Improving Energy System Resilience at Berkeley Lab and Beyond

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1 EXECUTIVE SUMMARY

This report provides recommendations for Lawrence Berkeley National Laboratory (Berkeley Lab) and other entities to improve energy-system resilience in response to electrical power disruptions for which Berkeley Lab receives advanced notice, as well as other hazards that may affect energy services without notice, primarily local fires and major earthquakes.

The recommendations are informed by Berkeley Lab's experience responding to Public Safety Power Shutoff (PSPS) events in the fall of 2019 that resulted in three days of electrical power disruption. The Lab was closed a total of nine days to accommodate an orderly process of powering down buildings before power outages and restarting operations thereafter. Loss of electricity services poses a significant cost to Berkeley Lab associated with disrupting research and its operation of public user facilities such as the National Energy Research Scientific Computing Center (NERSC), the Advanced Light Source, the Molecular Foundry, and the Joint Genome Institute. The recommendations are also based on an evaluation of the costs, environmental risks, space constraints, and resilience characteristics of several electricity generation and storage technologies. The evaluated technologies include gas turbine systems operating on natural gas, reciprocating engine gensets using a variety of fuels, solar photovoltaics, electricity storage using lithium-ion and redox-flow batteries, and various configurations of fuel cells with and without hydrogen storage.

High-level recommendations to improve energy-system resilience include:

- Deploy energy solutions able to respond to a range of likely hazards and disruptions to both electricity and natural gas service
- Avoid a single, centralized fossil-fuel based solution
- Take steps to create a flexible modular microgrid, where feasible, to increase resilience and improve operating performance
- Prioritize integrated renewable generation and storage systems that have the capability to produce year-round value in addition to providing backup power
- Integrate renewables and storage with engine gensets to improve genset utilization, increase flexibility, and address typical operational issues associated with standby generators
- Develop load shedding and demand-side strategies to reduce backup energy requirements
- Explore energy-related partnerships with neighboring organizations or entities

For Berkeley Lab, the analysis suggests that no single energy solution installed as a retrofit adequately addresses all constraints and significantly improves resilience at the Lab. However, a mix of energy solutions including supply, storage, and demand management integrated into a microgrid built upon the foundation of the Lab's existing electricity distribution system can significantly enable energy-system resilience.

Near-term recommendations to improve energy resilience at the Berkeley Lab main site include:

- **Flexible Deployment of Gensets**: Deploy gensets to provide benefit at the distribution level with paralleling switchgear (either directly at 12kV or by backfeeding through 12kV-480V

transformers) rather than restricted to a small subset of loads at individual buildings, as has been typical for standby generators. Mitigate air pollution and provide redundancy by using dual-fuel (diesel and natural gas or natural gas and propane) units and avoid long-term commitments to diesel genset expansion by using temporary (rented or portable) units. This would provide backup power with a capability for closed-transition (seamless) switching during planned outages like a PSPS, flexibility to allow generation and storage assets to serve multiple buildings (within one neighborhood or across neighborhoods at the Lab), and improve utilization and operating characteristics of gensets.

- **Integration of Renewables and Storage**: Integrate renewable technologies and storage with alternative and traditional gensets at the electricity distribution or building level. These integrated solutions can demonstrate approaches that both reduce environmental impact and increase resilience, provide year-round value, and create opportunities for learning and research.
- **Load Shedding**: Develop and pilot automated and manual load-shedding strategies to mitigate the size and cost of new energy solutions. A preliminary assessment of sheddable load indicates that the Lab's current peak load of 19 MW can be reduced to 10 to 12 MW while maintaining many mission-valuable activities.
- **A Microgrid Plan**: Create a phased microgrid transition plan for the Lab that incorporates both supply-side and demand-side management with the goal of achieving an energy system that is resilient to future power interruptions from the grid.

Over the longer term, a "living laboratory" approach in which targeted Laboratory research is coordinated with on-the ground experience could play a key role in accelerating technology development and the Lab's transition from backup solutions based primarily on diesel gensets to widespread deployment of cleaner distributed energy resources. The living-lab infrastructure would be designed for robust operation and fault-tolerant delivery of service while enabling development of and experimentation with new generation and storage technologies, systems management, data collection and controls. Contributing research agendas include development of:

- **Low-cost, low-emission electrochemical alternatives to diesel generators**, building upon Lab strengths in the Energy Storage and Distributed Resources Division in batteries and fuel cells
- **Demand-side load management and microgrid optimization for resilience**, building upon Berkeley Lab's unique capabilities in the Demand Response Research Center and Building Technologies and Urban Systems Division work on advanced controls
- **A resilience accelerator and microgrid testbed for emerging generation and storage technologies**, a unique integration of emerging generation and storage technologies, electric and fuel-cell vehicles

2 INTRODUCTION

This report provides recommendations for Lawrence Berkeley National Laboratory (Berkeley Lab) and other entities to improve energy-system resilience in response to electrical power disruptions for

which Berkeley Lab receives advanced notice, as well as other hazards that may affect energy services without notice, primarily local fires and major earthquakes.

Numerous resilience frameworks have been developed for different applications, including many focusing specifically on energy systems (Gasser et al 2019). Figure 1 shows commonalities across these frameworks and vocabulary commonly used to describe aspects of resilience. The key commonalities include (1) a time element that begins before the impact of a hazard event and extends through recovery from the impacts of the hazard, represented by the x axis on Figure 1, and (2) a quantitative measure of system performance, represented by the y axis of Figure 1. Examples of a quantitative measure of system performance could include the number of people that receive energy services or the number of building occupancy hours that meet a certain service threshold.

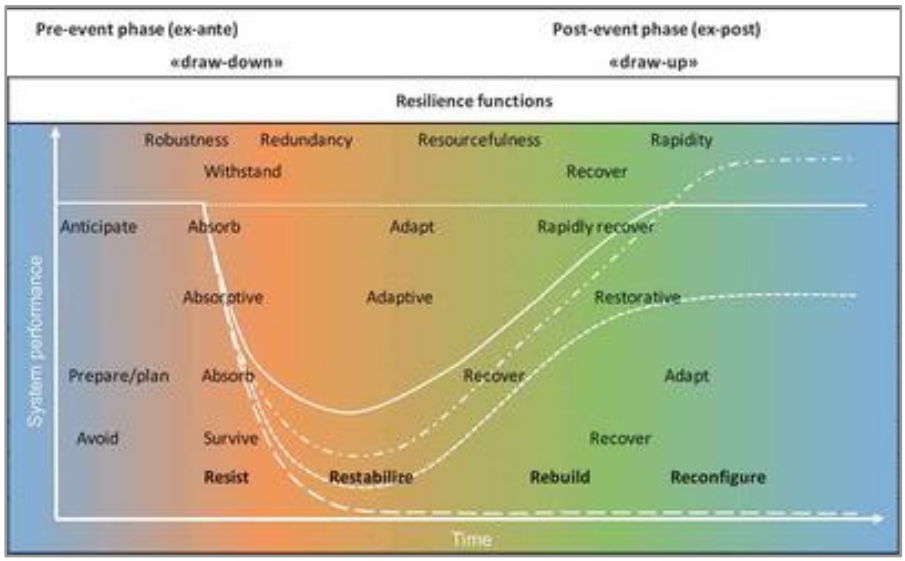

Figure 1: Resilience Frameworks (Gasser et al 2019)

While this report has not adopted a specific definition or framework for resilience, the discussion related to resilience herein assumes that a resilient energy system will tend to:

- Reduce or absorb the effects of hazard impacts, including those from unplanned hazard events
- Expedite restoration of system performance, not necessarily returning to pre-event conditions

Flexibility of resilient systems, for example the ability to seamlessly shed non-critical loads, is increasingly critical. Flexibility can help absorb impacts, speed recovery, and allow reconfiguration around new, post-event conditions.

3 Hazards and Impacts

This section explores the most likely hazards and their impacts to energy systems at Berkeley Lab. The most likely hazards are selected based on prior hazard assessments at the Lab and a review of

historical hazard events that have impacted, or come close to impacting, energy systems at the Lab. The most likely hazards include earthquakes and fires, as well as related impacts, such as a Public Safety Power Shutoff (PSPS), in which the utility preemptively turns off power during dry and windy conditions in order to eliminate the potential that the electric power system itself provides an ignition source that starts a wildfire. As energy systems involve both the supply of energy and demand for energy services, consideration is also given to potential hazards that affect operating patterns and the need for energy services in different locations and times. For example, a health epidemic can affect energy demand by sharply reducing the number of onsite staff and by necessitating changes in the way buildings are operated, affecting their energy consumption.

3.1 Hazards and Impacts

3.1.1 Prioritization of Hazards at Berkeley Lab

The Lab has established procedures to systematically review potential hazards within the context of a comprehensive emergency management system. These procedures are driven by Department of Energy (DOE) Order 420.1C and outlined in the Lab's Requirements and Policies Manual. The Lab's current assessment of natural phenomena hazards identifies seismic, wildland fire, and landslides as "notable hazard risks to be mitigated" (LBNL 2014). This assessment focuses on risks to buildings and does not address energy infrastructure directly.

In 2018, as required by an October 2016 DOE Secretary memo, the Lab conducted a climate vulnerability screening using an approach developed by DOE. The screening results were captured in a spreadsheet that cataloged site infrastructure assets and past extreme weather impacts, identified projected climate stressors, and assessed climate impacts based on the severity and likelihood of impacts to critical infrastructure. The result of the screening was a risk matrix, with relative ranking of climate-related risks. The screening identified increased frequency and intensity of precipitation events and increased wildland fire frequency as the two biggest risks along with increased frequency and intensity of heat waves, increased frequency and duration of drought, and higher average sea level and storm surge (affecting the Lab's locations outside of its main hill site). Generally, the climate vulnerability screening as well as the Lab's natural phenomena hazards assessments focused on hazards from local fires rather than the impacts associated with regional and distant fires.

3.1.2 Earthquakes

The Hayward Fault Zone runs between the University of California (UC) Berkeley campus and the Lab along the east side of Gayley Road (Figure 2). The United States Geological Survey (USGS) places the probability of one or more earthquakes between 2014 and 2043 in the San Francisco Bay Area with a magnitude of 6.7 or greater at 72% (USGS 2016). According to the USGS, "two factors combine to make the Hayward Fault very dangerous" (Brocker et al 2018). The first is the fault's proximity to urban centers (including Berkeley Lab) and the second is that it has been more than 150 years since that last damaging earthquake on the fault. Quoting from the 2018 USGS report:

> "USGS scientists have found evidence for 12 quakes on the southern Hayward Fault during the past 1,900 years. Notably, the last six quakes (in 1134, 1317, 1475, 1629, 1725, and 1868) occurred at intervals of 95 to 183 years, with an

average interval of about 150 years. The 150th anniversary of the 1868 quake is in 2018; scientists are convinced that the Hayward Fault has reached the point where a powerful, damaging earthquake can be expected at any time."

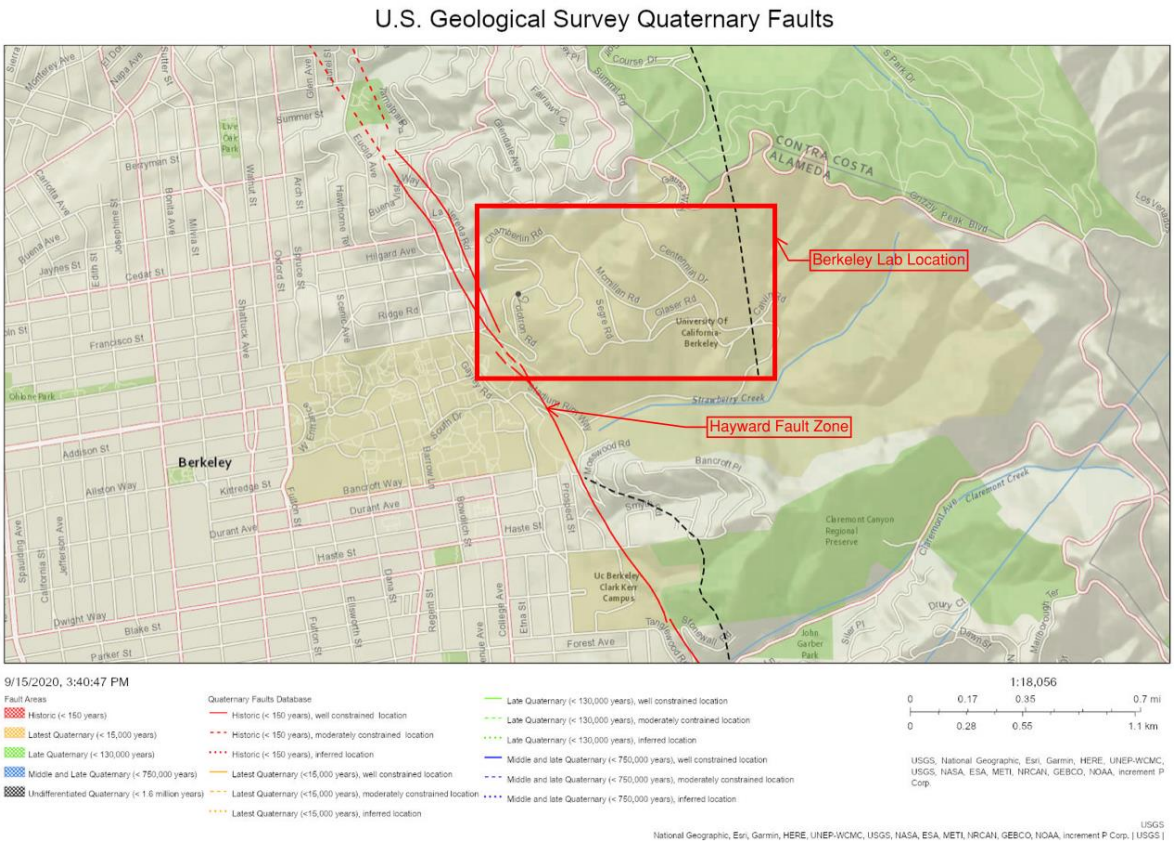

Figure 2: Hayward Fault Zone running between UC Berkeley and the Lab (USGS *US Quaternary Faults Database*)

A major earthquake in the Bay Area could significantly disrupt everyday life and energy services directly. The Association of Bay Area Governments estimates that a magnitude-7.0 earthquake on the Hayward fault in the San Francisco Bay Area would displace over 145,000 households (Brechwald 2018). Over half of the displaced households are expected to be in Alameda County (where the Lab is located), with approximately 14% of all households in Alameda County expected to be displaced. This would presumably affect the ability of Berkeley Lab staff to work, either at the Lab or remotely. The USGS conducted an extensive planning effort including assessment of impacts from a hypothetical magnitude-7.0 earthquake on the Hayward Fault (Detweiler and Wein 2017). They calculated infrastructure restoration curves for electricity service in Alameda County, indicating that about 90% of electricity service would be disrupted immediately following the earthquake. After three days, approximately 40% of service would remain unavailable, after seven days approximately 20% of service would remain unavailable, and approximately 5% of service would remain unavailable after 30 days. The infrastructure restoration curves for Alameda County in days following the main earthquake event for electric power, voice and data communications, water distribution, and transportation (BART public transit and highway bridges) are presented as Figure 3.

