globally is focused on energy time-shifting, and the majority of this capacity is provided by PHS (IRENA, 2017). However, in recent years the capacity dedicated to supporting variable renewables is growing, and a large portion of this is focused on grid resiliency, residential markets, and self-consumption through PV systems. For these applications battery electric systems (BES) show the greatest promise, due to their fast response time, slow self-discharge, and modular scalability.

8.1 Battery Storage

Since the invention of the Voltaic Pile in 1800, battery technology has come a long way. Some of the most widely used batteries for stationary storage, such as that required in a microgrid system, are lead-acid batteries, flow batteries, high-temperature batteries, and lithium-ion (Li-ion) batteries (Encyclopedia Britannica, 2020). Each of these technologies has its own unique advantages and disadvantages (see Table 1), however for the purposes of this paper, the focus will be on Li-ion systems due to their wide use and advantages in microgrid systems.

Table 1: Pros and Cons of Various Battery Technologies

Technology	Pros	Cons
Lead-Acid Batteries	- Proven technology - Low cost - Effective in large scale applications	- Charge-discharge cycles - Energy density - Performance impacted by local temperatures
Flow Batteries	- High efficiency - Long lifespan - Long discharge duration	- Cost - Sophisticated management systems required - Immature technology
High-Temperature Batteries	- Long-term storage - Low capital cost	- High temperatures must be maintained - High O&M cost - Energy/power density
Li-ion Batteries	- Rapidly declining cost - High round trip efficiency - High energy density - Low weight	- Limited peak voltage due to protection circuits - Efficiency reductions subject to ageing

Source: (IRENA, 2017; EIA, 2020a)

Analysts from IRENA predict that by 2030 the largest markets for stationary BES systems may be the pairing of such systems with residential scale, or small grid-scale, solar PV installations to provide backup power during periods of low solar radiation (IRENA, 2017). The key drivers for this trend are likely to be the ability to support self-consumption in non-daylight hours, and the developing economic prospects such as avoided demand charges during peak hours, and pay for service agreements to provide time-shifting services to the grid; all of which are paired well with microgrid applications.

As of 2017, Li-ion batteries made up over half of the electrochemical storage globally (IRENA, 2017). Since then, the growth of Li-ion systems has continued at a rapid pace. Currently the electric vehicle (EV) market is the primary consumer of Li-ion batteries. However due to the surging global growth of EVs, new economies of scale are beginning to drive down the costs of the technology. By 2016 prices of Li-ion batteries for use in EVs fell by roughly 70% when compared to prices just 6 years earlier. During the 2 years between 2015 and 2017 the average cost per kWh of energy capacity fell 61% from $2,153/kWh to $834/kWh, highlighting the still rapid decline in prices (EIA, 2020a). While not directly related, the research and development activity in the EV space is spilling over into stationary storage uses of the technology. As such Li-ion system costs are rapidly becoming an economically viable solution for residential, microgrid, and even macro grid applications. Currently over 90% of high capacity electrochemical storage assets in the US are made up by Li-ion batteries. It is expected that system costs for stationary storage will continue to follow the rapid declines seen in the transportation industry, and are predicted to fall to between $145-480/kWh by 2030; a further 55-60% from 2017 prices (IRENA, 2017). As manufacturing ramps up for stationary systems, some analysts foresee even further reductions in system costs.

With increased research and development, efficiencies and lifespans of Li-ion systems are expected to improve as well (IRENA, 2017). Over the next decade the lifespan of such systems could increase by up to 50% and the number of effective charge and discharge cycles could nearly double. Both these trends have great positive implications for the use of Li-ion BES in microgrid applications as the frequent charging and discharging of systems can result in more frequent replacement requirements, and thus increases the capital costs of the system.

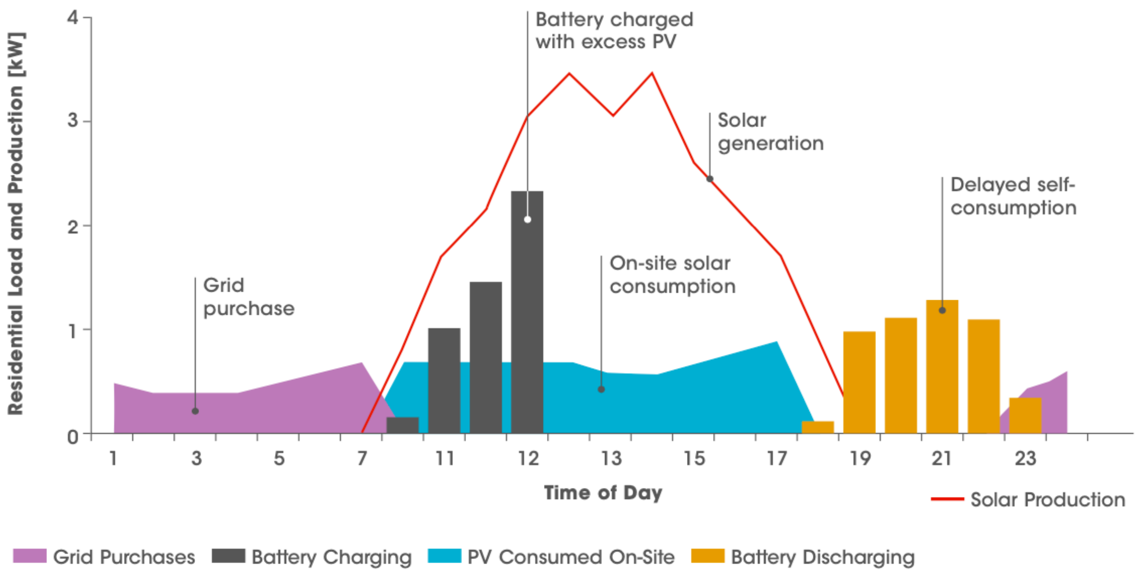
Within California the market is already primed for the acceptance of Li-ion storage in both large scale utility applications, and smaller-scale projects such as those that would be required for microgrid systems. In 2018 battery power capacity within the CAISO market made up 21% of the large-scale battery power capacity in the country, and 41% of the battery energy capacity (EIA, 2020a). This is disproportionate to the size of the CASIO grid, especially in terms of energy capacity, as the CASIO grid only accounts for 6% of the total electricity markets in the country. Much of this large-scale storage has been put in place in the last several years to mitigate the risk of unreliable access to natural gas, the state's main electrical resource. This risk stems from the 2015 detection of a major leak at the Aliso Canyon natural gas storage facility (EIA, 2016). However, since its installation the potential to use this battery storage to support the continued deployment of intermittent renewable resources has also come to light. In addition to the large-scale storage assets, California is estimated to hold roughly 90% of small-scale battery power capacity in the country (EIA, 2020a). Small scale storage being storage with less than a 1MW capacity. These small-scale solutions represent the greatest potential for microgrid integration.

Specific to their application in microgrids, behind the meter (BTM) BES can further support self-consumption, and demand side management within a local group of DER (IRENA, 2019a). BTM battery systems are BES which are located on the customer side of the electrical meter. This placement in relation to the grid allows BTM systems to support both local microgrid or customer services, as well as grid services for utilities. Looking at several BTM applications, including support of renewable self-consumption, community wide storage, peak shaving, altered time of use, island grid support, and increased power quality, Li-ion battery systems outperform all other stationary energy storage systems, including other battery types, PHS, compressed air storage, and flywheels (IRENA, 2017). In these applications PHS and compressed air storage are ineffective mainly due to their required large size compared to the community needs. Compared to lead-acid batteries, which have been widely used for community and residential storage in the past, Li-ion systems offer longer lifespans, easier installations, higher efficiencies, and superior safety. As such Li-ion systems are quickly replacing older lead-acid batteries. Flow batteries offer a lot of potential in BTM applications, however the technology is nascent, and so prices remain far higher per installed kW than the equivalent Li-ion system. However, with increased use of BES for BTM services, it is likely prices of flow batteries will continue to fall as well, and they may become an economic alternative in the future.

BTM BES open up a diverse set of economic opportunities for customers. The simplest of these is electricity bill savings by enabling time-shifting of renewable power generation (IRENA, 2019a). In areas where regulations allow it, and where time of use electrical tariffs are in place, batteries can be charged from the grid during times of low-cost power, such as during midnight hours, and sell this power back to the grid during peak hours (see Figure 10). This provides a service to the grid by load shifting, but also allows customers to take advantage of price arbitrage to generate their own revenue. This revenue opportunity can help to provide positive economics for BTM systems. Fortunately, the California regulatory environment is evolving to support BTM batteries and allowing for greater interaction with the grid.

Figure 10: Typical Daily Solar PV and Battery Chare/Discharge Schedule

Figure 5: Typical solar PV production and battery charging/discharging schedule



Source: (IRENA, 2019a)

Chapter 9: California Regulatory Environment

California represents one of the premier locations in North America for PV and storage microgrid systems. This is due not only to the superior solar resources but also to the rapidly evolving pro-microgrid regulatory environment. Spurred on in part by the increasing wildfire damage discussed earlier in this research, the state, local municipalities, and energy regulators, are all making a push to enable DER and microgrid development.