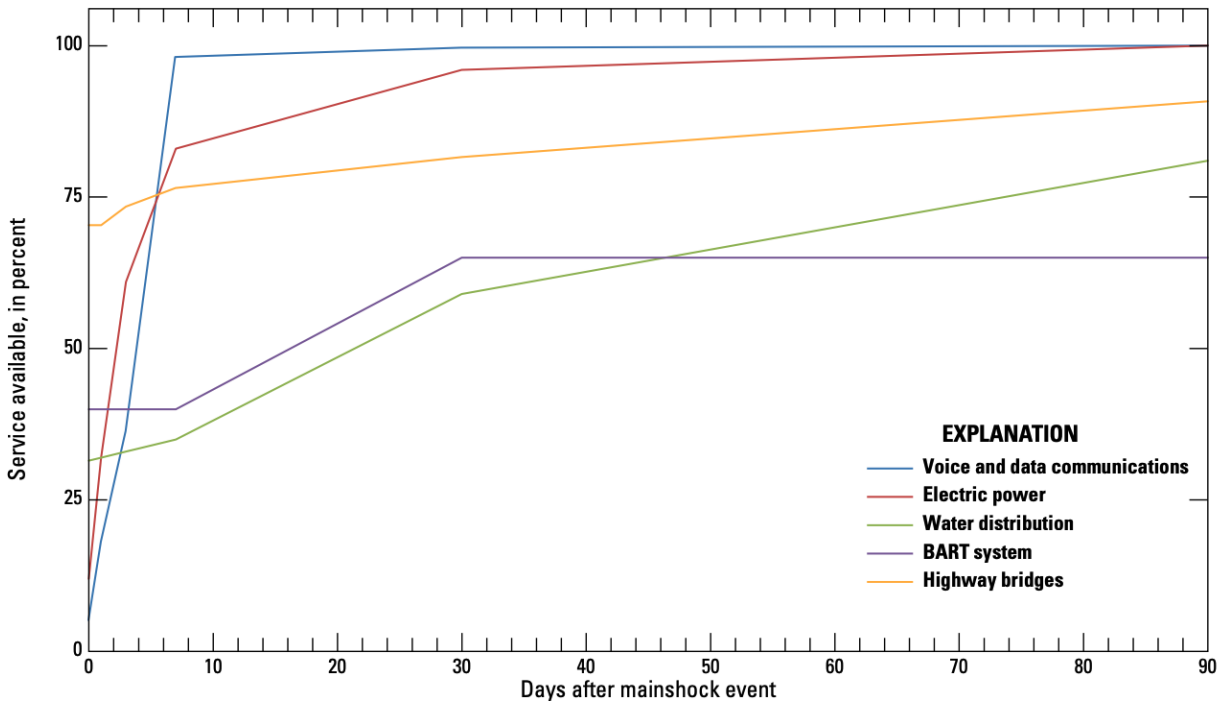

Figure 3: Infrastructure restoration curves for Alameda County (Detweiler and Wein 2017)

Although the USGS did not prepare a natural gas restoration curve, PG&E provided a written statement summarizing their internal models for a similar earthquake scenario, estimating that 40 transmission locations and 2,000 gas distribution leaks would need repair. According to the USGS study, "The amount of time to assess, repair, and restore gas service to customers would be significantly longer than that of electric power restoration." They estimated that restoration of gas service, involving relights at over 200,000 customer locations, would take many months to complete. A report by Sandia National Laboratory modeled disruptions to fuel infrastructure in the San Francisco Bay Area following a magnitude-7.0 earthquake on the Hayward fault, centered in Berkeley. Their model indicated a complete disruption of fuel delivery to the San Francisco Bay area for three days (due to power outage) and an 80 percent reduction in fuel deliveries for a period of 30 days as pipelines were repaired (Wilson et al 2015).

Fires following earthquakes are well-documented in California. An analysis prepared for the City of San Francisco, modeled a magnitude-6.9 earthquake on the Hayward Fault, yielding 27 to 46 ignitions that burned 3.6 to 11 million square feet of built space (Scawthorn 2010). A review of 110 ignitions following the 1994 Northridge earthquake indicated that about half of ignitions were caused by electrical sources, 25% by gas sources, and the remaining by other sources including chemical reactions (Scawthorn 2008, Scawthorn 2010). For Northridge, educational facilities accounted for about 3% of ignitions, mostly from spilled chemicals in laboratories. The American Society of Civil Engineers compiled a summary of fire ignition following 10 major earthquakes (nine in the US) and concluded that natural gas generally contributes between 20% to 50% of all earthquake-related fire ignitions (ASCE 2002).

3.1.3 Wildfires

The Lab is situated in an area of elevated and extreme risk of fire and also prone to experiencing smoke pollution impacts from regional and distant fires. The main hill Lab site is located in CalFire's highest Fire Hazard Severity Zone ("very high") and within the California Public Utilities Commission's (CPUC's) highest Tier 2 and Tier 3 Fire-Threat Area areas indicating risk of utility-associated wildfire. Figure 4 shows the CPUC Fire-Threat Area Map with the Lab location and Tier 2 areas of elevated risk in lighter orange, and Tier 3 areas of extreme risk in darker orange.

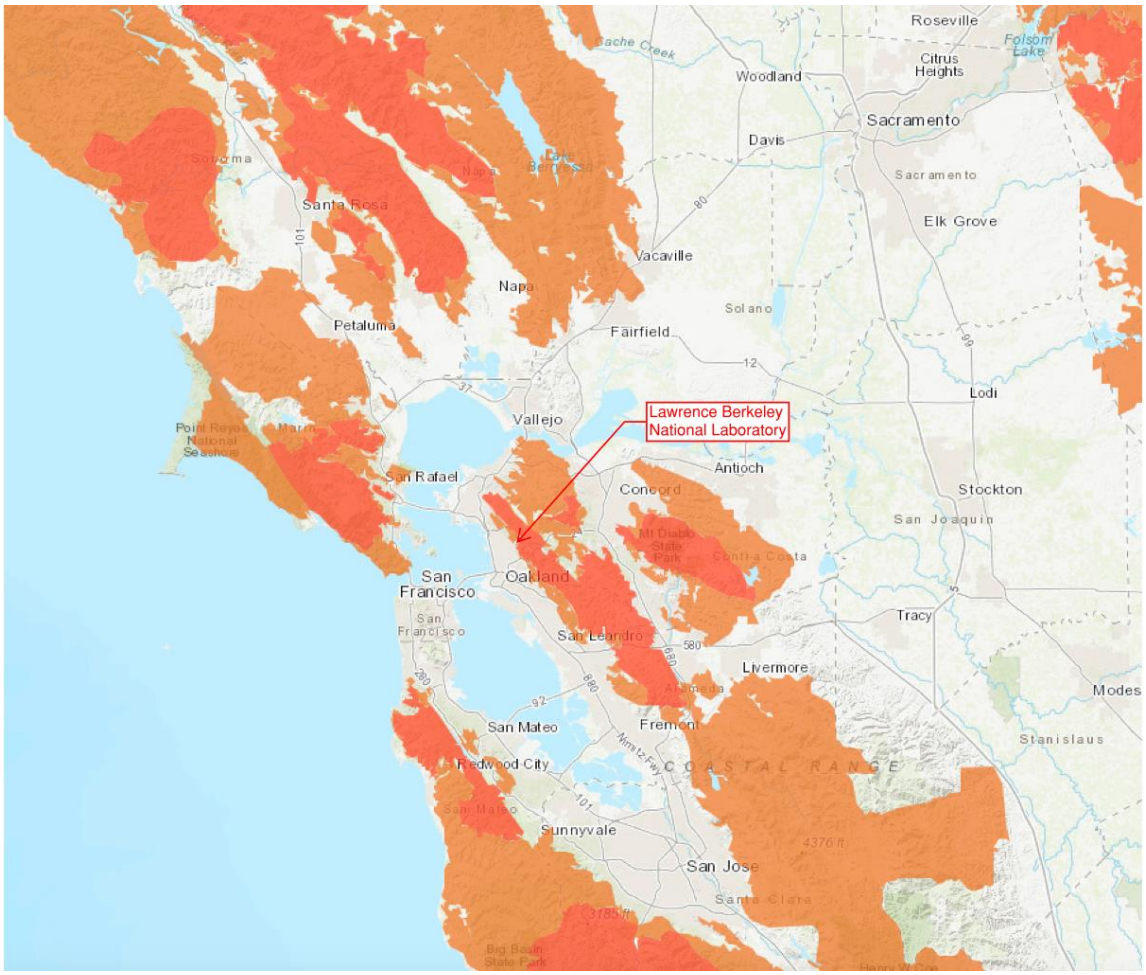

Figure 4: CPUC Fire-Threat Map (https://ia.cpuc.ca.gov/firemap/)

In August of 2017, the Grizzly Peak Fire, a suspected arson, burned 20 acres adjacent to the Lab and initiated a Lab evacuation. As part of the emergency event, the Lab was notified that electricity service would be cut by PG&E, although a power disruption did not end up occurring. In October 1991, a large fire in the Oakland-Berkeley Hills known as the Tunnel Fire burned more than 2,900 structures and killed 25. The Tunnel Fire initially started in grass near local highways, driven by seasonal hot and dry "Diablo" winds from the northeast. An article published by the Lab in 2001 described the steps the Lab was taking to reduce the potential destructive force of wildfires on its main site (Kahn 2001). The Lab's point-person for vegetation management stated that based on observations of the 1991 fire and modeling using the 1991 fire conditions, the Lab should expect a "flame front from a firestorm coming

at us from the east ... up to 60-feet-high." The same article cites 13 Diablo-driven fires in the east Bay Hills stretching evenly across recent history, with fires in 1923, 1931, 1933, 1937, 1940, 1946, 1955, 1960, 1961, 1968, 1970, 1980, and 1991, an average of approximately every five years. The 1923 fire destroyed about 600 homes, making it the second most destructive East Bay Hills fire after the Tunnel Fire. This fire started in Wildcat Park near Berkeley Lab, blowing over the Berkeley hills to neighborhoods immediately adjacent to the Lab and north of the Berkeley campus.

The Lab also experiences smoke impacts from regional and distant fires. In 2018 and 2019, the Bay Area experienced 66 days of air quality advisories and Spare the Air Alerts associated with impacts from wildfire smoke. The events occured mostly between August and November (63 of 66 days). In mid-August 2020, a series of over 12,000 "dry" lightning strikes in and around the Bay Area over the course of 72 hours led to over 550 wildfires and multiple days of poor air quality in the Bay Area. As of mid September 2020, the Bay Area had experienced 30 consecutive days of Spare the Air Alerts.

3.1.4 Public Safety Power Shutoffs

A Public Safety Power Shutoff (PSPS) is preemptive de-energization of power lines by a California investor-owned utility in areas where the electrical infrastructure is at risk of igniting a fire during high fire risk weather conditions. PSPS events are not necessarily related to active local fires, but are triggered by regional weather conditions that could lead to fire, typically the "Diablo" hot dry winds from the northeast.

At the Lab, about 2.75 days of power outages occurred over 2 events in 2019, leading to over nine days of Lab closure, including 4 weekend days. The two events also involved about 7 days of uncertainty and increased planning during which the Lab was under alert of a potential PSPS event but had not yet closed (or did not eventually close). These planned PSPS events require a significant investment of time by the Lab to anticipate the event, power down prior to the service disruption, and to safely restart after power is restored. This investment of time reflects the disruptive impacts of an unplanned power outage since an orderly shutdown and restart avoids the disruption of sensitive equipment and research that occurs from an unplanned outage. It is also notable that the preparation and recovery time was significantly reduced in the second event compared to the first. During the second event, power restart was reduced to 24 hours, half the time required for the first event.

3.1.5 Health Epidemics

The Lab workforce was directed by an Alameda County health order to shelter-in-place beginning in March 2020 in response to the COVID-19 pandemic. This has reduced the on-site population of the Lab to approximately 250 for the first two months of the shelter-in-place, increasing to about 800 by June 1, and 1,000 by August (relative to a full-time equivalent population of about 4,500 to 5,000). This experience has caused an unprecedented alteration of how, and where, work is conducted at the Lab that could extend for more than a year. A similar experience was endured by the San Francisco Bay area during the 1918 flu epidemic, in which influenza fatalities in San Francisco totalled over 3,500 (NPR 2018).

3.2 Future Trends

There is no indication that the prevalence of the hazards discussed here are decreasing. The Hayward Fault is due for an earthquake. Wildfires are a function of weather and ignition sources. California fire season weather is trending towards hotter and drier conditions, as shown in Figure 5 (NOAA data, graphic by Steve Bowen, reported in Samenow and Freedman 2019). Thus, the weather conditions that lead to fires and PSPS events are increasing. Generally, ignitions from electricity power lines on Cal Fire protected lands have not demonstrated a downward trend as have other ignition sources over recent decades (Keeley and Syphard 2018).

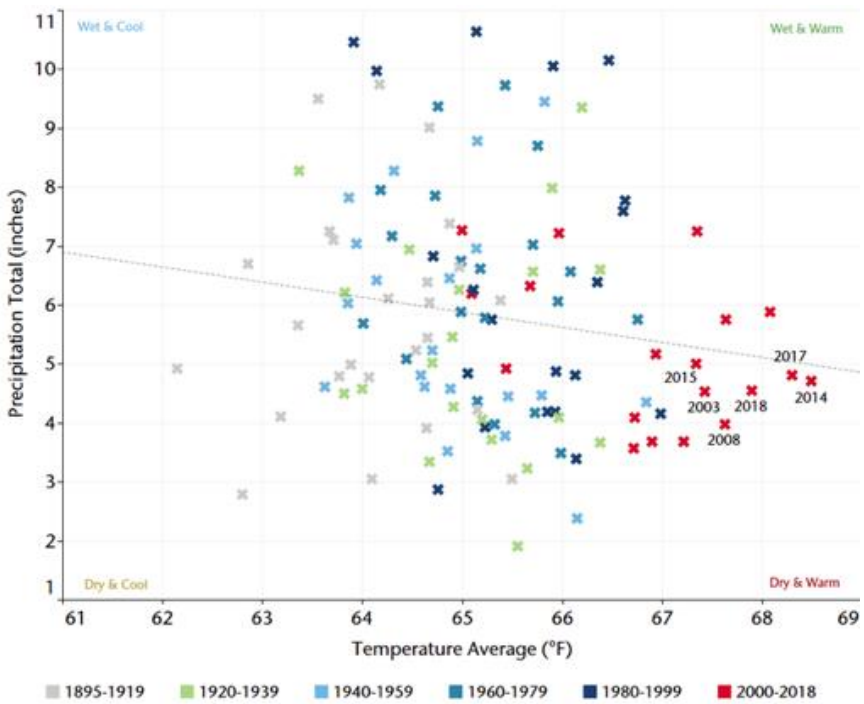

Figure 5: California Fire Season Weather, May - November (NOAA data, graphic by Steve Bowen, reported in Samenow and Freedman 2019)

Figure 6 shows that major grid disturbance events in the US are increasing over time and are dominated by weather causes. In 2003-2012, severe weather caused outages costing an annual average of $18B - $33B (McNamara et al 2015). California has been hit with wildfires, power grid outages, and has seen greater need for “resilience centers” or “shelters” that can withstand these events and outages.

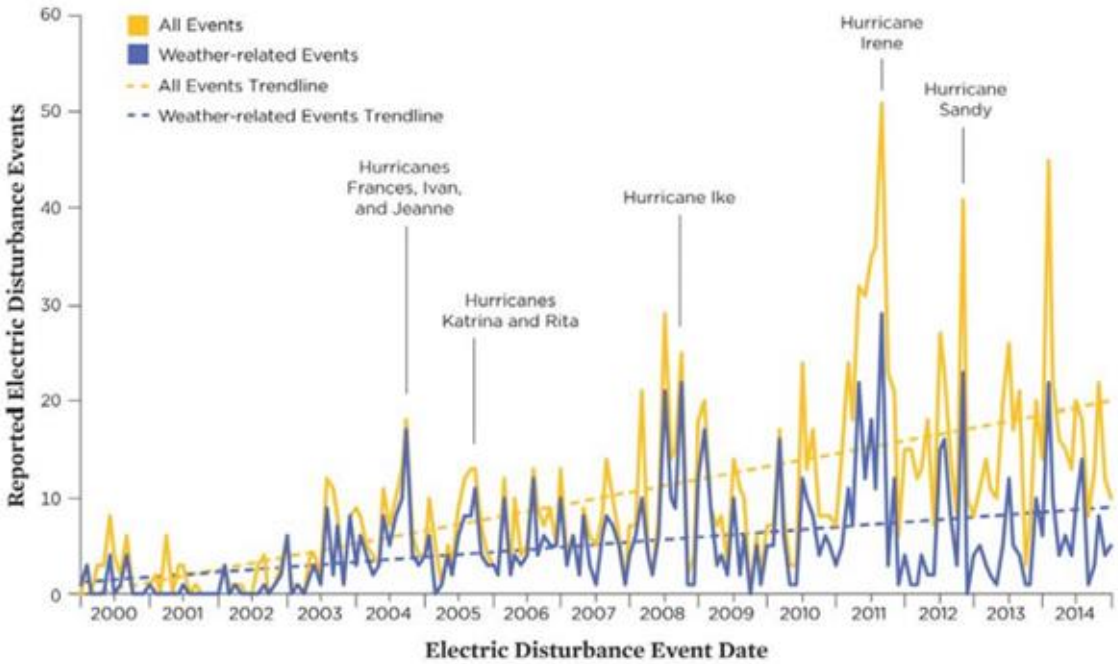

Figure 6: Reported Grid disturbance events in the United States (McNamara et al 2015)

The local utility, PG&E, is taking steps to manage vegetation to reduce the likelihood of fire in the area of the Lab, with a goal of reducing the number of customers impacted by PSPS events by one-third compared to 2019 (PG&E 2020). While the estimated schedule to reduce the frequency of PSPS events through improved equipment and vegetation maintenance is roughly five years, it remains unclear how soon, and to what degree, those efforts will reduce the occurrence of PSPS.

PG&E is installing more switches to segment the grid and reduce the size of outage areas. They are also using refined weather modeling and additional weather measurement locations to reduce the outage durations, as well as more inspection resources to return the grid to service faster than before. Based on historical weather, they predict one to two PSPS events per year in the Lab area based on a thirty-year history of weather data, but they recognize that climate change is driving the potential for more events. They are also planning to energize "microgrids" (islanded grids with portable generation) at some substations when their lines can be energized without risk, but this can occur only after their feeders from the grid are shutdown. There are no reported microgrid projects near to the Lab, except for Lab-initiated microgrid efforts on the Lab's main site, which may be assisted by PG&E. While the size and duration of PSPS events may be affected, it appears that PSPS events are likely for at least five years.

3.3 Summary

We provide the following summary of likely hazards for Berkeley Lab and potential disruptions.

Table 1: Summary of Berkeley Lab Hazards and Impacts

Hazard Scenario	**Hazard(s)**	**Likelihood**	**Potential Disruptions**
1	Public Safety Power Shutoff (PSPS) Events and Other Unplanned Grid Outages	PSPS Occurred 2 times in fall 2019, Expected annually for at least 5 years	● Work and home disruptions ● Need to find alternative work locations ● Electricity service interruptions, with notice ● Strain on availability of diesel deliveries
2a	Local Fires	Occurred 2017, 1991, 1980, 1970, 1968, 1961, 1960, 1955, 1946, 1940, 1937, 1933, 1931, 1923	● Work and home disruptions ● Need to find alternative work locations ● Disruptions of gas and electricity service with short notice ● Air quality and health impacts
2b	Smoke Events from Regional and Distant Fires	66 days of air quality advisories and Spare the Air Alerts in 2018 and 2019	● Work and home disruptions ● Need to find alternative work locations ● Air quality and health impacts
3	Major Earthquake	Occurred 1989 Loma Prieta and 1868 on Hayward Fault, as well as 1725, 1629, 1475, 1317, 1134	● Work and home disruptions ● Need to find alternative work locations ● Disruptions of gas and electricity service without notice ● Additional fire sources due to gas line disruption ● Health and safety impacts
4	Health Epidemic	Occurred 2020 (SARS CoV-2), 1968-70 (H3N2), 1957-58 (H2N2), 1918 (H1N1)	● Work and home disruptions ● Need to find alternative work locations ● Health and safety impacts

4 DEMAND SIDE CONSTRAINTS AND OPPORTUNITIES

Investigation of demand side constraints and opportunities was limited to electricity loads associated with facilities on the Lab's main site. Thermal loads were not evaluated. The current status is reviewed below followed by a discussion of future opportunities.

4.1 Current Status

4.1.1 Building Electricity Loads

To support planning at Berkeley Lab, recent peak electricity load data were summarized for the Lab's main site. Data was reviewed from June 2019 through December 2019 to evaluate current loads, since electricity load dropped following the retirement of the Edison high-performance computer in May 2019. The peak 15-minute electricity load for the site was 19.4 MW, observed on 2019-06-11 at 15:15 PDT. The daily peak electricity consumption was 410.7 MWh, observed on 2019-09-25. Total peaks and consumption by distribution switch are provided as Table 2.

Table 2: Peak Electrical Loads and Peak Daily Electricity Consumption, Berkeley Lab Main Site by Distribution Switch

Switch	Peak Electrical Load [MW]	Peak Daily Electricity Consumption [MWh]
A2	0.7	11.9
A3	3.1	74.6
A4	2.9	60.5
A5	2.1	42.7
A6	5.4	108.9
A7	5.2	112.0
Total	19.4	410.7

Loads by building are included as Attachment 1. At the building level, interval data was not always available to directly measure peak demand or consumption. After using as much submeter data as possible, the remaining non-submetered demand or consumption was split proportionally among remaining monitoring points using monthly consumption readings collected manually on 2019-09-12.

4.1.2 Potential Lower Load States

Conceptually, five potential lower load states were identified that could reduce back-up power capacity requirements.

- **Modified Operation** - Unessential loads are curtailed using automated load management (for example, building automation system controls) or manual intervention (for example, closing fume hoods, turning off unnecessary equipment)
- **Reduced Operation** - Additional, lower priority loads are curtailed (or example, large computing jobs, representing 20% of NERSC users, are deferred during an outage)
- **Minimum Operation** - Buildings are vacated and minimum loads maintained (for example, ventilation exhaust is maintained for safety)
- **Energy Efficiency** - The same services are provided using less energy, through operational improvements or capital retrofits
- **Load Shifting** - Loads are shifted to non-peak periods (for example, via thermal energy storage, or scheduled to match the generation profile of onsite solar)

These alternate load states were not analyzed in detail; however, one "reduced operation" scenario was analyzed as an existence proof: "safe and stable" electricity loads observed during the COVID-19 shelter in place. The "safe and stable" electricity loads represent a period in April 2020 during which buildings were only sparsely occupied and buildings were placed into "holiday schedules," with reduced constraints on temperature and ventilation in some spaces. To evaluate the reduction associated with safe and stable loads, switchable process loads associated with NERSC, the Advanced Light Source, and the 88" Cyclotron were removed and loads were compared to a previous period of similar weather. Overall, average energy consumption was observed to decrease by 14 percent, with a larger decrease in peak load (approximately 20%). Safe and stable loads represent just one reduced operation potential. The Lab could explore alternate reduced load states and test them to confirm load reductions.

This 20% average decrease in peak load was applied to a hypothetical scenario involving prioritizing, grouping and reduction of loads at the main site. Four user facilities were kept separate, and building electricity loads were grouped as either "critical facilities" necessary for site operations, "other priority facilities" including important scientific facilities, and the remaining "less critical facilities."

The peak NERSC load was reduced to 2.5 MW based on conversations with NERSC personnel indicating that NERSC would be able to process more than 80% of its customers' computing jobs at a load of 2.5 MW. For the other user facilities as well as the critical and other priority facilities, peak loads were assumed to be reduced by 20%. Less critical facilities were assumed to be curtailed completely. The example load shedding scenario reduces peak load from 19.4 to 12.4 MW and the peak daily energy consumption from 411 to 257 MWh.

Table 3. Example Sitewide Load Shedding Strategy at Berkeley Lab

Facility Group	**Facility Number**	**Recent Peak Electrical Load [MW]**	**Recent Peak Daily Electricity Consumption [MWh]**	**Reduced Peak Electrical Load (MW)**	**Reduced Peak Daily Electricity Consumption [MWh]**
NERSC	59, 59 super computing facility	5.2	112.0	2.5	54

Advanced Light Source	6, 6 accelerator, 34, 37	3.9	94.4	3.1	76
Molecular Foundry	67, 67A, 72	1.0	19.5	0.8	16
Joint Genome Institute	91	0.5	10.0	0.4	8
Critical Facilities	26, 43 ,48, 50B compute, 85, 86	1.1	22.7	0.9	18
Other Priority Facilities	2, 15, 30, 33, 50A compute, 62, 66, 70, 71, 74, 76, 77, 77A, 80, 84, 88, 90, 90X	5.6	106.6	4.5	85
Less Critical Facilities	All others	2.2	45.4	0	0
Total		19.4	410.7	12.2	257.0

An example load shedding strategy at the switch level is shown in Table 4 below. This scenario at Switch A6 is based on sending building occupants home, but keeping all facilities in an operable condition, with the exception of one building (B90, which is powered down and restarted on a separate generator). In this scenario, the complicated steps associated with powering down facilities and re-energizing equipment is mostly avoided. Steps 2 and 5 add generation resources instead of pursuing further load reduction. The size of the backup solution is reduced from 5.4 MW to 2.6 MW.

Table 4. Example Load Shedding Strategy at Distribution Switch A6, Berkeley Lab

Load Shedding Step	**Load Shed [MW]**	**Resulting Load [MW]**
Starting point, load at switch A6	N/A	5.4
Step 1: Move 88” cyclotron into low-energy state	1.1	4.3
Step 2: Switch B90 to its own generator	0.4	3.9
Step 3: Vacate buildings and move into "holiday" HVAC schedules	0.5	3.4
Step 4: Reduce non-critical 50B computing operations by 500 kW	0.5	2.9
Optional Step 5: Use additional local generators if needed.	0.3	2.6
Total	2.8	

4.2 Discussion of Future Demand Side Opportunities

During a power outage response, any load that can be avoided will reduce the demand on the back-up power system, lowering both initial and operational costs of providing a resilient power system, as well as reducing the logistical challenges associated with back-up power system maintenance, operation, and re-fueling. As in the case of energy efficiency and conservation, the averted load (commonly referred to as "negaWatts") is often the least costly and most appropriate approach, rather than simply assuming it is necessary to meet the full existing, or projected, load with back-up generation, especially when those conditions are limited in duration.

In this spirit, all planning for a resilient power system should be based on a foundation of a strong energy efficiency program to provide the necessary services with the least power practical, as well as a conservation mindset that even an efficient load is a waste of energy if the services it provides are not needed at the time. Berkeley Lab has steadily improved energy efficiency over time, both through retrofits and new construction, but this must remain a focus to mitigate unnecessary growth in loads that, not only present operational costs and environmental impacts under normal operation, but also make it much more difficult, and expensive, to meet desired levels of service during a power outage.

Historically, back-up power at Berkeley Lab has been accomplished with diesel gensets serving dedicated emergency power circuits. This approach sheds all loads deemed unessential to safety and maintenance of critical sensitive materials, stopping most productive work, as energy services are directed exclusively toward maintaining a safe and stable site.

A broader view of laboratory resilience, including some research productivity during a power outage, requires more levels of load prioritization and curtailment, such that it is possible to maintain some productive work activities at the Lab that can scale with the available energy resources.

In order to keep more laboratory functions operational when there is a power outage, generation equipment will likely need to be deployed at a higher level in the electrical distribution system, connected to an entire building or group of buildings at the distribution switch level, rather than just a few emergency power circuits within a building. One outcome of this topology is that there will be many loads connected to the generation source that are not essential, and would present a large, even unworkable, burden on the back-up generation source. As a result, it is important to have a robust load management program to optimally match the desired loads to the available energy resources.

An important element of planning for future opportunities is to document and design a framework to enable near-term investments to contribute positively toward the future vision and to avoid stranded investments from short-sighted project implementation along the way. For this reason, it is important to plan for both near-term and long-term solutions at the same time to productively coordinate near-term actions to ensure consistency with long-term visions.

4.2.1 Near-term Opportunities

Manual curtailment of unessential loads is the most immediately available option for managing loads, but it requires an investment of staff time and coordination and may not be as predictable or reliable as an automated solution. The most comprehensive way to implement a manual load management program would start with an inventory and prioritization of loads, including identification of how and

where they can be isolated and what other loads may be impacted if they are shut down. For a facility of the size and complexity of Berkeley Lab, this is a substantial task, but there are approaches to make it more manageable. Delegating the surveying and reporting of loads to operators who have considerable experience with their equipment will spread the burden and benefit from institutional knowledge about the associated needs and relationships to other equipment. Also, evaluating larger loads first can be a helpful strategy to reduce the burden of inventory and management. However, smaller plug loads on general purpose circuits should not be overlooked, as many buildings now have a significant portion of their demand coming from the aggregate of small plug loads, such as "idle" computers, monitors, printers, and other office equipment, a large fraction of which can likely be curtailed most of the time without significant sacrifice in productivity.

In addition to identifying loads that can be reliably managed with manual intervention, it is important to begin planning for automated load management by identifying opportunities to install automated load management devices on existing equipment (potentially at the load itself or otherwise built into the electrical distribution system). Opportunities to integrate automated load management into new equipment purchases should also be explored. To best support resilience goals, all equipment purchases (especially those with large loads) should favor the procurement of equipment with integrated load management capabilities, as a means to help build the capacity for automated load management over time. It is important to include a controls compatibility element in this procurement effort, as a disparate collection of devices may not readily integrate into a reliable cohesive system. Adherence to an established standardized communications and control system will be a key factor in the success of automated load management.

4.2.2 Long-term Opportunities

Ultimately, nearly all loads should be able to be managed remotely through an automated system to optimize the matching of desired loads, in a prescribed priority, to the available energy services at the time. This includes not only simple on/off control, but also proportional control of variable loads, such as variable speed motor drives, modification of temperature setpoints and other command signals that reduce a load without completely eliminating it. It is worth recognizing that, in addition to the flexibility of load management this functionality provides during a hazard event like a power outage, it is also a valuable tool during normal periods of grid operation to minimize unnecessary loads and respond to grid management signals that optimize stability and environmental impact of generation sources on the grid.

5 Supply Side Technologies

This section reviews the deployment and use of standby generators at Berkeley Lab and a range of energy solutions that could be deployed as retrofits to an existing energy system.

5.1 Existing Generators at Berkeley Lab

At Berkeley Lab, the total electrical capacity of standby generators is almost 9 MW. Table 4 lists the operable generators, fixed and portable.