9.1 Supporting Regulations

ESRB-8

Resolution ESRB-8, which was discussed in section 4.2, is the regulatory change responsible for the enablement of PSPS events. While not necessarily a microgrid-related regulation, it is mentioned here again as it creates the need for resiliency; and so in some way had facilitated some of the further regulatory changes mentioned in this chapter.

Net Energy Metering Successor Tariff

One of the most important regulatory changes with regard to the enabling of DER infrastructure is the establishment of the Net Energy Metering (NEM) Tariff. The original NEM tariff was put in place in 1995 to encourage the integration of BTM renewable DER, and was revolutionary for its time (Itron Inc., 2020). Since then the NEM tariff has been reviewed and replaced with the NEM Successor Tariff or NEM 2.0. This process for the new tariff was started in October of 2013 with Assembly Bill (AB) 327, which mandates that the CPUC develop a new tariff for customers who generated renewable power on their own property (CPUC, n.d.b). NEM 2.0 enables customers with solar PV systems, or other renewable generation resources, to sell their excess power back to the grid at the same retail prices at which it would be purchased, including distribution and transmission fees, and also lifts the maximum size restrictions on the DER systems. Payment for these exports are received against the customer’s monthly bill, up to the amount which offsets charges owed for consumed electricity. If at the end of the year the customer still has a positive balance of credits, payment is made at a net surplus compensation (NSC) rate, which is a 12-month average of the market rate of electricity. This NSC rate currently sits between $0.02-0.03/kWh. This is far below the average California electrical rate of $0.17/kWh (EIA, 2020b). Under NEM 2.0 customers must pay a one-time connection fee, as well as non-bypassable charges, which are charges that support energy programs and initiatives (CPUC, n.d.b). Customers must also transition to a time-of-use (TOU) rate so that proper charges and credits can be offset.

Beginning in February of 2020, the CPUC contracted Itron to investigate current outstanding issues regarding NEM 2.0, one of which concerns the tariff rates being offered for power exports (Itron Inc., 2020). As part of the review of the tariff, changes to the compensation for DER systems, including adjustments to further account for time of service, and a comparison to utility cost of power, will be considered. These changes could make the operation of personal DER systems more economically attractive to customers. While NEM 2.0 does not specifically regulate microgrids, it has been an important step in pushing forward the integration of DERs and can shed some light on what the future microgrid market may look like.

Self-Generation Incentive Program

Established in 2001 the Self-Generation Incentive Program (SGIP) provides financial incentives for the development of BTM DERs across California. In January 2020 changes were made to the program to allocate approximately $1 billion USD in funding for BTM DER and storage projects between 2020 and 2024 (CPUC, 2020d). This funding will be focused on renewable generation methods, and due to the PSPS events of 2019, will also give preferential funding to projects in communities with high fire risk, or those which have been impacted by two or more PSPS events. The program has also been expanded to include some non-residential customers located in these high-risk areas, including grocery markets and emergency services. PG&E customers have access to 44% of this budget, more than any other utility’s territory. Due to the new focus on resiliency, 52% of the budget will also be directed at large scale storage systems, the type that could be installed in larger community microgrids. Funding can range from $180-500/kWh of capacity, which on the high end can nearly cover the full cost of some battery technologies. Incentives are also provided for the installation of emissionless generation technologies so long as they are installed behind the meter as well. While there is no specific mention of microgrid technologies in the program requirements, microgrids appear to satisfy all eligibility requirements as the full system is located behind the utility meter.

One case study for the use of SGIP funding for a microgrid project exists already. An affordable housing project in Sacramento, California fully funded its $850,000 PV and Li-ion storage system using SGIP and other government incentives (Asmus, Forni, & Vogel, 2018). The capacity and size of the system is much smaller than that of the modelled communities in this research project, however it proves that these incentive programs can assist in reducing upfront capital costs of installation.

9.2 Microgrid Specific Regulation

<u>Senate Bill No. 1339</u>

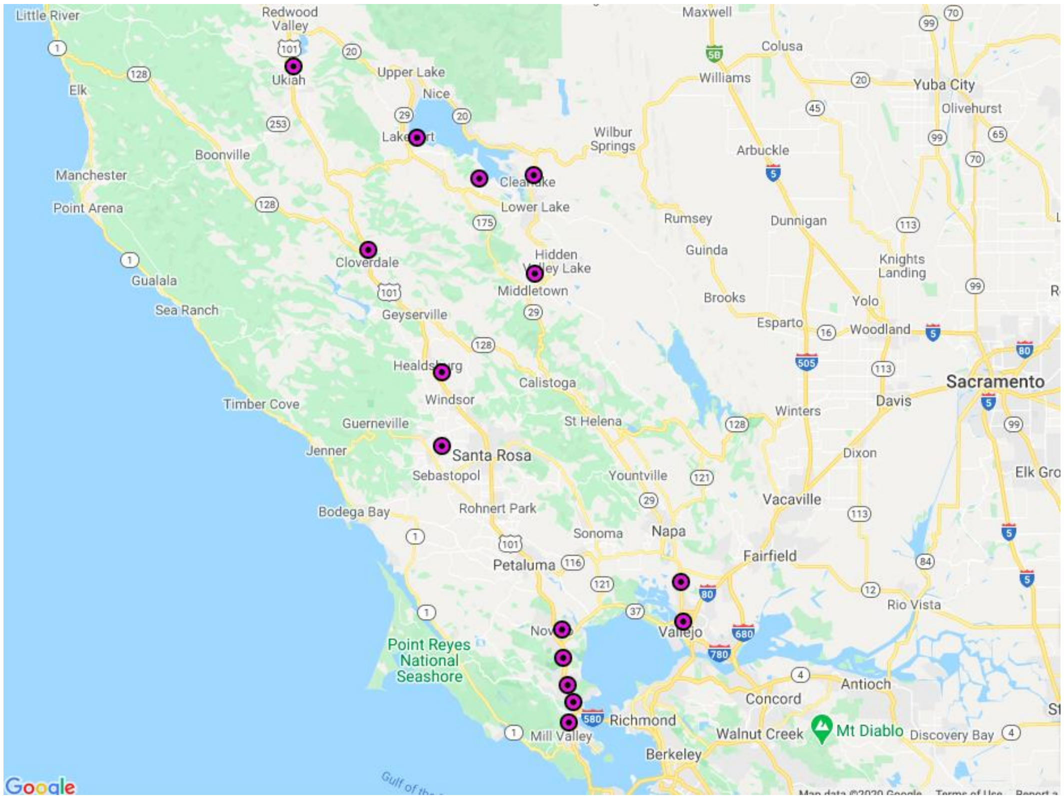
By far the most important regulatory event regarding microgrids has been Senate Bill No. 1339. The bill, which was passed in 2018, mandates that the CPUC, in conjunction with the CAISO and the California Energy Commission (CEC), take action to develop regulatory policies that support the commercialization of microgrids in the state (CPUC, n.d.e). The proceedings have been divided into 3 separate tracks, each with its own schedule and objectives.

Track 1, which began in January 2020, focuses on urgent needs, with the hope of taking action before the 2020 fire season. The scope of track 1 includes streamlining the interconnection process for key locations, adjusting tariffs to support resiliency, and facilitating cooperation between utilities and local governments on resiliency projects. The bill considers key locations to include medical baseline customers, emergency services such as fire and police, water treatment centres, schools, and at-risk populations such as seniors and disadvantaged communities. On June 11, 2020 a decision was made regarding issues identified in track 1 (CPUC, 2020b). The key outcome of this decision was to establish standardized designs for microgrid interconnection in order to accelerate approvals, and to adjust tariffs regarding energy storage systems to allow for grid charging of microgrid storage systems during the defined pre-PSPS window, as well as to remove any existing limits on energy storage system capacities.

In response to the track 1 objectives, PG&E created a Distributed Generation Enabled Microgrid Services (DGEMS) group to facilitate the integration of microgrid services at high-risk locations within the PG&E service area (PG&E, 2019). The request for offers, released December 11, 2020, is seeking projects which can be immediately deployed before September 1, 2020. The projects must be sited at or near pre-selected PG&E substations and be capable of supporting the islanded portion of the grid for which they are responsible for either a two or four day duration without access to grid power. The projects must also be capable of participating in the CAISO market when not providing resiliency services in island mode. PG&E has released locations for its proposed microgrid sites for the 2020 fire season (PG&E, 2020e). These locations are primarily located around San Francisco and up the northern coast (See Figure 11). The peak loads for these sites range from roughly 70MW down to 4MW, with minimum loads of between 26MW and 2MW. There are currently 20 proposed sites, however this can be expected to grow in future years.

Track 2 and 3 of the proceedings will focus on longer term planning for the use of microgrids as a grid resiliency measure (CPUC, 2020a). The focus of track 2 will be to develop a microgrid standard that can be applied at the regional and local government levels, better understand what impact assessments are required for future microgrid projects, further develop new energy rates and tariffs to encourage further development, and develop standards for net metering of direct current energy projects. Topics of possible consideration in track 2 and/or 3 include a focus on advanced net metering technologies to enable further isolation of grid segments, regulations mandating island functionality for new large storage projects, and policies regarding the integration, operation, and control of microgrid systems by non-utility third parties. Track 2 proceedings began in August 2020 and are expected to have a decision by fall 2020. Track 3 proceedings have not yet been scheduled at the time of this paper.