Table 4. Fixed and portable generators at Berkeley Lab as of August 2020

Generator Equipment Number	Buildings Served	Nameplate Capacity [KW]
02 EG 068	02, 02A	300
30 EG 114	30	350
31 EG 108	31	11.5
33U EG 113	33, 33U	350
37 EG 120	37, 6, 80, 34	300
37 EG 111	15 (10A)	150
48 EG 100	26, 28, 45,48, 76	230
50A EG 101	ICS Node	230
50B EG 095	50B, F, D	150
55 EG 069	55, 56, 90	230
59 EG 115	59	1,250
62 EG 102	62	175
62B EG 081	ICS Node	20
64 EG 079	64	150
66 EG 109	66	230
67A EG 110	67, 67A	350
70 EG 106	70, Fire Alarm B50	250
72 EG 098	72, A, B, C	125
75 EG 089	75	80
77 EG 094	77	125
84 EG 112	74, 83, 33A	400
84BEG 099	84	500
85 EG 096	85	350
88 EG 090	88, 33B	180
91U EG 001	91, 91U	600
	Total Fixed	7,087
76 EG 067	Portable	250
76 EG 075	Portable	100
76 EG 093	Portable	150
76 EG 116	Portable	250
76 EG 117	Portable	250
76 EG 122	Portable	275
76 EG 123	Portable	275
76 EG 124	Portable	275
	Total Portable	1,825

Notes:

1. The B88 generator runs on natural gas; all others are diesel.

2. Most generators have maximum allowable planned runtimes of 50 hours per year per Berkeley Lab's permit with the Bay Area Air Quality Management District (BAAQMD). Some have 30 hours. The two smallest and the natural gas generator have unlimited hours.

3. There is an additional 2,000 kW generator (64C EG 107) which is designed to connect in parallel with the 12kV distribution system; it is not functional but is being investigated for refurbishment.

4. Rental generators are not included in this list.

5.1.2 Fuel Storage and Distribution Onsite

There is a total of over 25,000 gallons of diesel fuel stored at the generators on site, plus a 10,000-gallon diesel tank at B76 that serves as a vehicle fueling station. Four generators include fuel storage in excess of 2,500 gallons and together include almost 16,000 gallons of fuel storage (Table 5).

Table 5. Generators with fuel tanks over 2,500 gallons

Name	Buildings Served	Diesel Gallons
02 EG 068	02, 02A	5,100
84 EG 112	74, 83, 33A	4,100
84B EG 099	84	4,000
85 EG 096	85	2,600
	Total	15,800

Note: 64C EG 107, not currently functional, has a 6,000-gallon tank.

All of these generators except 84B EG 099 have run times of over one week (calculated at 75% load). None of these fuel tanks at present have the ability to dispense fuel but adding this capability is possible, and is part of the planned scope of the 64C EG 107 refurbishment project. Berkeley Lab has its own 1,000-gallon tanker truck. Note that during the 2019 PSPS events, the fuel consumption of the operating generators was a total about 150 gallons per hour, with an average loading of about 24%.

5.1.3 Configuration and Connection to the Berkeley Lab Electric Power System

Of the 33 generators in Table 4, 26 are permanently installed with open-transition automatic transfer switches (ATSs) into either 277/480-volt (20 generators) or 120/208-volt (6 generators) in-building distribution systems. Eight are portable. As noted, there is another generator (64C EG 107) designed for parallel operation (with a closed-transition transfer switch) at 12kV switch A6 that was decommissioned and is currently being investigated for refurbishment. The open-transition switches are configured to start their generators on loss of utility power, and once the generators are running at nominal voltage and frequency, the dedicated loads are connected to the generator. When utility power is restored, the ATSs automatically switch their dedicated loads back to utility power and shut down their generators. There are thus two interruptions to the served loads, one switching to the generators, and one switching back to utility power.

5.1.4 Operation During PSPS

Most of the fixed generators ran during the two PSPS events in October 2019, but typically at very low loading. The estimated average load based on overall fuel consumption was 24%. Many of the optional loads were shut down before the power was shut off and not restarted on the generators.

The loads that do operate on the generators are typically well below the generator capacity, and it is not easy to reconnect other loads to the generators on short notice.

5.1.5 Operation and Maintenance Issues

Operating diesel engines for prolonged periods at low loads (significantly less than 50%) results in "wet-stacking," in which unburned fuel migrates into the exhaust stack, and clogging of exhaust particulate filters (where equipped). Eventually the wet stacking leads to engine failure (see ASCO Power Technologies 2018). Another problem with the existing configuration is that the open transition switches make loading and testing difficult, because testing and maintenance require double interruptions of the loads, and often require a whole-building shutdown to do maintenance on the ATS itself. It is also difficult to properly load the generators for testing and to burn off the excess fuel and particulates in the exhaust filters.

With open transfer ATSs, generators cannot be used to power anything other than the loads downstream of their transfer switch. This results in lack of flexibility and generator capacity that cannot be used.

5.2 On-site Generation and Storage Options

The research team evaluated on-site generation and storage options sized at 10 MW of power for two days (or 480 MWh). This sizing would meet likely loads at the Lab assuming that approximately half of peak load is shed, as discussed in section 4.1.2. The analysis included a "backup" power case in which a generator (such as a diesel or propane genset) would provide power only when called upon during grid power outages. The analysis also considered implementation options of onsite power generation and onsite generation with electricity or hydrogen storage both operating throughout the year since these options introduce significant capital costs and are thus much more economical to operate throughout a year, rather than only for a few days in which backup power is required.

5.2.1 Technologies Considered

The evaluated technologies include reciprocating engine gensets using a variety of fuels, gas turbine systems operating on natural gas, solar photovoltaics (PV), electricity storage using lithium-ion and redox-flow batteries, and various configurations of fuel cells with and without hydrogen (H_2) storage (Table 6).

Table 6. Generation and Storage Technology Options

Option	Solution Name	Fuel Source	Power Providing Equipment	Storage
1a	Diesel and Dual Fuel Genset with Storage	Diesel Including Diesel/NG/Propane Dual Fuel	Generator	Diesel Tanks

1b	Propane Genset with Storage	Propane	Generator	Propane Tanks
2	Natural Gas Cogeneration	Natural Gas (utility service)	Turbine with Cogeneration (use of waste heat for building heating)	None
3	NG Solid Oxide Fuel Cell (SOFC) without Storage	Natural Gas (utility service)	SOFC + Inverter	None
4a	NG Phosphoric Acid Fuel Cell (PAFC) without Storage	Natural Gas (utility service)	PAFC + Inverter	None
4b	NG PAFC with H_2 Storage, H_2 made onsite*	Natural Gas (utility service); electricity for H2	Electrolyzer to tank to PAFC + Inverter	H_2 Tanks
4c	H_2 PAFC with H_2 Storage and purchased H_2*	Natural gas ; Hydrogen (purchased)	PAFC + Inverter	H_2 Tanks
4d	Solar + PAFC with H_2 Storage, H_2 made onsite*	Natural gas; Solar PV	Electrolyzer to tank to PAFC + Inverter	H_2 Tanks
5a	Solar with Li-Ion Battery Storage	Solar PV plus Grid Electricity	Inverter	Lithium Ion Battery
5b	Solar with Flow Battery Storage	Solar PV plus Grid Electricity	Inverter	Flow Battery

Notes:
* These options have a few days of H2 storage onsite, either produced onsite or purchased, but would normally run on natural gas as the input.

5.2.2 Evaluation Criteria

The goal of the evaluation was to make a first-order assessment addressing the following three questions:

1. How much does a given option cost to install?
2. What is the levelized cost of energy over the lifetime of the distributed energy resource (DER) option?
3. How do the options compare to each other across the relevant comparison metrics?

The results are based on an evaluation of the costs, environmental risks, space constraints, and resilience characteristics of these various electricity generation and storage technologies.

5.2.3 Methodology

Capital costs as well as the levelized cost of energy or storage (LCOE) were calculated using standard LCOE methodology that included capital costs, fuel costs, as well as operations and maintenance costs (Ericson and Olis 2019, Schmidt et al 2019). Costs are for the plant only. In the case of the natural gas cogen solution, costs include those for the thermal network but not any building-level modifications to accept distributed thermal energy.

Costs were derived based on publicly available sources such as company websites and product specification sheets, news reports, and research literature (that is, journal articles and technical reports), as well as some vendor inputs for solid oxide fuel cells and flow cell batteries. The costs as presented represent "snapshots" of costs in 2020 since the costs of many distributed energy resource (DER) components are very dynamic and several have decreased rapidly over the past few years (for example, solar PV and battery storage) and these cost reduction trends are expected to continue. California state or federal incentives are not included, since the Lab is generally not eligible to receive these incentives. Such incentives could be significant for other eligible sites.

In some cases, a mixture of online tools and best estimates from the above sources were used for capital and/or levelized cost of energy estimates. Examples include an online calculator from Schmidt et al 2019 for levelized cost of storage (https://energystorage.shinyapps.io/LCOSApp/), cost per kW numbers for Li Ion batteries using from Mongird et al 2019, and an EPA CHP screening tool (ETSAP 2013) to help estimate cogeneration power unit costs. Cogen system costs for heat distribution across the Lab and heat exchangers and modifications at networked buildings were estimated from literature sources referenced in ETSAP 2013.

The analysis assumes a flat electricity rate for the Lab of $0.06/kWh that does not vary with the time of day. For storage technologies, this necessitated an arbitrary charging/discharging duty cycle since under these assumptions there was no opportunity for energy arbitrage. For simplicity, battery storage options were assumed to be charged and discharged with a nominal 48 hour charge and 48-hour discharge duty cycle throughout the year. Similarly, estimates for additional revenue or demand charge reduction(s) from installation of DER onsite were not included.

Area calculations for the physical area requirements of each technology option are first-pass estimates based on similar sources as above, estimated from product specification sheets, literature, and other online sources. Required area estimates are approximate to the extent that some technologies are

potentially available in “stacked” or “tall” (high aspect ratio) configurations that could reduce the assumed required area. But in general, the space analysis limits the vertical dimension to less than two stories since the stability of very tall structures in an active earthquake area might be a concern.. The space analysis does not account for items such as truck parking or provisions for additional roads or staging locations for on-road deliveries of fuel.

Environmental risks and resilience characteristics were evaluated more qualitatively in the context of the energy system risk factors described above. Direct criteria emission factors and CO_2 emission factors for each generation option were used in calculation, and full life-cycle emissions (including upstream or supply chain-related emissions) and CEQA-type environmental impact assessments were not considered. These effects are treated in other studies, but in general are not expected to markedly shift the overall high-level conclusions regarding the technology options developed herein.

5.2.4 Evaluation Results

Costs

Cost evaluation results are shown in Table 7 below. To aid in interpreting the results, the table results are shaded to group results of similar magnitude (green - lower, yellow - middle, red - higher). Some key observations include:

- Capital costs
    - Diesel with dual fuel, and propane gensets (Options 1a, 1b) have the least expensive capital costs by far. For the 10 MW, 2-day requirement, installed capital costs are estimated to be from $8.5 to $10M.
    - Several options have estimated capital costs which are in the $40-60M range (Options 2 through 4d). These include natural gas-based cogeneration (Option 2), two fuel cell options with natural gas (solid oxide fuel cell Option 3 and phosphoric acid fuel cell Option 4) and three options with hydrogen storage and onsite compressed hydrogen storage (Options 4b, 4c, 4d).
    - Battery options have the highest capital costs at $230 million and $130 million (for solar with li-ion Option 5a and solar with flow battery storage Option 5b, respectively) since battery costs are quite high and Li-ion costs increase rapidly with longer duration storage. The cost of flow cell batteries scales more favorably with energy capacity since its energy storage is decoupled from power generation, but the technology still has high capital costs for this application. Capital costs for Options 5a and 5b are dominated by storage costs, and (given the favorable grid electricity rates available at the Lab) that the batteries are assumed to be charged by the grid.
- Fuel Price Volatility
    - In terms of fuel price volatility, the two battery options are deemed to have the lowest price volatility since they are assumed to be charged by electricity from the grid and the Lab has a long term electricity contract with WAPA which is assumed to be in place for the near future.

- The next lowest fuel price volatility is natural gas for cogen or the fuel cell options, followed by propane and diesel.

- Levelized Cost of Energy
  - The diesel and propane genset Options 1a, 1b are for 2-day operation per year only and thus the levelized cost in $/kWh is very high since the annualized cost is apportioned over only 48 hours per year.
  - The lowest cost levelized cost options are natural gas Options 3 to 4b with levelized cost of electricity at $0.11-0.19/kWh. While these options are high with respect to the average Lab electricity cost of $0.06/kWh, several options are competitive with the average price of commercial electricity in California which is about $0.15/kWh (EIA 2019). Note the SOFC Option 3 has similar LCOE to the PAFC Option 4a since although the capital cost is higher, the efficiency is higher for the higher temperature SOFC technology (about 55% for SOFC compared to 35% for PAFC).
  - Battery storage cost is still high for Li ion and flow cell batteries. Note that no benefit from electricity arbitrage is included here (charging battery when electricity price is low and discharging when electricity price is high) as a flat (non-time dependent) electricity rate structure is assumed.

Table 7. Cost Estimates for Onsite Generation and Storage Technology Options

Option	**Solution Name**	**Installed Capital Cost at 10 MW / 2 Day [$M]**	**Fuel Cost, natural units and [$/MJ]**	**Cost Volatility [Standard deviation pct. of mean, 2000-2019]**	**Levelized Cost [$/kWh]**
1a	Diesel/Dual Fuel Genset with Storage	8.5 - 10	$3.78/gal [2.6 cents]	31%	1.5-1.8[1]
1b	Propane Genset with Storage	8.5-10	Retail $1.98; Wholesale $0.564 [2.1, 0.58 cents]	24%	1.8-2.1[1] (shorter lifetime than diesel)
2	Natural Gas Cogen - Plant Only [2]	40-65	$0.766/Therm industrial [0.73 cents]	21%	0.11-0.14
3	NG SOFC without Storage	60	$0.766/Therm industrial [0.73 cents]	21%	0.14
4a	NG PAFC without Storage	40	$0.766/Therm industrial [0.73 cents]	21%	0.14-0.15

4b	NG PAFC with H2 Storage made onsite from grid	60-80	$0.766/Therm industrial [0.73 cents]	21%	0.17-0.19
4c	H2 PAFC with H2 Storage, purchased H2	52-63	$0.766/Therm NG Industrial or ~ $1.18/Therm-eq for H2 [1.1 cents]	H2 from CH4 will track NG price	0.4-1.0
4d	Solar PV 2MW to produce H2; PAFC with Storage	58-75	$0.766/Therm industrial [0.73 cents]	21%	0.21
5a	Solar PV 2MW with Li-Ion Battery Storage	230	$0.06/kWh grid el. [1.7 cents] [2]	LOW	0.73
5b	Solar PV 2MW with Flow Battery Storage	131	$0.06/kWh grid el. [1.7 cents] [2]	LOW	0.43

Notes:

1. Note that 1a, 1b are for 2 day operation per year only.
2. Cogen costs include those for the plant and thermal network, but not include building-level modifications to accept distributed thermal energy.

Environmental attributes

Table 8 lists the emission factors for criteria pollutants (NOx, SOx, CO, PM), volatile organic compounds (VOC), and CO_2. Criteria pollutants and VOCs can lead to air pollution such as smog that is harmful to human health and small particulate matter (PM2.5 or particle sizes 2.5 microns or below) is particularly dangerous, contributing to premature deaths worldwide from cardiovascular disease and lung cancer.