Figure 11: PG&E Proposed Microgrid Sites for 2020 Fire Season



Source: Author – Developed from PGE (PG&E, 2020e)

While Senate Bill No. 1339 currently focuses on the use of microgrids for grid resiliency of key locations and infrastructure, the issues in scope for track 2 and 3 proceedings show promise in resolving policy barriers to third-party residential projects such as those that are the focus of this research.

Senate Bill No. 1215

Senate Bill No. 1215 was signed in February 2020 and seeks to build on the foundation of SB 1339. SB 1215 proposes that a database of critical infrastructure, high fire risk locations, and disadvantaged communities is established to assist with the prioritization of microgrid resiliency projects in California (Howland, 2020) (Senator Stern, 2020). The bill would also create the Local Government De-energization Event Resiliency Program to be overseen by the Department of Emergency. This program would provide funding to local governments and critical infrastructure owners to establish microgrids within their systems to maximize resiliency for at-risk populations. The amount of the funding is yet to be determined, however the focus of this program on disadvantaged communities is promising for the integration of residential microgrid systems.

Chapter 10: Systems Modelling Methodology

10.1 REopt Software

Based on the findings of the literature review, four possible community microgrid scenarios have been modelled using NREL's Renewable Energy Integration and Optimization (REopt) Lite software (NREL, n.d.). Modeled systems consist of roof mounted PV systems, Li-ion battery storage, and the microgrid specific infrastructure required to operate the system; including additional design/engineering work, bi-directional inverters to allow for two-way grid communication, and a single switch connecting the microgrid to the grid. Each scenario differs in its electrical load, and mix of residential and commercial infrastructure, and as such each modeled system has unique PV and battery capacity requirements.

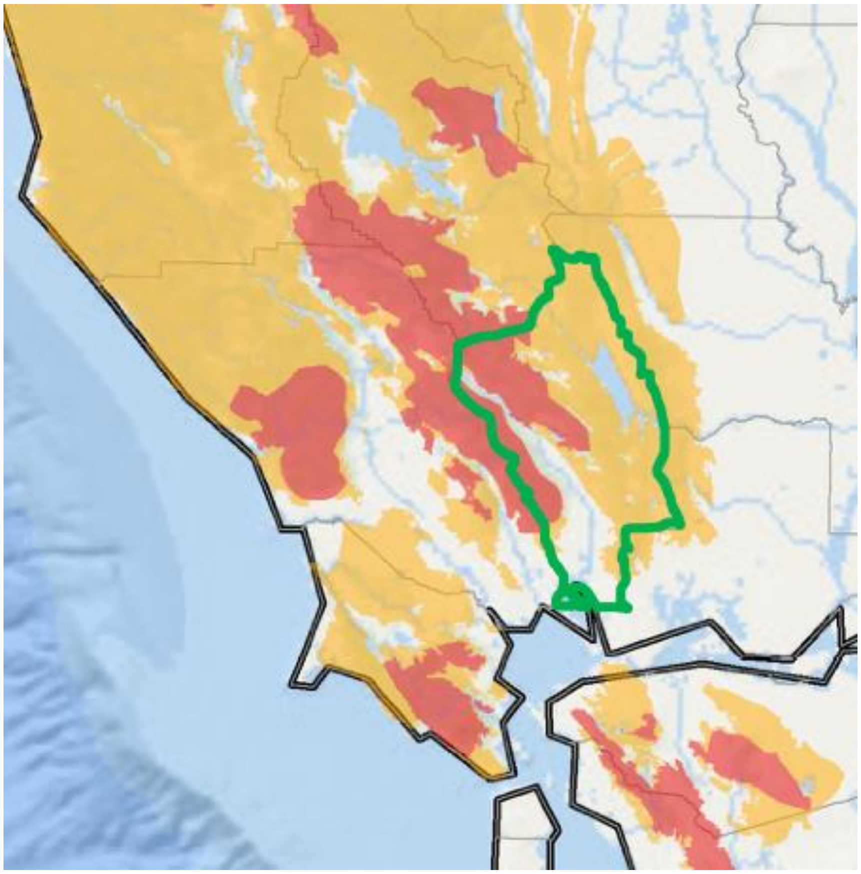
"The REopt™ techno-economic decision support platform is used by NREL researchers to optimize energy systems for buildings, campuses, communities, microgrids, and more. REopt recommends the optimal mix of renewable energy, conventional generation, and energy storage technologies to meet cost savings, resilience, and energy performance goals." (NREL, 2020)

The REopt software requires inputs such as location, utility electrical rates, building types and sizes, system load models, DER types, expected system outage durations, and economic factors such as total installed costs, operation and maintenance costs, and microgrid capital required as a percent of total capital, to model ideal system capacities to satisfy goals of either lowest economic impact, or highest resiliency impact. Each of the models in this paper are run based on the highest resiliency impact. Details on the rational for location and infrastructure choices, as well as inputs and outputs from the software program can be found in the section below. The exact inputs and assumptions for each scenario can be found in Appendix A and B, and the outputs from each scenario can be found in Appendix C.

10.2 Location Selection

All community scenarios are modelled within Napa County. The choice of Napa as the site location is for several reasons. Based on the review of PSPS event data for 2019, Napa county has been impacted by numerous PSPS events, including the longest duration outages on October 26, 2019. Napa county is also located in the heart of the high and extreme risk fire zones outlined by CPUC and Cal Fire, see Figure 12. The high percentage of the county with either high or extreme utility fire risk makes Napa a key location for piloting community resiliency projects. Lastly, Napa county is directly in the pathway of the Diablo wind events outlined in Section 3.3. This along with the existing fire threat in the county make Napa an area that is likely to see further deterioration in its electrical reliability as wildfire activity continues to rise.

Figure 12: Napa County Highlighted on CPUC High/Extreme Utility Fire Risk Map



Source: Author – Adapted from (CPUC, n.d.a)

10.3 Modelled Infrastructure Choices

A review of critical community infrastructure during natural disasters is used to determine what to include in community models. Ultimately four models have been chosen; a large community including 4,500 homes, a grocery market, and high school (S1), a large community including 4,500 homes and a high school (S2), a mid-sized community including 1,000 homes and a high school (S3), and a small community including 100 homes and a high school (S4). A market has been chosen to be included in S1 as communities of this size have a large enough customer base to support the need for nearby access to a food supply. As well, a market has the potential to increase the social resiliency impacts of the system by offering food access to members of neighbouring communities which may not be supported by their own microgrid system. The inclusion of a high school is important to the design of each system for two primary reasons. Firstly school closures and missed school days are proven to have potentially significant and lasting social impacts to a community, both through the loss of education hours for students, as well as the impacts to parents who may need to adjust working hours due to childcare needs (UNESCO, n.d.).The inclusion of a school enables education to continue throughout a PSPS event. Secondly, schools, particularly large high schools, are able to act as a community hub during times of crisis. The inclusion of a high school within a microgrid system could boost the social impacts of the project by offering a central location for community updates, and possibly provide shelter to impacted individuals outside of the residential microgrid.

10.4 System Inputs

In order to model each scenario (S1-S4), individual segments of each system were first modelled separately. These individual segments consist of the market, school, and residential loads. The outputs of each individual system segment is used to check final results for consistency, find any efficiencies that could be gained by bundling residential and commercial requirements, as well as to gain an accurate output of each separate portion’s annual electrical load profile.

Each segment is modelled to survive a 72-hour power outage event occurring annually on October 2nd for the full 25-year duration of the project. Each segment was modelled to include rooftop mounted PV panels with fixed tilt and azimuth, along with Li-ion battery storage. Key inputs for each segment included, location, electricity rate, eligible roof area for PV installation, building type, annual electrical consumption, critical load factor, financial discount rate, rate of inflation, capital costs of PV and storage, fixed and variable operations and maintenance (O&M) costs, microgrid capital costs, and cost of avoided outages. Details on specific segment inputs along with their data sources can be found in Appendix: A.

Based on California electrical usage data, annual electrical consumption of the segment, and building type, REopt produces an estimated annual hourly load curve. The load curves for separate segments are aggregated to develop a custom load curve for the specific community scenario. This load curve, along with the aggregated values of previously mentioned inputs are used to model the full community systems for S1-4 by combining the residential and commercial load data. Specific details on inputs for each scenario can be found in Appendix B.

Due to the lack of regulation directly aimed at residential microgrids and 3rd party owned/controlled microgrids, the following assumptions are made as to the operation of the community systems. Based on the expected loosening of regulations around DER control, the economic models assumed that excess power would be sold back to the grid at the TOU rate, and also that storage systems would be able to charge from the grid to provide time-shifting services and take advantage of price arbitrage.

Chapter 11: Analysis of REopt Lite Results

Outputs from the REopt software models include recommended solar PV capacity, recommended battery power, recommended battery capacity, the survival rate of each system (see Table 2). Financial information such as capital cost of PV system and battery, 25-year cashflows, system power production, system grid exports, and the value of exported power are also provided (see Table 3).