Diesel and propane emergency generators have by far the highest criteria pollutants and VOC levels among the generation technologies considered here, with PM2.5 extremely high for diesel generators. Combined heat and power (CHP) with natural gas turbines are much cleaner for pollutant emissions than emergency generators, and the two fuel cell technologies, SOFC and PAFC, and in turn, cleaner for criteria pollutants since they are a chemical conversion process and not a combustion-based generation source.

For CO_2 emission factors, higher conversion efficiency gives lower CO_2 emissions. SOFC is best followed by PAFC, and diesel generators are the highest.

Table 8. Emissions Factors for Fossil Fuel Emergency Generators, CHP with Natural Gas Microturbines

Air Pollutant	**Diesel Generator - Emergency [1]**	**Propane Generator - Emergency [1]**	**CHP with Natural Gas Turbines [2]**	**SOFC with Natural Gas [2]**	**PAFC with Natural Gas [2]**

NOx (kg/MWh)	18.857	16.252	0.023	Negligible	0.0045
SOx (kg/MWh)	0.007	0.003	Negligible	Negligible	Negligible
CO (kg/MWh)	4.063	10.946	0.023	Negligible	0.0091
VOC (kg/MWh)	1.502	0.378	0.032	Negligible	0.0091
CO_2 (kg/MWh)	758	653	664	334	477
PM10 (kg/MWh)	1.338	0.073	Negligible	Negligible	Negligible
PM2.5 (kg/MWh)	1.338	0.073	Negligible	Negligible	Negligible
Overall	Poor	Fair to Poor	Fair	Fair to Good	Fair

Notes:

1) On-site solar PV and battery storage have zero onsite pollutant and GHG emissions

2) Fuel cell systems with pure H2 input fuel have zero CO2 emissions and negligible pollutant emissions, but as these are assumed to be running with natural gas input fuel for most of the year, their emission factors will be dominated by the factors above.

3) Emission Factors from USEPA (https://www.epa.gov/sites/production/files/2016-07/engines_ci_pte_calculator_version_1.0_0.xlsx, accessed July 16, 2020) and the Catalog of CHP Technologies (US EPA 2017).

Space requirements

Attachment 2 includes a discussion of installed area estimates for onsite distributed generation and storage options with a summary table in Table A2-1.

Resilience to hazards

A qualitative hazard resilience assessment of the various generation options is provided in Table 9 below. Overall concerns for diesel and propane generators are related to the need for onsite fuel

storage and ensuring robust fuel delivery across the range of hazards. All of the natural gas fueled options (CHP, SOFC, PAFC, PAFC with H_2 storage) are vulnerable to a loss of fuel supply due to the risk of natural gas pipeline ruptures in a major earthquake on the Hayward Fault. Fuel cell systems with H_2 storage would be able to provide power if natural gas supply is lost but only for two-days per the H_2 storage volume assumed above. Beyond that, for the onsite H_2 production cases, the nominal 2 MW electrolyzer would not be able to keep up with H_2 demand for 10 MW of continuous power. For the H_2 delivery cases, H_2 would need to be supplied from an external source on a regular basis which is also not practical.

The hardware and 'fuel supply' for solar PV with battery storage has good resilience to the hazards below, but the available continuous power output from this solution is very limited due the high cost of storage and the diurnal generation profile and space constraints of solar PV. Thus none of the evaluated technology options are a clear stand-out in terms of resilience to the hazards under consideration.

Table 9. Qualitative Hazard Resilience Assessment of the Various Generation and Storage Options

Hazard Scenario	Hazard(s)	Diesel Generator - Emergency	Propane Generator - Emergency	CHP with Natural Gas Turbines	SOFC with Natural Gas	PAFC with Natural Gas	PAFC with H2 storage	Solar PV with Battery Storage
1	Public Safety Power Shutoff (PSPS) Events and Other Unplanned Grid Outages	Potential concern with fuel delivery for long events		Good				Limited power output set by PV size, diversifies supply and reduces fuel consumptio n rates
2a	Local Fires with Significant Smoke Impacts at Minimum	Flammability hazard and explosion risk for onsite fuel storage in worst case		Worst case might result in temporary shutdown				Some risk of reduced solar PV output under high smoke conditions
2b	Smoke Events from Regional and Distant Fires	Good						Some risk of reduced solar PV output under high smoke conditions
3	Major Earthquake	Risk of fuel supply disruption; fuel storage design needs to withstand major e-quake		Risk of natural gas pipeline rupture for major quakes				Ok if installation is designed to withstand major e-quake
4	Health Epidemic (no grid power loss is assumed)	NA						

	Overall resilience assessment	Fair: Large onsite fuel storage needs to be managed and/ or fuel delivery risks	Fair: Key risk is natural gas supply integrity from a major earthquake	Fair: Slightly better than NG-only fed FC systems but still have NG supply risk from e-quake	Fair: System hardware is good overall for resilience but output is very limited due high cost of storage and the diurnal profile and space constraints or solar PV

Overall assessment of evaluation results

A summary of evaluation results is shown in Table 10 below for the generation/storage options considered across a range of evaluation criteria: installed capital cost, levelized cost, pollutant emissions and CO_2 emissions, area requirements, and resilience to several hazards. This represents the combined output of Tables 7-9 above and Table A2-1 in Attachment 2. To aid in interpreting the results, the table results are shaded to group results of similar magnitude (green - lower, yellow - middle, red - higher).

From the table, none of the options is good to excellent for all of the criteria. Diesel and propane generators have the highest air pollutant emissions and have risks associated with fuel supply and fuel delivery. Natural gas-based options (Options 2-4d) - especially fuel-cell based options - are better for air pollutant emissions and/or CO_2 emissions but still generate CO_2 emissions. Solar PV and battery storage has the zero direct air pollutant and CO_2 emissions, but battery storage is still very high cost for the 2-day duration design, and although its system hardware resilience is good overall, continuous system power output is very constrained due to the diurnal generation profile and space requirements for solar PV.

Table 10. Overall Assessment of Evaluation results for Generation/storage Technology Options

Option	**Solution Name**	**Installed Capital Cost at 10 MW / 2 Day [$M]**	**Levelized Cost [$/kWh]**	**Air Pollutant emissions and CO2 emissions**	**Approximate installed area [m2 for 10 MW for 2 days]**	**Overall resilience to hazards**

1a	Diesel/Dual Fuel Genset with Storage	8.5 - 10	1.5-1.8[1]	Poor	1600	Fair: Large onsite fuel storage needs to be managed and/ or fuel delivery risks
1b	Propane Genset with Storage	8.5-10	1.8-2.1[1] (shorter lifetime than diesel)	Fair to Poor	2200	
2	Natural Gas Cogen - Plant Only	40-65 [1] .	0.11-0.14	Fair	1,500-2,500	Fair: Key risk is natural gas supply integrity from major e-quake
3	NG SOFC without Storage	60	0.14	Fair to Good	3,000	
4a	NG PAFC without Storage	40	0.14-0.15	Fair	3,000	
4b	NG PAFC with H2 Storage made onsite from grid	60-80	0.17-0.19	Fair	10,000	Fair: Slightly better than NG-only fed FC systems but still have NG supply risk from e-quake
4c	H2 PAFC with H2 Storage, purchased H2	52-63	0.4-1.0	Fair	10,000	
4d	Solar PV 2MW to produce H2; PAFC with Storage	58-75	0.21	Fair	10,000[2]	

5a	Solar PV 2MW with Li-Ion Battery Storage	230	0.73	Excellent	6,600[2]	Fair: System hardware is good overall for resilience but output is very limited due high cost of storage and the diurnal profile and space constraints or solar PV
5b	Solar PV 2MW with Flow Battery Storage	131	0.43	Excellent	30,000[2]	

Notes:
1. Note that 1a, 1b are for 2 day operation per year only.
2. Does not include 2 MW solar area: 13,500 m^2 of which about 7,100 m^2 is rooftop and 6400 m^2 is on parking lots

6 Integrated Microgrid Opportunities

Many opportunities arise from the inclusion of generation and storage technologies within a microgrid. The value of a microgrid is discussed below, followed by near-term and long-term opportunities

Decentralized energy systems are not new, nor is the concept of onsite generation, backup, or emergency systems. However, it was not until recently that the currently accepted concept of microgrid was clearly defined as a cluster of small sources, storage systems, and loads, which presents itself to the main grid as a single, flexible, and controllable entity (Lasseter 2001, Marnay et al 2001). By introducing onsite generation, storage, and bidirectional power flow, microgrids can be seen as a valuable resource to the grid, while also being more independent from it. This creates the settings for flexible operating conditions, albeit at a cost: microgrids are complex energy systems that require specific infrastructure, resource coordination, and information flows, as well as added protection and power quality assurance. Guaranteeing all of these conditions can potentially jeopardize the economic viability of microgrids, making it vital that design steps account for all different revenue streams, both direct and indirect, that result from microgrid deployment.

A cluster of interconnected loads and distributed energy resources does not qualify as a microgrid by itself unless several technical requirements are met, among which are the ability to operate in grid-connected and islanded modes, the ability to transition smoothly between the two modes with minimal load disruption under scheduled and emergency conditions, proper relaying and protection, and power quality assurance (Xu et al 2012, Yang et al 2011, Li et al 2014). It is only when these requirements are met that a microgrid is effectively implemented and its benefits can be obtained.

Renewable microgrids can lower a customer's electric utility costs, reduce the customer's overall carbon footprint, and provide critical electric reliability and resilience. Providing resilience for longer periods may require generation and storage system sizes that exceed what is needed for normal operation or even peak operation. To ensure that this renewable power does not go to waste during grid-connected periods requires a supervisory control layer that can participate in electricity markets

and provide grid services. Renewable generation and storage can provide days of power for a facility at any time of the year, but can be wasted if not used for grid support or community or regional power sharing. A microgrid designed for long outages (for example, weeks rather than days) will have generation and storage capabilities that will exceed what can be used by the facility or community on most days. Electric interconnection rules often limit the amount of power a microgrid can export or at least limit the amount that will be compensated. Installing additional storage and participating in retail and wholesale grid services markets will minimize the loss of resources whose primary purpose is for resilience.

Campuses are vulnerable to two types of outages: those due to utility disruptions and those due to internal faults. Modular microgrids provide two levels of resilience: (1) an islanded operation of the entire campus in the event of an outage, and (2) a resilient nodal building block that supports nesting in the event of an internal fault (for example, transformer failure or cable fault). Integrated resilient nodes (IRNs) can function independently or together. The IRN design provides a standardized housing and package for clustering critical buildings and loads (for example, electric vehicle service equipment) and connecting the clustered loads to sources of co-located generation (for example rooftop PV or diesel generators) or energy storage (for example, battery energy storage systems).

IRNs, as shown in Figure 7, will consist of low-voltage switchgear distribution boards, motorized circuit breakers, control, communication, and safety equipment. If the nodes are connected to medium-voltage service, the IRNs will also include medium-voltage switchgear and a step-down transformer. The initial IRN at any installation will consist of both a real-time controller for communicating set-points and retrieving data from DERs and loads connected to the IRN and a supervisory controller. Any other IRNs installed at the same facility will be controlled by the supervisory controller instance in the first IRN and will only need their own real-time controller instances. The coordinated operation of several node microgrids will often require power exchange between the nodes and reactive power compensation to maintain voltage at each node.

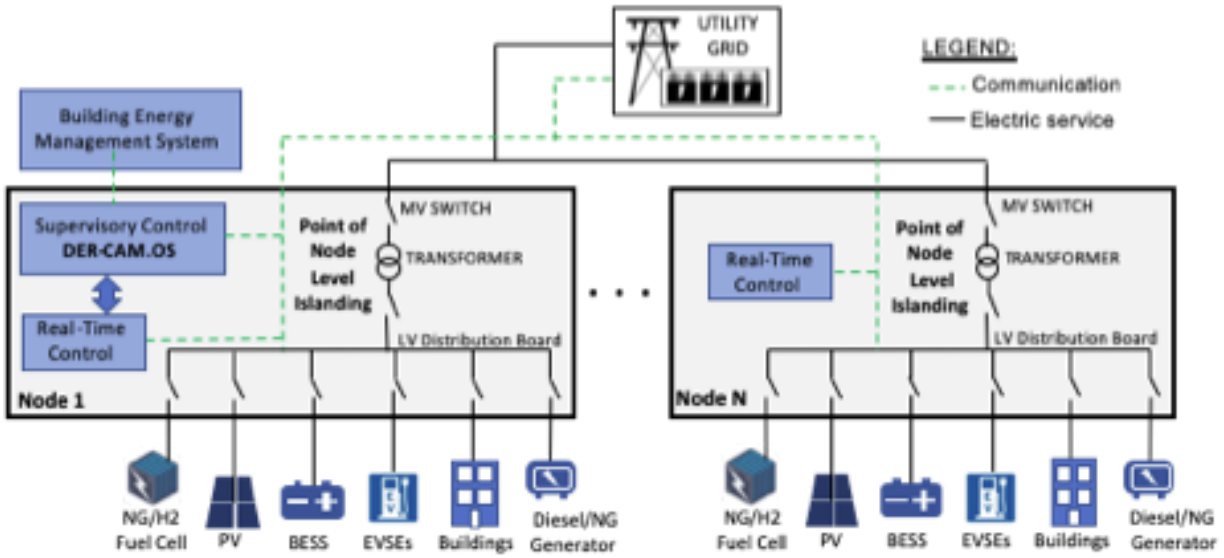

Figure 7. Schematic of IRNs for an example scenario with N Nodes showing internal HW and the various loads that can be connected to each. The types and numbers of DERs and loads can vary across IRNs.

A version of this technology is being developed and demonstrated in a California Energy Commission (CEC) funded microgrid demonstration specifically for the Parks Reserve Forces Training Area in Dublin, California.

6.0.1 Near-term Opportunities

Evolve generators to dual fuel and paralleling for microgrid operation

The larger fixed diesel generators at the Berkeley Lab site could be converted from their existing diesel-fuel-only operation to a dual-fuel mode in which up to 80% of the fuel burned is natural gas. Any fraction of diesel from 20% to 100% can be used, giving greater resilience and operating flexibility when natural gas is available. Fuel and maintenance costs are reduced and engine life is extended when operating on significant fractions of natural gas.

Also, these generators could be reconfigured from their existing open-transition ATSs serving dedicated loads to closed-transition operation in parallel with the grid in combination with load-shedding of non-essential loads to match generator capacity. Such a configuration would have the following benefits:

1. Much better flexibility on which loads are served by the generators
2. Ability to load generators to their optimal load (typically 75%)
3. Ability to stage generators on the microgrid for redundancy
4. Ability to test and maintain generators and transfer switches without outages

About two-thirds of the existing fixed generation capacity could be converted this way with only 8 generators; 80% could be converted with only 12 generators.

Combine generators with on-site PV and storage

While fossil fuel generators are likely to be a large part of the immediate electrical resilience solution at Berkeley Lab and most other facilities with very large back-up power demands for the near future, it is important to begin to design and use fossil generation differently than in past installations by planning new infrastructure with the intention to migrate to increasingly renewable-sourced power generation and storage facilities using a flexible microgrid platform. Short-term investments should not risk stranding infrastructure investments by installing equipment that can not be easily adapted to contribute productively to a longer-term resilient microgrid solution.