Table 2: REopt Lite Modelled Systems Specifications

REopt Outputs	S1	S2	S3	S4
Solar PV Installed Capacity (kW-DC)	76,507	73,459	19,091	4,772
Battery Power Capacity (kW)	8,361	8,078	2,135	607
Battery Energy Capacity (kWh)	91,322	88,620	22,388	5,570
Survival Rate	40%	39%	39%	38%

Source: Author, 2020

Survival rate refers to the number of 72-hour outages that could be survived throughout the year. Although the systems are designed to survive outages occurring on Oct 2nd each year, REopt also calculates whether these systems would survive an outage on any other given day of the year as well. It should be noted that all systems are more likely to survive outages during the summer and fall months than they are during winter months due to the availability of solar resources.

Table 3: System Economics ($ million USD)

REopt Outputs	S1	S2	S3	S4
Total Capital Cost	$201.3M	$193.8M	$50.1M	$13.1M
PV System Cost	$122.4M	$117.5M	$30.5M	$7.6M
Battery System Cost	$45.4M	$44.0M	$11.2M	$2.8M
Microgrid Cost	$33.6M	$32.3M	$8.3M	$2.6M
Average Value of Power Exports/year	$11.5M	$11.0M	$0.5M	$0.7M
PV Energy Produced (MWh)	110,656	106,246	27,613	6,902

Source: Author, 2020

The REopt output values are used to calculate financial metrics of each system scenario, including net present value (NPV), internal rate of return (IRR), levelized cost of electricity (LCOE), payback period, and a capital cost per customer. These financial metrics are used to evaluate the microgrid systems against the base case of California grid electricity (see Table 4). Comparisons are also run on the systems with and without microgrid investments, and with and without the impacts of avoided outage costs. Avoided outage costs are considered an external benefit as they are a reduction in possible expenses or lost revenue, rather than real revenue. These external benefits can only be realized with the microgrid system.

Table 4: Calculated Financial Metric

Metric	S1	S2	S3	S4	CA Grid 2019*
NPV w/o Microgrid (Million USD)	$69.4M	$66.3M	$18.1M	$6.0M	N/A
NPV full system (Million USD)	$164.0M	$87.6M	$23.7M	$10.9M	N/A
IRR w/o Microgrid Investment	9.7%	9.6%	7.7%	11.3%	N/A
IRR full system	11.6%	9.1%	7.1%	11.7%	N/A
LCOE PV Only ($/kWh)	$0.09	$0.09	$0.08	$0.09	$0.18
LCOE Full System ($/kWh)	$0.09	$0.09	$0.13	$0.10	$0.18
Payback Period full system (yrs.)	7.8	10.8	12.0	7.8	N/A
Average Household Capital Cost (USD)	$40,739	$40,836	$40,170	$37,770	N/A
School Capital Cost (Million USD)	$10.1M	$10.1M	$9.9M	$9.3M	N/A
Market Capital Cost	$8.0M	N/A	N/A	N/A	N/A
$/W	$2.37	$2.38	$2.36	$2.44	N/A

*Source: (EIA, 2020d)

Electrical output and grid electricity consumption values are used to calculate avoided emissions when compared to emission factors of California grid power. Microgrid systems are assumed to have net-zero emissions for produced power, however grid electricity consumption for the charging of storage systems is factored into the annual emissions of the microgrids. Baseline values are calculated based on the annual electrical requirements of each community, were they to consume grid sourced electricity only. Avoided emissions are calculated based on the total energy production of each system per year at the California grid emission factor (see Table 5), as this production would offset the need for grid sourced power for the community, as well as for the main grid for any exported electricity from the system. These values are then used to present the net reduction as a percent of the baseline values (see Table 6).

Table 5: Emission Factors

Compound	CA Grid*	Microgrid Systems
Carbon Dioxide (kg/MWh)	223.2	0.0
Nitrogen Oxide (kg/MWh)	0.3	0.0
Sulfur Dioxide (g/MWh)	6.8	0.0

*Source: (EIA, 2020b)

Table 6: Calculated Emissions

Values	S1	S2	S3	S4
Baseline (CA Grid)				
Carbon Dioxide (Tonnes)	10,393	9,982	2,622	730
Nitrogen Oxide (Tonnes)	16	15	4	1
Sulphur Dioxide (kg)	315	303	80	22
Avoided Emissions				
Carbon Dioxide (Tonnes)	24,696	23,712	6,163	1,540
Nitrogen Oxide (Tonnes)	38	37	10	2
Sulphur Dioxide (kg)	750	720	187	47
Percent Reduction from Base Case				
Carbon Dioxide	238%	238%	235%	211%
Nitrogen Oxide	238%	238%	235%	211%
Sulphur Dioxide	238%	238%	235%	211%

Source: Author, 2020

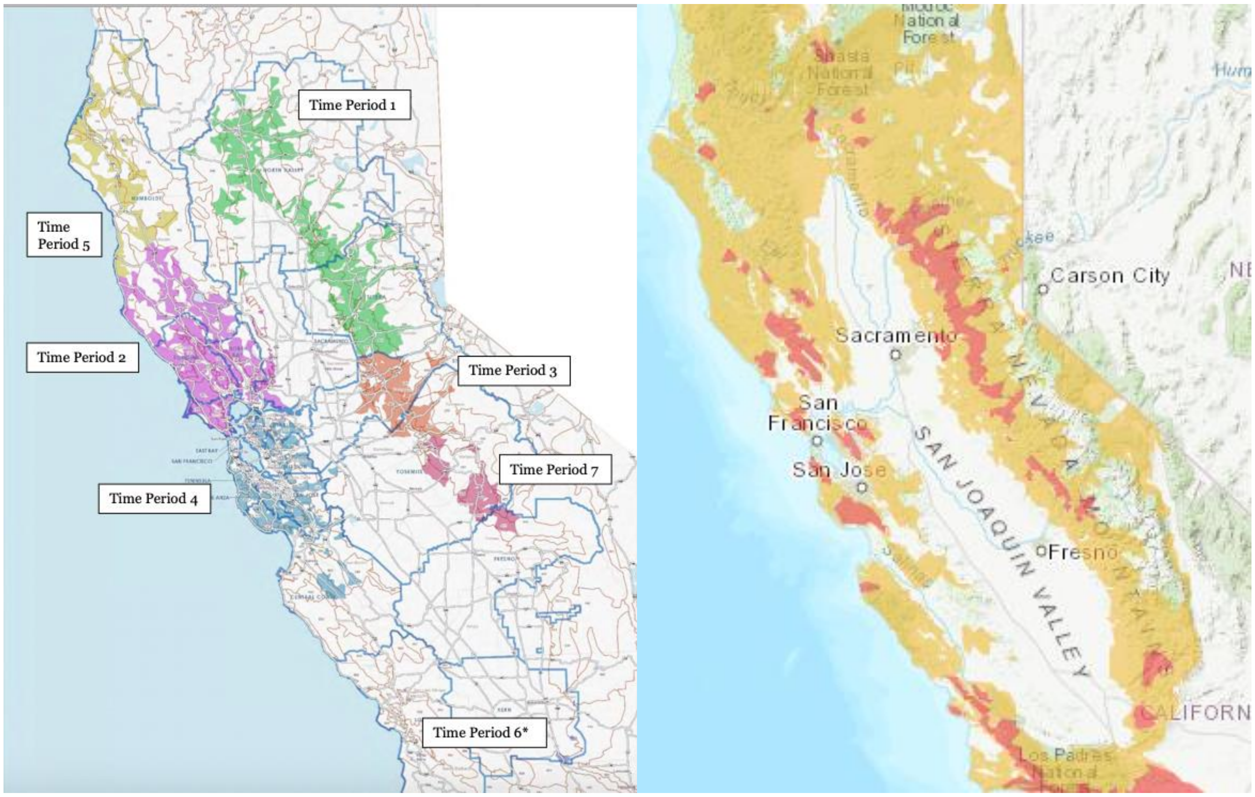
Chapter 12: Discussion

12.1 Location

The chosen location is key to understanding the extent to which the different factors discussed in this paper will impact a project’s success. Location impacts everything from the need for the project and the regulatory environment, to the efficiency of the system and the attractiveness of the project economics. This applies to both locations within California, as well as an expanded scope of locations across North America, or the globe.

Firstly, the chosen location should offer the maximum resiliency benefit. If designed for resiliency rather than maximizing profit, siting the projects in regions with the highest likelihood of frequent power outages will offer the largest social benefit. As can be seen in Figure 13, not all of California is impacted equally by fire activity, or by regular PSPS events. Considering the overlap of these two maps the most ideal locations for microgrid resiliency benefits are throughout the Bay Area, and up the coast through Sonoma, Napa, Mendocino, and Humboldt counties. There is also a large range of overlap throughout the Sierra Nevada mountain range, which would also pose an ideal location for such projects.

Figure 13: Comparison of 2019 PG&E PSPS Events to High Fire Risk Locations

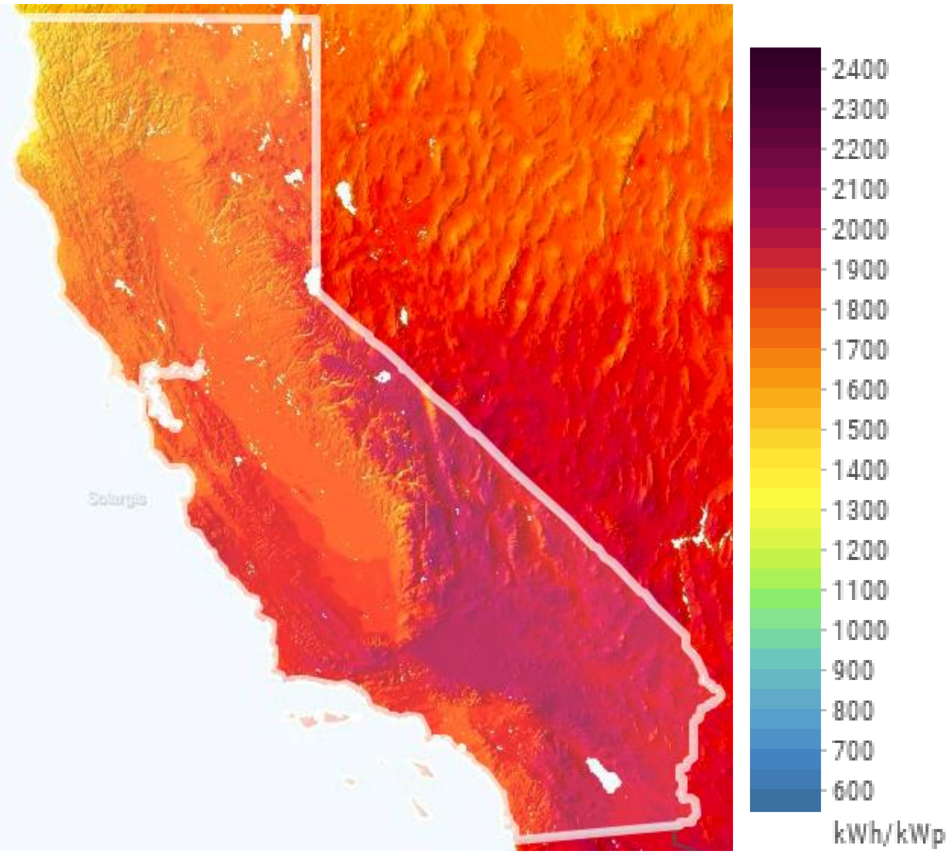


Source: (PG&E, 2020c), (CPUC, n.d.a)

Secondly, location impacts the intensity of solar radiation available to support a PV and storage system. As solar radiation decreases so does power production. This can impact the microgrid in two key ways. First assuming no change to the size of the PV array, the lower solar radiation results in less produced power. This has the dual impact of lowering power exports to the grid which negatively affects annual profits and also requires a larger battery system to enable it to survive long-duration outages. The need for a larger storage system also negatively impacts project economics as it greatly increases the upfront capital cost, while not increasing the revenue generated, as storage systems have lower IRR than PV systems. The second way it could impact the microgrid project is by requiring a much larger solar array to generate the same amount of power. In this case, the annual revenue generated by the system does not change, nor does the size of the storage system. However, due to the larger solar array, upfront capital costs are increased resulting in a longer payback period and lower IRR.

As seen in Figure 14, the solar radiation across California is not evenly distributed. Radiation through the southern portion of the state, specifically in the Death Valley region, is much higher than the radiation on the northern coasts. Direct normal irradiation across the state ranges from 4.31-8.18 kWh/m$_2$-per-day, representative of the difference between the two aforementioned regions (Global Solar Atlas, 2020). However in the regions identified as high risk by CPUC and Cal Fire, we see irradiation values ranging from ~6.2kWh/m$_2$-per-day in Napa, to ~4.3 kWh/m$_2$-per-day in northern Humboldt, and over 7 kWh/m$_2$-per-day in some areas of the Serra Nevada mountains. As such the location of a microgrid system may have some potential trade-offs between high solar irradiance and in turn high PV efficiency, and areas with higher resiliency benefits.

Figure 14: Average Solar Radiation California



Source: (Global Solar Atlas, 2020)

12.2 Regulations

As discussed throughout Chapter 9, California is on the cutting edge of pro-microgrid regulatory change. Since the early 1990s California has been paving the way for integrated renewable DERs. However, specific regulations regarding 3rd party owned and operated residential microgrid systems do not yet exist. Due to this, assumptions are made in the modelling of each system regarding tariffs allowing the systems to buy and sell power from the grid, and to charge from the grid to take advantage of price arbitrage. These assumptions are made based on the decisions that will be made through track 2 and 3 of Senate Bill No. 1339 proceedings in the coming year (CPUC, 2020a). It can be predicted that the outcomes of these proceedings, along with advances in smart metering technology, and a growing consumer interest in participation in microgrid systems will enable these changes in the next several years. That being said, without these changes the economics of the modelled systems would suffer due to lower revenue generation. However, even without these changes, the systems are still able to provide power at an LCOE less than that of the grid, and no impact would be made to the ability of the systems to survive PSPS events, as recent regulatory changes have allowed grid charging of storage systems in the pre-PSPS window.

It can be expected that the requirement for microgrid systems, even those which are 3rd party owned, to fully participate in the CAISO market will not change. While this has the potential to erode profits associated with price arbitrage by forcing the sale of produced power rather than allowing for storage and export at a more favourable rate, the risk of this is not expected to be material. This is due to the large benefit that load shifting has for the grid, and the ability of PV and storage systems to assist in reducing the impact of the duck chart phenomenon. By reducing the impact of the duck chart for IOUs, price arbitrage becomes an added benefit for the producer by allowing for the export of midday solar power in the evening hours when consumption, and therefore prices, remain high.

The majority of microgrid regulations are being made at the state level and will thus apply consistently across all utilities and all regions of the state. However as is stated in Senate Bill No. 1339, greater interlock with municipal and regional governments is being mandated. This could result in a variety of programs being established in different municipalities, some of which may offer more favourable development conditions. For example the City of Napa released a plan in December 2019 to utilize solar and storage microgrid technology to radically increase the resilience of the city’s electrical system, and decentralize itself from the PG&E grid by 2040 (Brookshire, Paulo, & Rubalcava, 2019). The goals of this plan include lowering the price of power in the city, lowering emissions in the city, increasing reliability, and ensuring access to power for vulnerable groups throughout a PSPS event. As such they are very well aligned with the objectives of the systems in this research. This type of plan will likely make the City of Napa, and other municipalities who choose to adopt similar plans, a preferred location for the implementation of microgrid technology.

Although the future of microgrid regulations in California looks very promising for residential microgrid development, it remains one of the largest unknowns of this project. Enough momentum has already been created that there is no doubt there will be a surge in microgrid growth in the near future. The biggest question remains what those grids will look like. Will they be heavily focused on critical infrastructure support, and utility managed, as is suggested with PG&Es RFOs for 2020? Or will they be allowed to grow into self-funded, self-operated, and community-specific systems as have been modelled in this analysis?

12.3 Project Economics

Due to the reliance on the future of microgrid regulations in California, the tariffs that will be applied to 3rd party systems remain unknown. However, by calculating the LCOE for each system, both with PV alone, as well as with the PV and storage microgrid, we can see that even without tariff changes these systems are able to produce power at a fraction of the price of the California grid. The key information which is not yet available, is what the cost will be for non-bypassable charges on new microgrid tariffs, as this would increase the LCOE of microgrid systems proportionately to the charge.

Understanding that the assumptions made in the economic models may not perfectly represent the future of tariffs in California, all 4 systems produced excellent IRRs and Payback Periods. Payback periods ranged from between 7.8-12 years or 31-48% of the 25-year project duration. IRRs ranged from 7.1-11.7% which, when compared to the average discount rate for large solar PV projects of 4.7% (Neff, 2019), represents a positive return on investment. These economic outcomes show that these systems are not only economically viable when compared to the cost of grid power, but can be treated as revenue-generating assets by third party operators.

The economic analysis of modelled systems revealed some key findings regarding the pairing of system segments (i.e., homes, schools, and markets) to gain efficiencies and ultimately lower costs. By first modelling each segment separately the $/W for the school, market, and each of the three residential customer bases can be first calculated individually. By comparing the aggregated costs of each segment, with the costs of the systems when modelled as a whole, a comparison of the $/W of each system before and after bundling the loads can be made. What this shows is that in systems where the power requirement is dominated by a single segment, residential for example in S1 and S2, the savings are minimal. However when the power requirements are more evenly divided between two loads with different peak hours, such and in S1 between residential loads and the school, the offset in peak hours reduced the required capacity of the storage system, thus drastically lowering the $/W when compared to the individual segments; by 49% in the case of S1. This shows that while economies of scale will help to reduce the overall cost of capacity in large systems, with the strategic pairing of alternating loads, small systems can see incremental savings as well.