It may be tempting, and appear the most cost effective option, to simply deploy fossil fuel back-up generation to cover the relatively limited periods of time the electrical grid is down in most areas, but even with increasing stresses causing a decline in grid reliability, it is important to consider that an investment in back-up generation is always quite expensive per unit of useful runtime, given the long periods of time this equipment is idle. For that reason, there is a strong motivation to choose back-up power solutions that add value to the operation continuously, not just when there is an outage. A very effective example is coupling renewable generation with storage, such as solar PV and batteries. The grid already needs, and is being incentivized to connect, renewable generation sources and storage to bridge the timing gaps between generation and use patterns. Grid connected solar and storage can be used on a daily basis and provide value to the grid under normal operating conditions. The same

equipment becomes a very effective power supply when the facility microgrid islands to provide back-up power.

There are larger system level (grid) design implications to the placement of solar and storage. While it is currently less expensive per kW and kWh to install solar and storage in large centralized "utility scale" facilities at some distance from population and load centers, the value of these resources for resilience are much more limited, compared to locating the same resources in a more distributed fashion near the end uses, as part of a microgrid structure. In PSPS, fire and earthquake scenarios where large transmission lines may be out of service for long periods of time, solar and storage assets cut off by those broken transmission lines will not contribute to resilience where the need is greatest. For that reason, solar and storage facilities should be integrated as close to load centers as possible with provisions to island these resources within microgrids with important loads to enable resilient operation.

Operate one or more Berkeley Lab switch areas as separate microgrids

Below is a description of a "local resilient node" integrating generators, PV, and storage using an example site at B91 (Integrative Genomics Building and future adjacent buildings). This concept potentially interacts at the switch level (in this case, switch A6) and consists of the following elements. Similar configurations can be replicated at other buildings and switches across the Berkeley Lab site.

- Convert the existing 600kW generator at 91U (the common utility building) from dedicated emergency panel circuits to parallel operation with all B91 loads, serving the entire building as an island, or optionly backfeeding through the existing transformer to the 12kV distribution system at the A6 switch.
- Add ~200kW of solar photovoltaic (PV) modules on the B91 roof with inverter(s) connected to the 480-volt distribution system in parallel with the generator.
- Add a battery storage system that can be charged by the PV system and/or the generator, the latter of which could then be operated as needed in an emergency in an islanding mode at optimal load and cycle as needed to keep the battery charge in the desired range state of charge (40-80%) for the best battery life. This battery, with an inverter, could serve as an Uninterruptible Power Supply (UPS) that would prevent key building loads from being dropped in an unscheduled power outage and switching transitions.
- Implement prioritized automated load shedding and scheduling based on model predictive control (MPC), including forecasts of solar generation and environmental loads. Some loads could be shed immediately upon battery UPS transition to limit the peak load for the battery inverter under a backup scenario. Just as with UPS systems in many data centers, the buffering capacity of the batteries provides some reasonable response time for demand management and safe/orderly curtailment, as well as ramp-up of the genset from an unplanned outage without an open transition.

This system can be expanded and integrated with the following options:

- Refurbish and add the currently decommissioned 2MW (64C) paralleling generator on the switch A6 distribution system (12kV), or equivalent.

- Deploy additional rooftop solar on several buildings across the switch (in this case A6, including B90, the B50 complex, B71, B88, etc.). In each case, couple the solar with storage and inverter to provide UPS support to the most critical local loads. The total PV potential capacity in the A6 zone is estimated in the 1-2 MW range and may be larger in other switch zones.
- Move additional building generators from dedicated circuits to be able to parallel into a generation pool across the switch zone, allowing for staging and redundancy.
- Transition smaller existing diesel generators using a DC-coupling scheme to allow the same inverter to be used for the PV and battery, as well as rectified output from the generator. Such DC coupling limits the number of devices that must synchronize on the AC, potentially realizing both operational and regulatory advantages, as well as freeing the generator to operate under wider parameters without sacrificing AC power quality.
- Implement prioritized automated demand response across the entire switch zone using MPC or other control algorithms.

6.0.2 Long-term Opportunities

Operate the Berkeley Lab site as one microgrid with five or six sub-grids

For maximum resilience, Berkeley Lab 12kV switches A2 through A7 could be all separated or tied together in any combination through switch A1. The Lab's 12kV distribution system consists of six switch zones (A2 through A7) all tied together through switch A1. The entire site could be one microgrid, or could be up to six separate sub-grids, configured as appropriate to meet prioritized loads with the available generation and storage capacity.

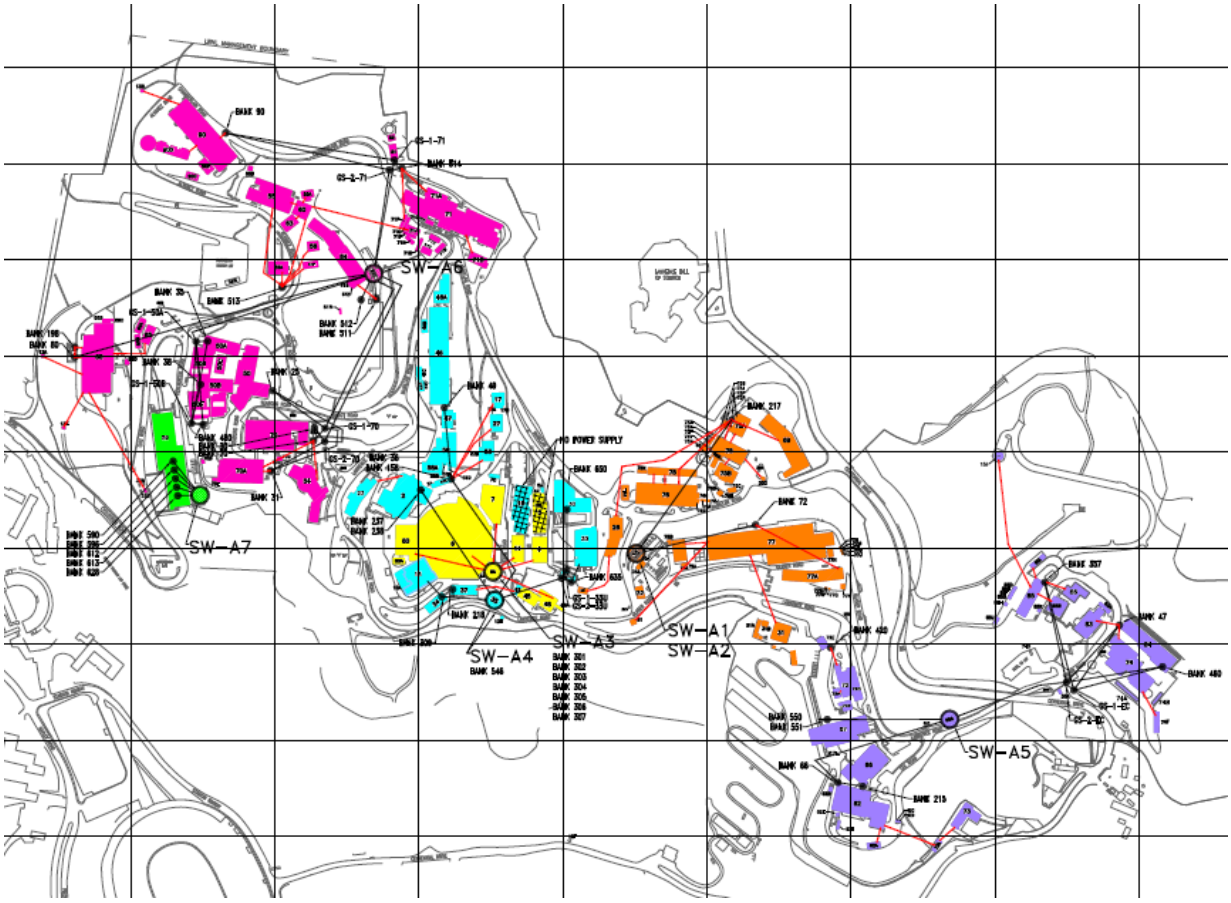

Figure 8. Map showing Berkeley Lab's 12kV distribution system, color-coded as follows: Switch A2, orange; Switch A3, yellow; Switch A4, aqua; Switch A5, blue; Switch A6, pink; Switch A7, green

Existing loads on the 6 switches, and generator capacity as currently configured, are listed in Table 11.

Table 11. Berkeley Lab Load and Generators Listed by 12kV Switch

Switch	Peak Electrical Load [MW]	Peak Daily Electricity Consumption [MWh]	Underlying Standby Generator Capacity [MW]
A2	0.7	12.9	0.5
A3	3.1	75.7	0.3
A4	2.9	67.8	1.3
A5	2.1	45.4	2.1
A6	5.4	143.3	1.7
A7	5.2	112.0	1.3

Note that switch A6 is in the process of adding 4 MW of temporary, paralleling generators as a PSPS mitigation measure for 2020, and the existing 2 MW paralleling generator 64C EG 107 is anticipated to be back online for 2021. This combination would more than meet the existing peak load even without optimizing the generation/load management balance. Likewise switch A5 already has approximate parity between supply and demand, and A2 could mostly likely be easily brought into balance. And these do not include the on-site renewable generation and storage options noted above.

Coordinate with UCB, EBMUD, possibly other Sobrante Sub users

Ultimately, because Berkeley Lab is a site with intense energy demand and relatively limited space to serve that demand with on site generation (particularly large scale renewables), it is worth looking beyond the Lab facility to enlarge the scope of resilience opportunities, even though it is challenging to maintain a high level of reliability with a more extensive infrastructure system. In particular, there are opportunities to partner with the UC Berkeley campus with which Berkeley Lab already shares significant electrical infrastructure. Also, given the location of the Sobrante Substation, where the dedicated transmission line serving the Lab originates, there are opportunities to stage both large scale renewables and storage near that substation with the potential to continue to serve the Lab during an outage on the feeders of that substation, provided that the transmission line from the substation to the Lab is hardened and configured to island the Lab along with those local storage and renewable generation resources surrounding the substation.

The University of California, Berkeley campus is already partially fed through the Grizzly Substation on the Berkeley Lab site, with another connection serving the campus from the other side in the City of Berkeley. This configuration of major feeders from two different directions with a connection in between can be exploited to increase resilience for both campuses. It is less likely that the feeds from both sides will be lost at the same time, compared to experiencing an outage on one or the other at once. While the individual feeds are not currently sized or configured to fully power both campuses, there could be improvements to the overall capacity of each feed and the connection in between campuses to increase the amount of support each campus can provide to the other when an outage is experienced in either location, but not both simultaneously. With load shedding and the use of other

supportive generation sources, the power supply provided by the other campus would still be highly useful, and perhaps one of the less expensive systems to implement, even with link capacities substantially lower than the typical facility demand.

The land surrounding the Sobrante Substation that feeds Berkeley Lab from the east side of the hills is owned by the East Bay Municipal Utility District (EBMUD). In early 2020, that agency approved the construction of a 5 MW PV installation adjacent to the Sobrante Substation. There is quite a lot of other open land surrounding this facility and it is near other EBMUD infrastructure including Briones Reservoir, San Pablo Reservoir, and the Orinda Treatment Plant. Although the EBMUD solar project does not currently include storage, roughly two-thirds of new utility scale solar systems are now including storage because of the importance of adding storage to the grid with the expansion of solar and wind generation (Gorman et al 2020). There is an opportunity to install more solar and storage around this substation. The Lab's close electrical proximity, with a dedicated line, provides a unique opportunity to utilize these resources for resilience purposes, in partnership with EBMUD. The community choice aggregator in Contra Costa County, Marin Clean Energy, may also be interested in partnering on utility scale solar and storage in this location because of the Resource Adequacy benefits it provides during normal grid-tied operation. To make use of these resources at the Lab when the substation is otherwise shut down, there would need to be effort into hardening the transmission lines from the substation to the Lab such that they will not be de-energized during a PSPS, because they are at risk of starting a fire.

7 RECOMMENDATIONS

High-level, broadly applicable recommendations to improve energy-system resilience based on this analysis include:

- **Deploy energy solutions able to respond to a range of likely hazards and disruptions to both electricity and natural gas service.**
  Resilient energy systems are able to limit the negative effects of hazard events and reduce the time needed to recover after energy services are disrupted. Many hazard events are not known in advance, but the range of likely hazards can be identified by reviewing historical hazards experienced at a particular location over the last few hundred years. Potential new hazards may also be identified based on recent trends. Resilient energy systems are more likely to respond favorably to unforeseen events. For example, a system that includes a battery bank that can be charged using solar energy or by a dual-fuel generator that can run on diesel or natural gas is flexible and can adapt to many different unforeseen conditions. Note that after a hazard event, the goal is not necessarily to return to the initial starting condition. The goal is to restore critical energy services, and this may involve a reconfiguration around new conditions.

- **Avoid a single, centralized fossil-fuel based solution**
  A centralized fossil-based system that is intended to operate continuously, such as a new natural gas cogeneration plant, will become a single point of failure, and would introduce risks

by running counter to current efforts in California to reduce greenhouse gas emission and air pollution. Moreover, the supply to a centralized natural gas-based solution could likely be disrupted in an earthquake. Other centralized fossil-based back-up solutions, such as a diesel generator plant, also have drawbacks. They can introduce a single point of failure, can be difficult to permit, can be highly polluting, and can be impractical to refuel, especially after a hazard event such as an earthquake.

- **Take steps to create a flexible modular microgrid, where feasible, to increase resilience and improve operating performance**
  Where conditions allow, a microgrid can become a foundation for many strategies that improve resilience. Such strategies include those for:
    - Redundancy - Multiple distributed systems that eliminate single points of failure
    - Flexibility - Allowing generation and storage assets to serve multiple applications
    - Continuity - Finding opportunities for closed-transition switching (no loss of power) and flexible strategies to restore service after a hazard event
    - Load Management - Reducing unnecessary loads to minimize first costs, maintenance costs, and challenges associated with keeping an energy system operating throughout a hazard event

- **Prioritize integrated renewable generation and storage systems that have the capability to produce year-round value in addition to providing backup power**
  Fossil fuel based backup generation that only operates during an outage will have very limited use. Such systems can not be run productively outside of outages because of criteria and carbon emissions. Onsite solar generation and storage systems can provide value on a daily basis and contribute to resilient power backup without the refueling challenges of fossil fuel generation. Such value propositions include minimizing costs under time-of-use differentiated utility tariffs, removing demand requirements from the grid, and in some circumstances providing ancillary services to the grid. Year-round operation also allows for better understanding and maintenance of systems.

- **Integrate renewables and storage with engine gensets to improve genset utilization, increase flexibility, and address typical operational issues associated with standby generators**
  As noted above, the existing genset configuration (all diesel, open transition switching only to local dedicated loads) is suboptimal from a service and maintenance point of view. Converting most of the existing generator capacity to dual-fuel operation with closed-transition switching and parallel operation would add significant operational flexibility and maintainability. Combining these gensets with on-site renewable sources and storage would make for a much more resilient and cleaner standby system.

- **Develop load shedding and demand-side strategies to reduce backup energy requirements.**
  Adding hardware and procedures to manage loads optimally provides year round energy, GHG

and cost savings, as well as greatly reduces the size of a backup power solution during outages, allowing a nuanced match of available resources to desired loads in a prioritized fashion. As renewables and storage reach higher and higher penetration on the grid, the ability to respond to demand signals from grid regulators will become an increasingly important factor in managing the cost of electricity during normal operations. Investment in this technology and its effective implementation is highly prudent independent of resilience events, but is also a key component to managing a microgrid during a grid power outage. Dispatchable loads can be timed to coincide with variations in available resources like solar, while keeping the most essential loads continuously powered, with a continuum of prioritized load deployment matched to generation and storage capacity.