The economic analysis of these systems does carry some limitations and should only be used as a reference to the general economic viability of solar plus storage residential grids. Specifically, the cost of BTM residential Li-ion batteries varies widely depending on the data source. The values used in these calculations are the default REopt values, and are seemingly low in terms of $/kW for long-duration systems when compared to the 2013-2017 values from the EIA (EIA, 2020a). However, the default $/kWh are much more representative of the EIA data. Due to the rapid evolution of the Li-ion battery market, current and accurate prices are difficult to determine (coupled with the fact that prices can vary depending on scale and purchasing agreements). For this reason I believe that the economics related to the storage system specifically are likely more reflective of future investments over the next several years, than of the investments made in existing systems as they appear to account for a portion of the expected price reduction in Li-ion technology.

Although the economic modelling of the systems attempts to account for the benefit of maintaining power through a PSPS event, it is difficult to know how to value this. Michael Wara's estimate of over $10 billion USD as the total cost of PG&E's 2019 PSPS events alone equates to approximately $5,000 per customer (Wara, 2019). When compared to the rates used in S1-S4 however, this is far higher than the average cost per customer of the models which range from $600-$4000 annually depending on the proportion of power consumed by residential customers, which has a far lower avoidance cost than commercial customers. While the tools available to estimate the cost of PSPS events are still very limited, this points to the possibility that avoided outage benefits in the models could be understated, and the potential benefits of the microgrid systems could be larger than portraited here.

12.4 Operation Business Models

Another factor that will greatly impact the cashflows and economics of any microgrid project is the business model on which It operates. Although very few residential microgrid systems exist currently, by reviewing existing commercial and utility-owned microgrids, both inside and outside of California, as well as industry publications, a better understanding of possible models for their operation can be gained. The most common models used for DER generation currently are net metering, net billing, power purchase agreements, and virtual power plants. Within each of these general categories variations can also be found.

Net Metering

Net metering, as discussed in Chapter 9, is already in place within California. This operating model allows the producer to buy and sell power from the grid, and uses the balance of kWh consumed vs provided to determine net compensation at the end of each period (IRENA, 2019b). As discussed, this model can be very effective for generating revenue from DER assets, however the price of power can be set at a fixed rate, thereby eliminating the benefits of price arbitrage.

Net Billing

Net billing is the business model on which S1-S4 were modelled and is used to calculate the financial metrics presented in Chapter 11. Net billing is very similar to net metering with one key difference. Power is purchased and sold to the grid at real-time prices (IRENA, 2019b). This means that producers are able to take advantage of peak hours to generate greater profit from their assets, but in turn, have to directly purchase power from the grid when needed rather than simply offsetting consumption as is the case in net metering. Depending on the producers needs this can allow for greater profitability, however if the producer consumes a large quantity of power during peak hours, it could erode profits in much the same way. Net billing has been widely used internationally and is currently in place in New York and Arizona. If California chooses to allow for this type of tariff, it would very likely result in increased profitability for microgrid systems.

Power Purchase Agreements

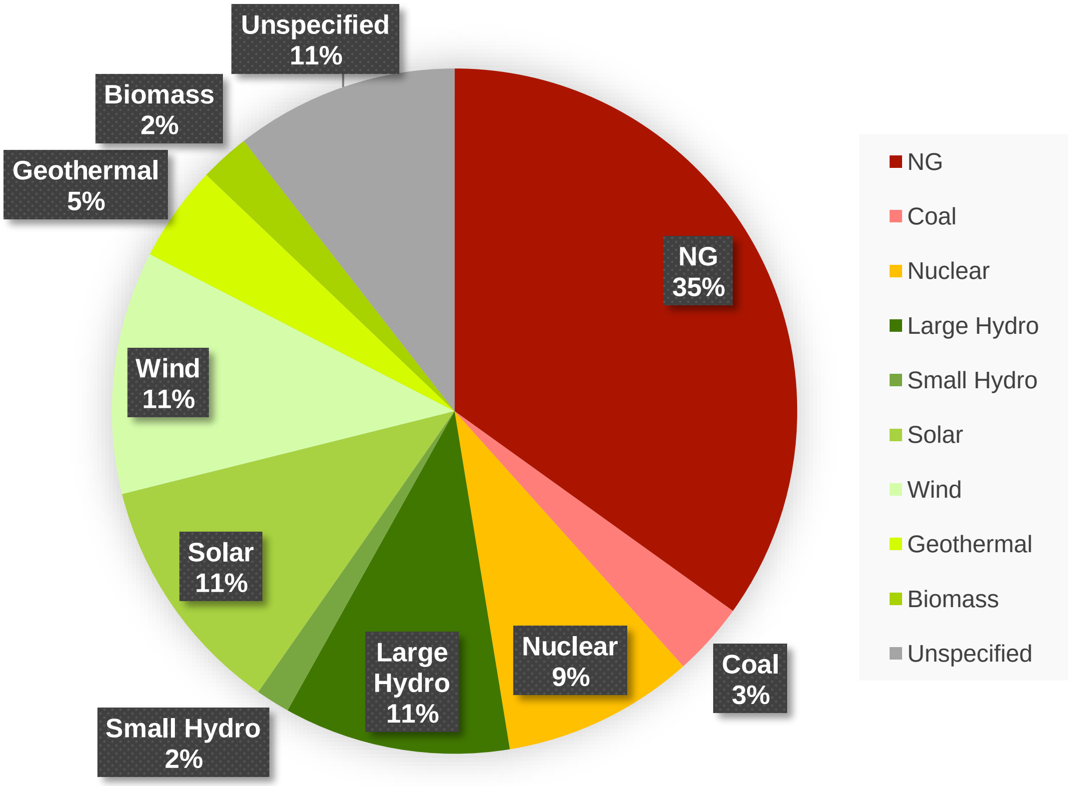
Power Purchase Agreements, or PPAs, offer the greatest diversity among all business models. They involve long term contracts with local utilities for the purchase of power produced by the DER or microgrid (IRENA, 2019b). These agreements often involve fixed prices for the guarantee of a specific quantity of power production. The fixed prices allow for stable cashflows and highly predicable revenue from the systems, however in order to receive this, system control is often forfeited to the utility. This reduces the flexibility of the system to manage its own storage and load requirements.

In addition to fixed power prices, many PPA models have the added benefit of utility funding or financing. An example of this is the Inland Empire Utilities Agency water treatment facility. In exchange for full control of their DER and storage system, Southern California Edison power company fully financed the integration of microgrid technology at the facility (Asmus, Forni, & Vogel, 2018). The water treatment facility is only responsible for small O&M fees annually and receives payment mainly through bill savings. Savings over a specified threshold are then split evenly between the utility and producer, resulting in a small revenue stream if managed efficiently. This type of agreement benefits both parties, the utility benefits from the additional DER capacity, and the producer receives electrical savings for next to no upfront capital costs. Other examples of this type of agreement exist with 3rd party technology developers (such as PV or storage), where the 3rd party will fund a project within a microgrid in return for a portion of the project, or will offer financing for the project through bill savings resulting in no upfront capital costs. In return the developer gets free access to the land the project is built on, and a portion of the profits. These business models are already being applied to commercial microgrid developments, and can have great benefits for residential grid developments as well.

12.5 Emissions

The reductions in emissions from power production enabled by the modelled systems should not come as a large surprise. Although California has the highest production of solar, geothermal and biomass of any state as of 2018, its power mix still contains a large amount of fossil fuel-based generation (EIA, 2020c) (CEC, 2019). As of 2019, 38% of California power is generated from fossil fuels; 35% from natural gas, and 3% from coal (see Figure 15). When compared to the United States as a whole, which relies on fossil fuels for 62.7% of its power needs, including a 24% reliance on coal, California’s power mix clearly reflects the states push for further integration of renewable energy (EIA, 2020f).

Figure 15: California Electrical Grid Mix 2019



Source: Author – Developed from (EIA, 2020c)

As is reflected in Figure 15, renewable power, including large hydro, makes up 42% of California's power mix (EIA, 2020c). Adding nuclear generation into the mix, 49% of the state's power is generated from carbon-free resources. The current goals established in the Clean Energy and Pollution Reduction Act and Senate Bill No. 100 require 60% of power sales to be sourced from carbon-free resources by 2030, and 100% by 2045 (CPUC, n.d.d). While the ramp-up to 100% is still 25 years away, it can be expected that programs encouraging renewables investment will continue to grow to support these goals. This offers an excellent opportunity for renewable DERs, including microgrid designs such as the ones modelled in this research project.

The analysis of the avoided emissions for each system also shows that renewable DERs paired with microgrid technology are very effective at offsetting personal and community level greenhouse gas (GHG) emissions. Based on the EPA’s emissions equivalency calculator, S1 is able to avoid emissions equivalent to removing 7,782 vehicles from the road, or the equivalent of the carbon sequestered by 47,040 acres of forest land (EPA, 2020). S4, the smallest system, is able to avoid GHGs equal to 461 vehicles or 2,790 acres of forest. When looking at this compared to the populations of the communities, S1 is able to eliminate the equivalent of 1.7 vehicles per household, and S1 4.6 vehicles per household. This the equivalent of offsetting roughly all vehicle emissions for the entire population of the community.