- **Explore energy-related partnerships with neighboring organizations or entities.** While it is easier to implement resilience on a facility level where choices are largely under the control of one organization and there is limited coordination necessary with outside entities, there is often additional resilience benefits to be gained by expanding the scope of possible interaction and support between neighboring organizations/facilities, especially when there are physical/geographic constraints that make it difficult to achieve the full scope of desired resilience within the bounds of a single facility. For instance, a facility with a large amount of solar generation and relatively modest loads and storage will have surplus solar resources at times that might not be able to be put to use as a facility level island. A neighboring facility with larger loads relative to their available solar generation, could put the excess solar from another facility to use either by a direct microgrid connection, or even without a direct infrastructure connection by using electric vehicles as mobile storage that can charge at the facility with excess available power and then relocate to discharge where there would be otherwise unmet loads. Coordinating with other entities can also improve the economics of a large infrastructure project by sharing some fixed costs or regulatory processes, allowing both facilities to achieve a higher level of performance than that of a system confined to either organization alone.

Near-term recommendations to improve Lab energy resilience at Berkeley Lab include:

- **Flexible Deployment of Gensets**: Deploy gensets to provide benefit at the distribution level (either directly at 12kV or by backfeeding through 12 kV-480 V transformers) rather than restricted to a small subset of loads at individual buildings, as has been typical for standby generators. Mitigate air pollution and provide redundancy by using dual-fuel (diesel and natural gas or natural gas and propane) units and avoid long-term commitments to diesel gensets by using temporary (rented or portable) units. This would provide backup power with a capability for closed-transition (seamless) switching during planned outages like a PSPS, flexibility to allow generation and storage assets to serve multiple buildings (within one neighborhood or across neighborhoods at the Lab), and improve utilization and operating characteristics of gensets.

- **Integration of Renewables and Storage**: Integrate renewable technologies and storage with alternative and traditional gensets for multi-resource islanding at the electricity distribution or building level. While fossil fuel gensets will remain an important component of near term backup power resilience, they have associated air pollutants, GHG emissions and high prices for delivered power because they are used for very few hours per year. Integrating onsite renewable power generation, predominantly solar photovoltaic panels, will reduce environmental impacts for the Lab year-round, while also increasing resilience during power outages. Because solar is not dispatchable like a fossil-fuel generator, it must be combined with storage for resilience. Grid tied storage is increasingly valued and necessary, with two-thirds of new California solar projects including battery storage (Gorman et al 2020). Similar to the solar panels themselves, battery storage can provide value to the Lab year round by shifting the timing of generation and loads to adjust the Lab's load shape and potentially reduce the cost of future electricity contracts during normal operation. With the extremely low current contract price for electricity at the Lab, there is a significant risk of future cost increases as the transmission, distribution and storage investments needed on the grid are transferred to customers like the Lab. Having battery storage during an outage also improves the robustness of the back-up power system giving time for gensets to reach operating conditions and/or to perform necessary switching and load shedding while still providing uninterrupted power, whether the outage was planned or not. Batteries also enable the gensets to operate at optimal load conditions while cycling on to charge a battery bank, improving efficiency, and reducing fuel use and pollution as the fossil-fuel genset effectively becomes a backup to the renewable generation. This flexible, resilient and optimizable configuration provides many opportunities for learning, establishing best practices and performing valuable research aligned with Berkeley Lab research areas.

- **Load Shedding**: Develop and pilot automated and manual load-shedding strategies to mitigate the size and cost of new energy solutions. Adding hardware and procedures to manage loads optimally provides year round energy, GHG and cost savings, as well as greatly reduces the size of a required backup power solution. Load shedding is also a key component to managing a microgrid during a grid power outage. Dispatchable loads can be timed to coincide with variations in available resources like solar, while keeping the most essential loads continuously powered, with a continuum of prioritized load deployment matched to the available generation capacity. At the level of the entire Lab main site, a preliminary assessment of sheddable load indicates that the Lab's current peak load of 19 MW can be reduced to 10-12 MW while maintaining many mission-valuable activities. At the switch level, a preliminary assessment identified a strategy that reduced the size of the required backup generation from 5.4 MW to 2.8 MW. These assessments suggest that serving about half of the current peak electricity could be a more practical starting point, rather than assuming that all peak loads must be addressed by the backup system.

- **A Microgrid Plan**: Create a phased microgrid transition plan for the Lab that incorporates both supply- and demand-side management with the goal of achieving an energy system that is resilient to future power interruptions from the grid. Such a plan would define a vision for

transforming the existing electrical distribution system into a flexible microgrid that can increase energy system resilience at the Lab. The plan would provide a vision of the system requirements, and define parameters to which individual projects (likely developed over time) would need to conform in order to allow full realization of benefits.

Over the longer term at Berkeley Lab, a "living laboratory" approach in which targeted Laboratory research is coordinated with on-the ground experience could play a key role in accelerating technology development and the Lab's transition from backup solutions based primarily on diesel gensets to widespread deployment of cleaner distributed energy resources. The living-lab infrastructure would be designed for robust operation and fault-tolerant delivery of service while enabling development of and experimentation with new generation and storage technologies, systems management, data collection and controls.

8 Research and Development Opportunities

Based on the analysis presented above the resilience research team suggests three prioritized areas for follow up research and development (R&D):

1. **Low-cost, low-emission electrochemical alternatives to diesel generators**, building upon Lab strengths in the Energy Storage and Distributed Resources Division in batteries and fuel cells
2. **Demand-side load management and microgrid optimization for resilience**, building upon Lab's unique capabilities in the Demand Response Research Center and Building Technologies and Urban Systems Division work on advanced controls
3. **A resilience accelerator and microgrid testbed for emerging generation and storage technologies**, a unique integration of emerging generation and storage technologies, electric and fuel-cell vehicles

8.1 Low-cost, Low-emission Electrochemical Alternatives to Diesel Generators

Diesel gensets for backup power are inexpensive relative to other options, however they produce GHGs and generate significant air and noise pollution. Thus the research team identifies a key research opportunity to develop a low-cost, low-emissions electrochemical alternative to diesel or other fossil-fuel powered gensets. Electrochemical technologies have no direct combustion emissions, thus overall GHG and criteria pollutants as well as noise would be much lower than those from diesel generators.

Electrochemical technologies such as fuel cells, flow batteries, and Li-ion batteries in particular have achieved large cost reductions in the past few years but are typically designed for long lifetimes as measured in operating hours or number of charge/discharge cycles. There is the potential for much deeper cost reductions if this lifetime or durability constraint is relaxed to a very different use case where the technology is only used for a few hours a year as a source of backup power. As an example, one can go to deeper depths of discharge of batteries or run fuel cells at power densities above their rated capability. Either of these alternatives result in more degradation and less cycle life, but this is

not as important for resilience applications. The tradeoffs need to be explored, in particular, the benefits of driving the technologies harder versus their reliability and a chance for catastrophic failure.

Possible avenues to explore would be primary batteries where the active component is an inexpensive solid that can easily be stored and “recharged” in a similar manner to diesel fuel. These systems will naturally have high calendar life since the reactants are stored external to the conversion stack with no crossover and capacity fade over time.

Low-cost, limited operation batteries provide a larger set of possibilities for chemistries and component materials. For redox flow cell batteries, less expensive redox couples for “rechargeable” batteries and designs for low cost and/or low power can be pursued such as the use of solid couples that can be stored or delivered to the storage site. Common metals such as Cu, Zn, Ni, S, Mn, and Fe could bring energy storage costs in the range of $3-$50/kWh.

Figure 10 below illustrates some of the key concepts of the proposed R&D. Key areas of research here include: operating conditions, reduced cost designs, and novel chemistries. Limited operation removes durability concerns and enables consideration of lower cost electrochemical cell and stack designs since cycle life is not a main concern. These components include metal flow field plates, inexpensive separator layers such as hydrocarbon-based separators, and redesigned stack architectures. Durability, efficiency, and cost tradeoffs for these more intermittent operating conditions are not known, nor are the maximum achievable designs for low cost or operational parameter set points understood.

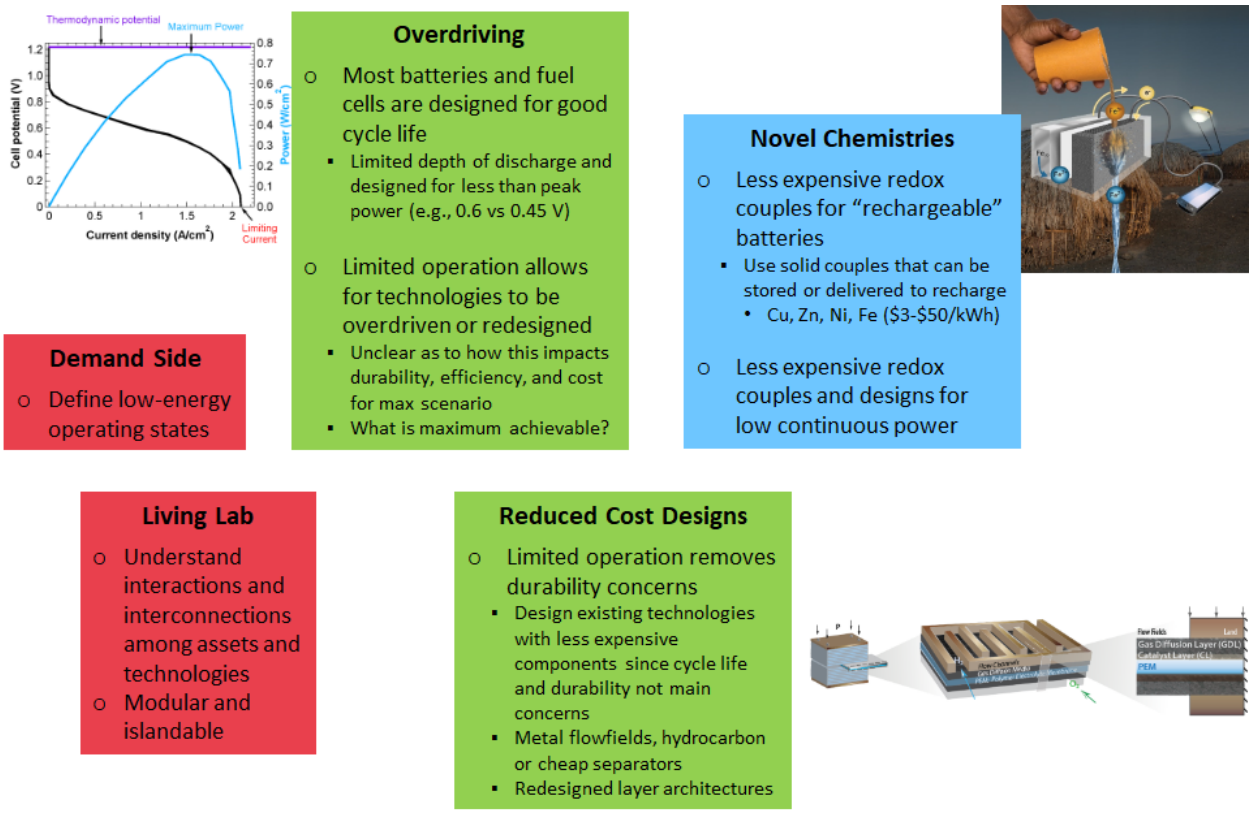

Figure 10. Low cost electro-chemical alternatives to diesel generators is a new R&D opportunity. Key features can include overdriving/operations, reduced cost designs, and novel chemistries.

8.2 Demand-side Load Management and Microgrid Optimization for Resilience

Demand-side management and microgrid optimization for resilience is a second key R&D area of focus.

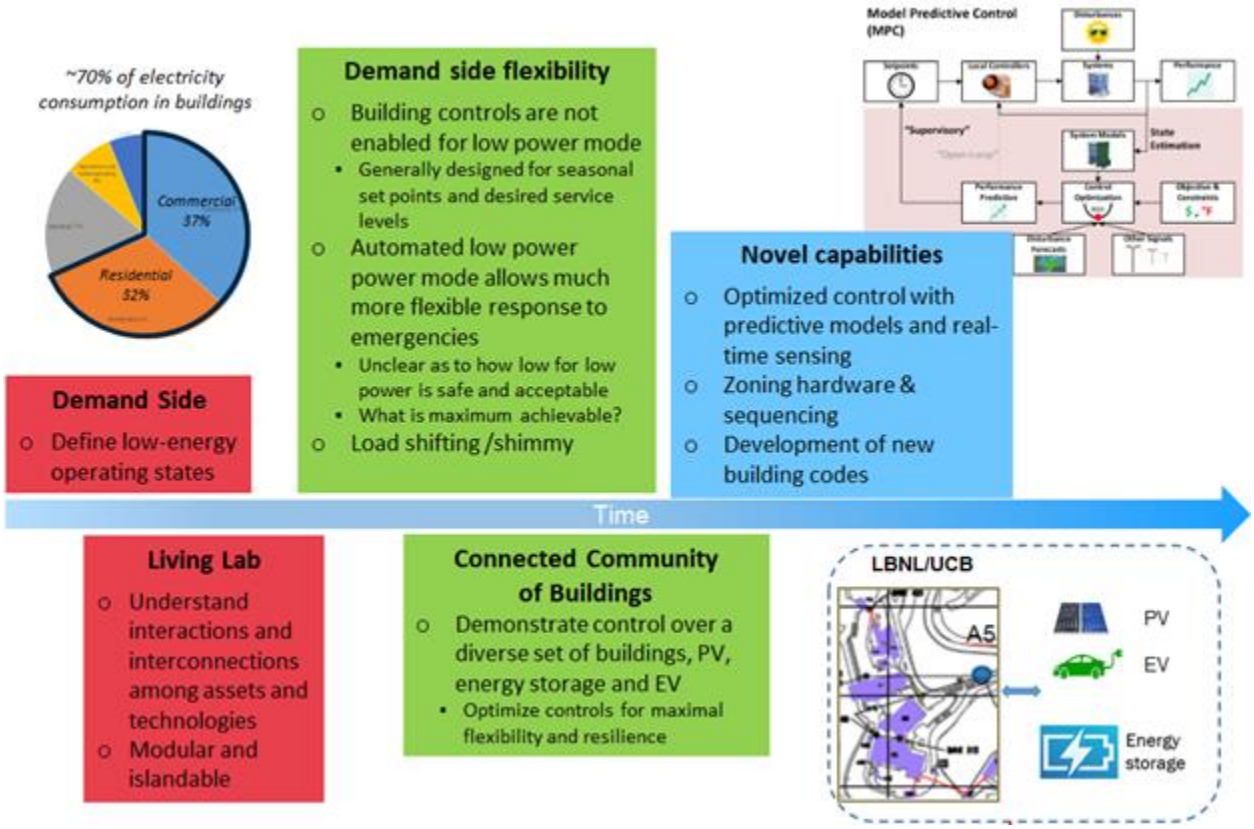

Figure 11. Microgrid and demand side load management optimized for resilience is a key R&D opportunity. Features of this R&D include enabling demand side flexibility and automated low power mode building operation, demonstrating a connected community of building and distributed energy resources, and developing novel capabilities.

On the demand side, building controls are not enabled for low power mode but are generally designed for seasonal set points and desired service levels. Automated low power mode operation in buildings is a critical new R&D area and would allow for much more flexible response to emergencies. It is unclear as to what low power modes are safe and acceptable and what is the maximum achievable load reduction by building type and external conditions. Automated low power mode operation could be more widely demonstrated and deployed for both grid support and microgrid resilience.

Figure 6 in Section 2 above shows that major grid disturbance events in the US are increasing over time and are dominated by weather causes. In 2003-2012, severe weather caused outages costing an annual average of $18B - $33B (McNamara et al 2015). California has been hit with wildfires, power grid outages, and has seen greater need for “resilience centers” or “shelters” that can withstand these events and outages. Microgrids can be a lead technology for providing resilience to power shutdowns, but for the case of Berkeley Lab as with other microgrid cases, reducing the load requirements to minimal but acceptable levels would be ideal, and enabling and automating low power mode building operation would be a critical enabling technology .

Office buildings heating, ventilation and air conditioning (HVAC) systems that circulate water and air for ventilation can see limited load reduction due to minimum water flow requirements set by

corrosion concerns and minimum ventilation requirements for any remaining building occupants. Thus, systems and technologies need to be developed to enable lower power states. During the COVID-19 shelter in place, commercial building electricity was reduced by an average of 25% about three weeks after the first shelter-in-place orders compared to the week prior to shutdowns (Table 12), despite presumably much larger than 25% reductions in occupancy. In the Western United States, where shelter-in-place was instituted the earliest, electricity reduction was 27%.

Table 12. Commercial building electricity reduction as compared to the week of March 1st (St John 2020, data from hatchdata.com)

	March 8 - March 14	March 15 - March 21	March 22 - March 28	March 29 - April 4	April 5 - April 11
US Total	5%	12%	18%	22%	25%
Northeast	7%	16%	21%	23%	26%
Midwest	4%	3%	11%	19%	25%
South	5%	10%	16%	22%	24%
West	4%	14%	21%	22%	27%

hatchdata

Source: www.hatchdata.com

Automated low power mode operation in buildings can also help to stabilize the electric grid during extreme weather or periods of high load. Developing this capability thus has multiple benefits:

- Enables emergency mode operation
- Helps to stabilize the electricity grid in extreme weather
- Improves the resilience and performance of microgrids during times of grid electricity loss
- Provides a framework and data for a new class of building standards

A second aspect of this R&D is the concept of a “Connected Community of Buildings" or demonstrating a microgrid over a diverse set of buildings, PV, energy storage and EV for maximal flexibility and resilience. Berkeley Lab recently published a large study for the California Public Utilities Commission on the potential for demand response and demand shifting in particular to support greater variable renewable electricity sources (Gerke et al 2020). The proposed new research would extend that framework to a networked collection of resources in a multi-parameter optimization. This R&D could help enable smart, resilient communities and neighborhoods that are safer and remain powered up during extreme weather or other disasters.

Some potential novel capabilities that could emerge from this research include optimized control with predictive models and real-time sensing, zoning hardware and sequencing to enable automated low power mode or emergence response in building, and the development of new building codes that take these factors into consideration.

8.3 A Resilience Accelerator and Microgrid Testbed for Emerging Generation and Storage Technologies

To support the R&D described in Section 8.2 above, we propose a "Resilience Accelerator and Microgrid Testbed" to be housed at Berkeley Lab (Fig. 12). This could be a staged microgrid implementation with the goals of, for example, a resilience capability at Berkeley Lab of at least 10 MW of low to zero-carbon onsite power and/or storage, and to develop technologies, microgrid designs, configurations, and controls that can deployed more widely in the next several years.

The microgrid testbed would be an onsite facility or grow organically within the Lab site, perhaps leveraging the current FLEXLAB facility to test and demonstrate emerging generation and storage technologies (for example, flow cell batteries, and H_2 electrolysis, fuel cells, and storage). Such a capability would allow understanding and characterization of degradation mechanisms and performance limitations and be integrated with demand side-load management.

Thermal storage is an emerging area and new lab spaces could be dedicated to thermal storage integration in new and existing buildings, grid support demonstrations with emerging technologies/ building-integrated storage, development and testing of novel dynamic thermal elements, and high temperature thermal storage.

Novel capabilities for the testbed include the capability to compare new supply technologies and the networking of a diverse set of buildings and distributed energy resources with advanced controls.

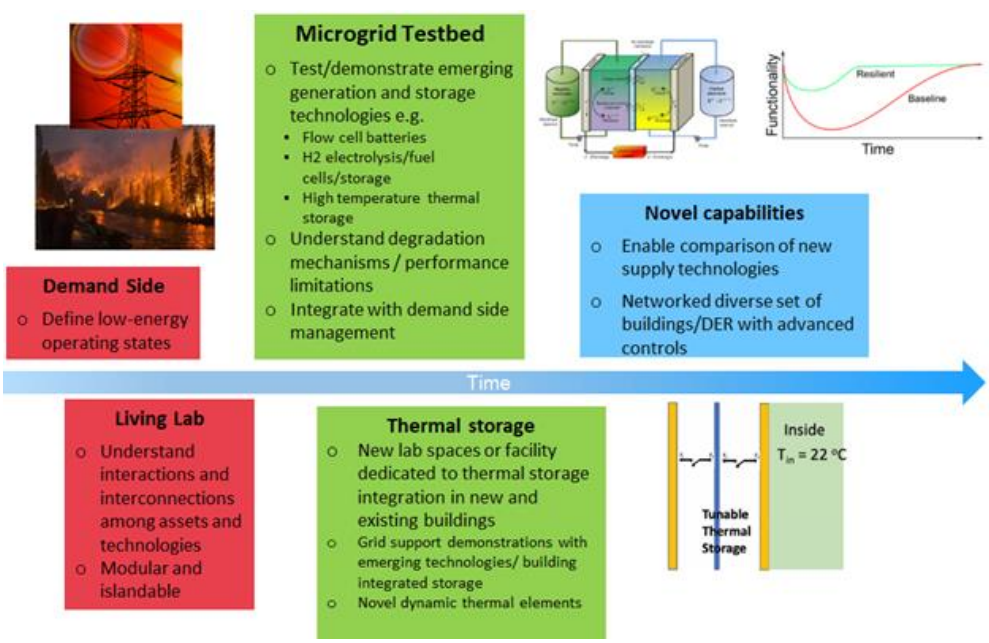

Figure 12. Key features of a proposed Resiliency Accelerator and Microgrid Test Bed for emerging generation include the capability to test and demonstrate emerging generation and storage technologies, development and demonstrations of new and emerging thermal storage technologies, and networking a diverse set of building and distributed energy resources with advanced controls.

10 ATTACHMENTS

Attachment 1: Berkeley Lab Electricity Loads by Building

Building	Category	Switch	Peak Electrical Load (MW)	Peak Daily Electricity Consumption (MWh)
A2 Others	Less Critical Facilities	A2	0.04	0.8
A4 Others	Less Critical Facilities	A4	0.68	14.6
A5 Others	Less Critical Facilities	A5	0.00	0.1
A6 Others	Less Critical Facilities	A6	0.95	20.5
83	Less Critical Facilities	A5	0.04	0.7
15	Other Priority Facilities	A4	0.13	2.5
2	Other Priority Facilities	A4	0.53	8.6
26	Critical Facilities	A2	0.05	1.1
30	Other Priority Facilities	A4	0.18	3.4
33	Other Priority Facilities	A4	0.35	6.5
34	ALS	A4	0.22	7.9
37	ALS	A4	0.70	13.9
43	Critical Facilities	A4	0.16	3.2
48	Critical Facilities	A3	0.02	0.4
50A PR	Other Priority Facilities	A6	0.18	3.9
50B PR	Critical Facilities	A6	0.75	16.2
59	NERSC	A7	0.14	2.8
59PR	NERSC	A7	5.01	109.2
6	ALS	A3	0.63	15.2
62	Other Priority Facilities	A5	0.31	6.6
66	Other Priority Facilities	A5	0.19	4.6

67,67A	MF	A5	0.86	15.9
6PR	ALS	A3	2.34	57.4
70	Other Priority Facilities	A6	0.34	6.9
70A	Less Critical Facilities	A6	0.43	8.7
71	Other Priority Facilities	A6	0.37	6.8
72	MF	A5	0.00	0.1
72A	MF	A5	0.05	1.2
72B	MF	A5	0.03	0.5
72C	MF	A5	0.09	1.9
74	Other Priority Facilities	A5	0.22	3.8
76	Other Priority Facilities	A2	0.09	1.5
77	Other Priority Facilities	A2	0.54	7.8
77A	Other Priority Facilities	A2	0.02	0.7
80	Other Priority Facilities	A3	0.08	1.6
84	Other Priority Facilities	A5	0.25	5.6
85	Critical Facilities	A5	0.05	1.1
86	Critical Facilities	A5	0.03	0.7
88	Other Priority Facilities	A6	1.41	30.3
90, 90X	Other Priority Facilities	A6	0.44	5.6
91	JGI	A6	0.42	7.6
91U	JGI	A6	0.10	2.4

Attachment 2: Installed Area Estimates for Onsite Distributed Generation and Storage Options

Installed area calculations are shown in Table A2-1. These are first order estimates based on online product spec sheets and online technical literature (reference sources are summarized in Table A2-2). To aid in interpreting the results, the table results are shaded to group results of similar magnitude (green - lower, yellow - middle, red - higher). We assume a 3.5 enclosure area factor, or a total installation area that is 3.5 times the footprint area of the generation and storage units themselves to account for safe keepaway distances consistent with product spec sheets and layouts (for example, based on the Rongke flow cell battery spec sheet and GE battery system cited in Table A2-2). Area estimates in the technical options Table A2-1 with solar PV (2 MW) do not include the area for PV. We assume that the area for the solar is either on building rooftops or as elevated panels in parking lots and thus does not require additional storage area (not including any area required for solar inverters).

We find that diesel and propane gensets, natural gas cogeneration, and the Li-ion storage system occupies the least amount of area, from about 1,500-2,000 m^2. The two fuel cell systems supplied by natural gas are each about 3,000 m^2. Adding two days of hydrogen storage adds about 7,000 m^2 of area. The flow cell battery takes the largest amount of area at an estimated 30,000 m^2 because of its low energy density.

Diesel and propane genset area is taken from commercial system spec sheets and other online information. Fuel is assumed to require separate storage space, and commercial fuel storage units are assumed to be configured in a single layer or single stack. Stacking either generation and/or fuel storage units (and battery units below) is certainly possible and can reduce overall system area, but care must be taken to secure taller units to ensure their structural integrity during any seismic activity.

SOFC system area is based on a 200 kW Bloom Energy system; while PAFC system is based on a 400 kW Doosan System. H2 storage area is based on existing compressed H2 storage tank configurations and DOE estimates for H2 fueling stations for vehicles as noted in Table B2 below.

Li-ion battery system size is based on a GE 4,184 MWh unit and flow cell battery system size is based on data from Vionyx and Rongke Power as noted below.

Table A2-1. Installed area estimates for onsite distributed generation and storage options

	Solution Name	**Source Energy Density [MJ/L]**	**Installed Area [m2 for 10 MW for 2 days]**
1a	Diesel and Dual Fuel Genset with Storage	37	1,600

1b	Propane Genset with Storage	23	2,200
2	Natural Gas Cogen	10	1,500-2,500
3	NG SOFC without Storage	10	3,000
4a	NG PAFC without Storage	10	3,000
4b	NG PAFC with Storage	~3	10,000
4c	H2 PAFC with Storage	~3	10,000
4d	Solar PV with PAFC and H2 Storage	~3	10,000 [1]
5a	Solar PV plus Li-Ion Battery Storage	~0.5	6,600 [1]
5b	Solar PV plus Flow Battery Storage	~.05	30,000 [1]

Notes:

1. Does not include 2MW solar area: 13,500m^2 of which about 7,100m^2 is rooftop and 6400m^2 is on parking lots
2. Area calculations assume an enclosure factor of 3.5 above equipment footprint. See for example the Rongke Power link 5b in Table B2 below.
3. Single level or single stack storage is assumed for diesel/propane storage and battery storage. Storage areas could be reduced with two-level stacking of fuel storage of battery storage units.

Table A2-1. Reference sources for installed area estimates in Table A1-1.

	Solution Name	Sources, area calculations
1a	Diesel and Dual Fuel Genset with Storage	https://apelectric.com/winco-dr100f4-100kw-diesel-generator/?msclkid=8ddb8e0c804413c9334ad0706a82affe&utm_source=bing&utm_medium=cpc&utm_campaign=02%20-%20Everything%20Else&utm_term=4582283430908747&utm_content=Everything%20Else https://www.plastic-mart.com/product/17283/1000-gallon-doublewall-fuelcube-fcp1000?gclid=EAIaIQobChMIgYjsjpGM6gIVgxx9Ch2cAg2UEAQYASABEgLAKPD_BwE
1b	Propane Genset with Storage	https://www.northerntool.com/shop/tools/product_200335165_200335165?cm_mmc=Google-pla&utm_source=Google_PLA&utm_medium=Generators%20%3E%20Commercial%20Generators&utm_campaign=Generac&utm_content=167304LPC&gclid=EAIaIQobChMItbzFhMng5wIVsh-tBh2AAAF0EAQYASABEgIqJfD_BwE http://www.missiongas.com/lpgastankdimensions.htm
2	Natural Gas Cogen	https://www.asme.org/topics-resources/content/a-greener-less-expensive-cogeneration-plant
3	NG SOFC without Storage	https://www.bloomenergy.com/datasheets/energy-server-es5-200kw
4a	NG PAFC without Storage	Spec sheet: http://www.doosanfuelcellamerica.com/download/pdf/catalog/pafc-400kw_us_en.pdf Web site: http://www.doosanfuelcellamerica.com/en/fuel-cell-solutions/purecell-system/
4b	NG PAFC with Storage	See 4a; H2 storage: https://www.energy.gov/sites/prod/files/2015/10/f27/fcto_webinarslides_ref_designs_h2_stations_101315.pdf
4c	H2 PAFC with Storage	See 4a; H2 storage: https://www.energy.gov/sites/prod/files/2015/10/f27/fcto_webinarslides_ref_designs_h2_stations_101315.pdf
4d	Solar PAFC with Storage	See 4a; H2 storage: https://www.energy.gov/sites/prod/files/2015/10/f27/fcto_webinarslides_ref_designs_h2_stations_101315.pdf

5a	Solar PV plus Li-Ion Battery Storage	https://www.ge.com/renewableenergy/sites/default/files/related_documents/RSU-4000_Data%20sheet_0.pdf https://www.gegridsolutions.com/products/brochures/services/energystorage-brochure-en.pdf
5b	Solar PV plus Flow Battery Storage	https://www.vionxenergy.com/products/ http://www.rongkepower.com/Product/show/catid/175/id/103/lang/en.html

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12 GLOSSARY

ATS Automatic transfer switch

CEQA California Environmental Quality Act

CHP Combined heat and power

DOE Department of Energy

DER Distributed energy resource

EBMUD East Bay Municipal Utility District

GHG	Greenhouse gas emissions
HVAC	Heating, ventilation and air conditioning
IRN	Integrated resilient node
LCOE	Levelized cost of electricity (or levelized cost of energy)
MPC	Model predictive control
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
R&D	Research & Development
UPS	Uninterruptible power supply
WAPA	Western Area Power Administration