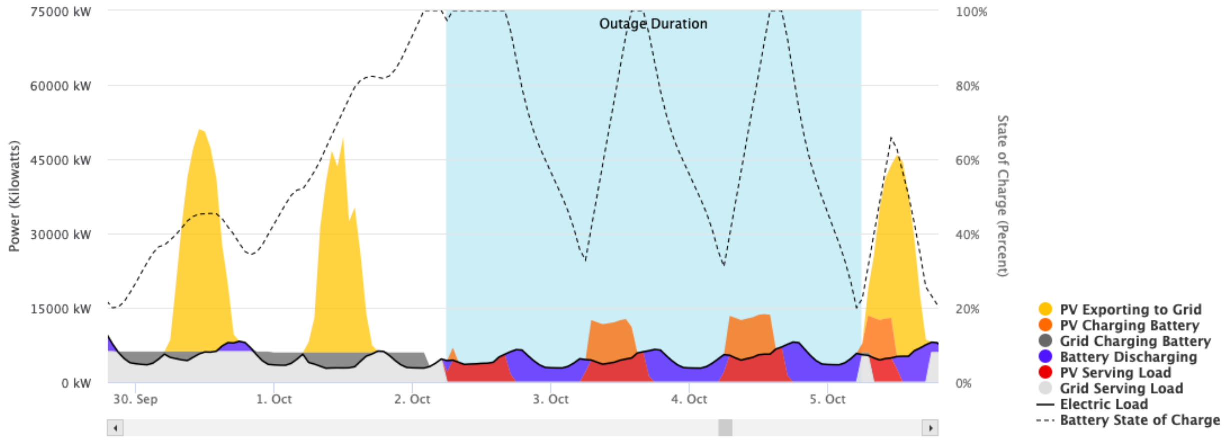
12.6 Resiliency

The primary factors impacting the resiliency of a microgrid system are the duration of outage, the storage systems energy capacity, and the ability to charge the system to maximum capacity prior to an outage. All of these factors culminate in the ability or likelihood of a system to survive a given outage period. There are several of these factors that have a unique advantage and/or disadvantage based on the location of the projects within California.

Firstly, the outage durations in California, based on 2019 PSPS event data, have the potential to be very long-duration outages, such as the nearly 6-day blackouts seen on Oct 26, 2019. This has a distinct impact on the design requirements of the storage solutions. The batteries in these resiliency-focused microgrids require a higher energy capacity-to-power capacity than would be needed in systems with shorter expected outage durations.

Although outages are expected to be several days in duration, it is also required that IOUs provide advanced notice of PSPS events before de-energizing the grid. This window allows for the energy storage system to charge to its maximum energy capacity using grid sourced power prior to the outage. This charging during this pre-PSPS window can be seen in Figure 16, showing the charge and discharge of the Li-ion battery before and during an outage. This ability to fully charge lessens the need for larger PV systems which would only be fully utilized for charging during these pre-PSPS windows. These regulatory requirements enable a smaller system to survive longer outages than they would in other regions that do not or cannot provide this advanced notice.

Figure 16: Pre-PSPS Window Charging of Modelled Storage System (S2)



Source: REopt Lite (2020)

The ultimate indicator of the resiliency of each of the modelled systems is the survival rate presented in Table 2. At first glance these survival rates, ranging from 38-40%, may seem quite low for a project built specifically for its resiliency benefits. However, it is important to understand what these values truly mean. Each score is a measure of the percentage of 72-hour PSPS events which could be survived by each system in a given year. To calculate this, a 72-hour outage is modelled on each day of the year and the specific power loads and solar resources available during that period are used to calculate whether the system can sustain power throughout the full outage. What is important to understand is that solar resources and electrical loads vary greatly depending on the time of year. Lower solar resources are available throughout the winter along with increased heating and lighting demands, and higher solar resources are available along with higher cooling needs in the summer. Due to this, the likelihood of a system to survive an outage is far higher in the summer months, and far lower in the winter months. This can work in a system's favour as the highest risk of a PSPS event is throughout the fall and later summer months, when resiliency is higher compared to winter. In the same way that seasonality can impact the resiliency of the system, low solar resources during an outage at any time of year can result in a failure to maintain power. Microgrid systems need to be built with the ability to survive the expected conditions, however this does not mean they will always perform as expected.

During periods of lower solar radiation, or when a higher risk survival is present, increases in energy efficiency can prolong the available supply of power. Long term this may present itself as appliance upgrades and high-efficiency lighting within communities with microgrid systems. However, short term solutions also exist which can be rapidly deployed when needed. This includes simple restrictions on electricity consumption during and leading up to PSPS events. Such restrictions could include reducing or eliminating the use of heating and cooling appliances among non-vulnerable populations, limiting the power quality for lighting throughout the community, or restricting usage of non-critical electrical devices. With advancements in smart grid technology, these limits, or lowering of power quality, will soon be able to be controlled remotely and applied to specific customers within the microgrid.

More so than power consumption, the intermittency of solar PV generation is the greatest hurdle to overcome in the resiliency of a solar plus storage microgrid, and introduces nearly all of the risk related to not surviving a specific outage. For this reason, while outside the scope of this paper, access to small scale NG turbines, or other fuel-based generators, can greatly increase the resiliency of a microgrid, while only moderately increasing emissions related to the system if used sparingly. Fuel based systems still provide far superior resiliency when compared to solar or wind power, and should continue to be utilized for critical infrastructure such as health care and emergency services.

Chapter 13: Conclusions

This research project has highlighted the key factors for consideration when implementing a successful community microgrid within California, and the high-level of interaction between each factor. This chapter will conclude the study by offering recommendations for investing in resilient community microgrid projects throughout the state, along with outlining the key limitation of this research, and the possible focuses of future research in the field.

13.1 Recommendations

Before deciding to invest in a community microgrid system, project location and local regulations must be carefully considered. Based on the results of this study the most promising regions of the state for these projects are the northern coastal counties of Sonoma and Napa, and the Sierra Nevada mountain range. Along with high solar resources, projects in these regions will offer the greatest resiliency benefits for the communities they serve, and will have further reaching social impacts. Due to the high need for increased power reliability, these counties and local municipalities are likely to be more receptive to microgrid projects and may offer greater incentive for investment.

Due to the standardization of IOU tariffs throughout the state, the greatest impact to project economics is likely to come from the choice of business model. As outlined in the discussion of this research, many options are, or are likely to become, available. The size and purpose of each individual project, along with potential stakeholders, is likely to impact which options are best suited to each development. That being said, net billing and PPA business models will likely offer the greatest economic benefit for community-level projects. Where upfront capital is available, net billing models are likely to offer the greatest return on investment. This is due to the control the producer has over the timing of electrical consumption and export to the grid. It enables price arbitrage and load-shifting to a greater degree than other operational models. However, if upfront capital is difficult for the developer to secure, PPAs may be a better option for these projects. PPAs can offer excellent funding and financing options through either utilities or 3rd parties, which can result much lower, or in some cases no upfront capital requirements. These agreements can also accelerate the implementation of a project, and therefore the resiliency benefits for the community, by reducing the time required to raise capital.

The biggest concern for developers of these systems should be regarding the resiliency of the system and its ability to survive long-duration outages. The systems modelled in this study were based on outage durations of 72 hours, only half the duration of the longest PSPS events experienced in 2019, and were still only able to achieve a 40% survival rate. This points to the massive storage requirements needed to survive long duration power shutoffs. The risk of not maintaining power throughout a PSPS event should be carefully considered. For low-risk populations the guarantee of power throughout the full outage may not be required, and the benefits of several days of backup, along with lower quality power after the grid charging of the battery has been consumed, may offer enough benefit to warrant the investment. However, for at-risk populations, medical customers, or critical infrastructure, this risk may be outside the tolerance of the customers. In these situations, communities should consider pairing PV panels with small fuel-based generation methods for the added resiliency factors they provide.

Although the added resiliency of fuel-based generators may be required for some customers, the benefits of lower environmental impacts offered by PV or other renewables should not be ignored. The emission reduction goals established by the California regulators have resulted in funding being directed almost entirely to net-zero emission producers. Projects promising emissionless generation are also being fast tracked through regulatory processes, and pairing these projects with storage has opened the doors to further economic incentives over the past year. The appeal of renewable power generation in other regions can also be seen through the utilization of carbon credits. Where net metering or net billing operating models are not in practice, the sale of carbon credits can offer an additional revenue stream for developers.

Overall the future of microgrid projects in California looks very promising and should be expected to see high growth in the coming decade. The opportunities for the implementation of this technology in other regions around the world are likely to grow as well. The impacts of global warming are seen differently around the globe, from increased tropical storms, wildfires, flooding, other devastating weather events. Each of these events has the potential to interrupt local electrical services in a region, and microgrids offer a means to mitigate this risk. It is my hope that the findings of this study can be applied, not just to California, but to other at-risk regions as well, and assist in the way the development of these projects is approached.

13.2 Research Limitations

The primary limitations encountered throughout this study were the result of a rapidly evolving regulatory environment, the equally rapid evolution in power storage and PV technology, and the lack of tools available to calculate the cost of power outages.

Regulations

As stated throughout this research project, the regulatory environment of California promises to be highly beneficial to the integration of microgrid systems. However, the rapid evolution of this field, stemming mainly from the high use of PSPS events in 2019, has made it difficult to predict what the end result will look like. Revolutionary changes to the treatment of DERs and storage systems offers ample opportunity, but it is difficult to say if different treatment or tariffs will apply to islandable systems. As a result, the assumption made throughout this study carry with them a high level of uncertainty. However, it is not expected that the ultimate state of regulation will differ greatly from what has been predicted here based on the progress thus far.

PV and Storage Technologies

The greatest uncertainty with the rapid growth and development of PV and Li-ion technologies is regarding the price of these technologies in the future. The decline in cost over the past decade has been unprecedented among other power infrastructures, and as such, it is difficult to predict where the cost savings will end. What is known for certain is that the cost of renewables and battery storage will continue to drop over the next decade. This creates a challenge determining whether it would be worthwhile to wait for prices to drop further before investing, or if the price reduction can be offset by years of revenue generation if investments are made now.

The cost of systems introduced another limitation to the economic evaluations of S1-S4. Without a lot of reference points for microgrid cost, or residential microgrid costs, it is difficult to determine how economies of scale may impact these systems. For this reason, all modelled scenarios used the same costs of technology. It is very likely however that larger investments will see a reduction in the $/W installed over smaller projects. The degree to which this will impact project economics is not well understood however. As such no economies of scale were factored into this study.

Cost of PSPS Events

Finally, due to the infancy of the PSPS phenomenon, there are very few tools available to accurately calculate the societal cost of these events. Without these tools the true benefits of resilient microgrids are difficult to calculate. As more microgrids are established, and additional years of PSPS data become available, more tools for calculating their impacts will become available. Until such time however a significant assumptions are required.

13.3 Opportunities for Future Research

The opportunities to utilize microgrid for resiliency benefits, the range of system designs, and the factors that will impact their deployment are limitless. The factors and system designs studied in this research are only a small sample of what is available. As research on the topic continues I hope the following topics will be evaluated.

1. Application of combined heat and power to community-scale microgrids
2. Evaluation of the impacts of community design on microgrid efficiencies
    a. Centrally located PV systems vs roof-mounted
    b. Single large-scale storage system vs many small-scale household models
    c. Integration of EV storage
3. The social benefits of community microgrids
4. Further investigation into new business models for DER and microgrids

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Appendix A: REopt Segment Inputs and Data Sources

Table 1: Common Inputs to All Models and Segments

Input	**Unit**	**Value**	**Source**
Location		Napa	
Electricity Rate		E-20 Demand of 1000KW or more Option R (Secondary)	(PG&E, n.d.)
Net metering System size Limit	kW	1,000,000	
Outage Durations	Hrs	72	
Outage Start Date		02-Oct	
Outage Start Time		6:00 AM	
Type of Outage		Annual	
Discount Rate	%	4.68	(CEC, 2019)
Electricity Cost Escalation	%	2.3	REopt
PV System Capital Cost	$/kW	$1,600	REopt
Battery Energy Capacity Cost	$/kWh	$420	REopt
Battery Power Capacity Cost	$/kWh	$840	REopt
Allow Grid to Charge Battery?		YES	
PV O&M Fixed	$/kW	$20.08	(CEC, 2019)

Source: Author, 2020

Table 2: REopt Inputs Grocery Market

Input	**Unit**	**Value**	**Source**
Land Available	Acres	0	
Roof Space	sq-ft	45,000	(Forni, Asmus, & Willette, 2019)
Roof available for PV		90%	Calculated
Total PV Area	sq-ft	40,000	(Forni, Asmus, & Willette, 2019)
Type of Building		Market	
Annual Energy Consumption	kWh	1,841,655	REopt
Critical Load Factor	%	90%	(Klemick, Kopits, & Wolverton, 2015)
Microgrid Cost Upgrade	% of Total	33%	(Giraldez, Flores-Espino, MacAlpine, & Asmus, 2018)
Avoided Outage Costs	$/unserved kWh	$94	Calculated from ICE (See Table 6)

Source: Author, 2020

Table 3: REopt Inputs High School

Input	**Unit**	**Value**	**Data Source**
Land Available	Acres	0	
Roof Space	sq-ft	105,000	REopt
Roof available for PV		85%	
Total PV Area	sq-ft	90,000	Calculated
Type of Building		School	
Annual Energy Consumption	kWh	2,327,074	REopt
Critical Load Factor		100%	Assumed 100% expecting use as community hub
Microgrid Cost Upgrade	% of Total	10%	(Giraldez, Flores-Espino, MacAlpine, & Asmus, 2018)
Missed School Cost	$/student-day	$29	(Faryon, 2011)
Average School Size	Students	1,330	(Education Data Partnership, n.d.)
Cost of School Closure	$	$38,570	Calculated based on above
Average October School Day	kWh	8,725	REopt
Avoided Outage Costs	$/unserved kWh	$4	Calculated based on above

Source: Author, 2020

Table 4: REopt Inputs Large Community

Input	**Unit**	**Value**	**Data Source**
# Customers/Homes		4,500	
Energy Consumption/Home	kWh/yr.	9,422	(PG&E, n.d.)
Land Available	Acres	0	
Roof Space/Home	sq-ft	1,700	(Roofing Calc, n.d.)
% of Roof available for PV		27%	(Paidipati, Frantzis, Sawyer, & Kurrasch, 2008)
Total PV	sq-ft	2,065,500	$= homes \times sqft\ pre\ home \times \%\ roof\ available$
Type of Building		Midrise	
Annual Energy Consumption	kWh	42,399,000	$= homes \times energy\ consumption\ per\ home$
Critical Load Factor		80%	Reduced heating, lighting, and cooling
Microgrid Cost Upgrade	% of Total	20%	(Giraldez, Flores-Espino, MacAlpine, & Asmus, 2018)
Avoided Outage Costs	$/unserved kWh	$2	See Table 7

Source: Author, 2020

Table 5: REopt Inputs Medium Community

Input	**Unit**	**Value**	**Data Source**
# Customers/Homes		1,000	
Energy Consumption/Home	kWh/yr.	9,422	(PG&E, n.d.)
Land Available	Acres	0	
Roof Space/Home	sq-ft	1,700	(Roofing Calc, n.d.)
% of Roof available for PV		27%	(Paidipati, Frantzis, Sawyer, & Kurrasch, 2008)
Total PV	sq-ft	459,000	$= homes \times sqft\ pre\ home \times \%\ roof\ available$
Type of Building		Midrise	
Annual Energy Consumption	kWh	9,422,000	$= homes \times energy\ consumption\ per\ home$
Critical Load Factor		80%	Reduced heating, lighting, and cooling
Microgrid Cost Upgrade	% of Total	20%	(Giraldez, Flores-Espino, MacAlpine, & Asmus, 2018)
Avoided Outage Costs	$/unserved kWh	$2	See Table 7

Source: Author, 2020

Table 6: REopt Inputs Small Community

Input	**Unit**	**Value**	**Data Source**
# Customers/Homes		100	
Energy Consumption/Home	kWh/yr.	9,422	(PG&E, n.d.)
Land Available	Acres	0	
Roof Space/Home	sq-ft	1,700	(Roofing Calc, n.d.)
% of Roof available for PV		27%	(Paidipati, Frantzis, Sawyer, & Kurrasch, 2008)
Total PV	sq-ft	45,900	$= homes \times sqft\ pre\ home \times \%\ roof\ available$
Type of Building		Midrise	
Annual Energy Consumption	kWh	942,200	$= homes \times energy\ consumption\ per\ home$
Critical Load Factor		80%	Reduced heating, lighting, and cooling
Microgrid Cost Upgrade	% of Total	20%	(Giraldez, Flores-Espino, MacAlpine, & Asmus, 2018)
Avoided Outage Costs	$/unserved kWh	$2	See Table 7

Source: Author, 2020

Table 7: Interruption Cost Estimator (ICE) Tool Calculations (Lawrence Berkeley National Laboratory, n.d.)

Scenario	**Market**	**Small Community**	**Medium Community**	**Large Community**
ICE Inputs				
State	California	California	California	California
Non-Residential Customers	1	0	0	0
Residential Customers	0	100	1,000	4,500
SAIFI	1.5	1.5	1.5	1.5
SAIDI	500	500	500	500
CAIDI				
ICE Outputs				
Cost Per Event	$27,303.05	$11.41	$11.41	$11.41
Cost Per Average kW	$521.08	$13.88	$13.88	$13.88
Cost Per Unserved kW	$93.80	$2.39	$2.39	$2.39

Source: Author, 2020

Appendix B: REopt S1-S4 Model Inputs

Table 1: S1-S4 Model Inputs (Sourced from aggregate of segment parts)

Inputs	**Units**	**S1**	**S2**	**S3**	**S4**
Total PV Area	sq-ft	2,195,500	2,155,500	549,000	135,900
Type of Building		Custom	Custom	Custom	Custom
Annual Energy Consumption	kWh	46,567,729	44,726,074	11,749,074	3,269,274
Critical Load Factor	%	81%	81%	84%	94%
Microgrid Cost Upgrade	% of System cost	20%	20%	20%	25%
Avoided Outage Costs	$/unserved kWh	$6	$2	$2	$4

Source: Author, 2020