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Scaling Solar+ for Small and Medium Commercial Buildings

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PREPARED BY:

Peter Alstone Jim Zoellick
Kristen Radecsky Marc Marshall
Schatz Energy Research Center

Rich Brown Anand Prakash
Lazlo Paul
Lawrence Berkeley National Laboratory
Primary Authors

Tanner Kural
Project Manager
California Energy Commission

Agreement Number: EPC-17-002

Kevin Uy
Branch Manager
ENERGY GENERATION RESEARCH BRANCH

Jonah Steinbuck, Ph.D.
Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Drew Bohan
Executive Director

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission, and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas and Electric Company, and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

This project focused on developing and validating technology that can lead to market scaling for resilient Solar+ microgrids (systems combining solar, batteries, or other equipment) at small commercial buildings. The research project deployed a Solar+ microgrid at a fueling station and convenience store operated by the Blue Lake Rancheria Tribe in Northern California near the cities of Arcata and Eureka in Humboldt County. The pilot system included a 50-kW photovoltaic array, a 109-kW/174-kWh lithium-ion battery, interconnection switchgear with microgrid automation controls, and advanced building controls on the heating, ventilating, air conditioning, and refrigeration systems. The project work resulted in advances toward a standardized switchgear and controls setup for microgrids, improved open-source software for automation and integration of distributed energy resources and loads, and market scaling insights that support continued work toward commercially viable and widespread application of the technology. Demonstrated benefits include electricity bill savings, reduced greenhouse gas emissions and increased renewable-based resilience for the host site, as well as the ability to provide a response that is appropriate for grid services. Additional investment in the deployment of Solar+ microgrids could be targeted for critical community facilities that serve roles in disaster response, with a focus on wildfire-prone and disadvantaged communities. These investments can provide immediate and valuable assistance to communities and would have spillover benefits in technology learning and cost reductions for Solar+ microgrids that serve small to medium commercial buildings.

Keywords: Solar plus storage, battery energy storage, microgrid, resilience, demand response, standardization, cost reduction, market scaling, open-source software, controls, switchgear, grid services

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Introduction

Wildfires, hurricanes, earthquakes, and other natural disasters stress every segment of society, including the built environment. Continued performance and resilience are critically important to emergency response facilities like fire stations and hospitals, but also to grocery stores, fueling stations, and other basic services. However, despite this necessity, the electric power system is unable to maintain operations in many extreme events.

The conventional pathway to resilient power has been to install fossil-fueled backup generators with automatic transfer switches at critical facilities, sometimes in combination with battery-based uninterruptible power supplies on particularly critical equipment. While these systems do improve reliability, they are also costly and polluting. These fossil-fueled backup systems are also not always fully reliable. Threats to the fuel supply chain or generator maintenance issues in turn introduce risks of system failure.

Clean energy microgrids support energy resilience with climate-friendly technology, allowing single sites or isolated community clusters to maintain electricity service during outages. Solar+ microgrids (systems combining solar, batteries, or other equipment) encompass solar photovoltaic generation, battery energy storage, and flexible loads able to respond to changes in electricity demand. These systems provide a range of benefits, including lower bills (from solar generation, battery dispatch, and load management) and resilience. With wildfire risks exacerbated by climate change across California, both planned emergency power shut-offs and grid failures from wildfires have increased the need for system resilience, particularly in rural, underserved communities that often endure the brunt of these risks.

This project developed, deployed, commissioned, operated, and studied a technology framework for integrating Solar+ microgrids. The framework incorporated hardware for integrating and interconnecting power electronics elements of microgrids, and software for coordinating control of diverse, multi-vendor building energy systems. The project pilot, shown in Figure 1, served a critical gas station and convenience store at the Blue Lake Rancheria, home to a federally recognized Native American tribe located five miles inland from the Pacific Coast along California Highway 299, near the Humboldt County cities of Eureka and Arcata.

Figure 1: Solar+ Microgrid at Blue Lake Rancheria

Microgrid hardware includes PV array on canopy and battery storage and switchgear at rear corner of store.

Source: Blue Lake Rancheria

This research project focused on reducing the need for custom engineering while providing open-source software to coordinate diverse devices and systems within the microgrid; these advances will also reduce the cost of future Solar+ microgrids. With the cost of solar and battery systems also falling, investments in distributed energy resource systems are increasingly economical propositions. However, customers cannot install these systems without additional, often customized, interconnections and controls that both manage the point of connection with the regional power system and coordinate operations between photovoltaic arrays, the battery, and responsive loads during islanded operations.

Currently, a custom switchgear costs $50,000-$250,000 per system and requires $10,000+ in professional work to prepare the site and support installation and commissioning. The soft costs of designing the microgrid controls, managing the interconnection permitting process, programming controls, and overall integration of software systems adds up to about $100,000 per site, depending on the details. Due to economies of scale, these switchgear and controls costs are particularly significant in the small- and medium-sized building sector. This project addressed these two significant microgrid cost areas by laying groundwork toward developing standardized and scalable approaches to the design and engineering of both the hardware and software components.

Project Purpose

The purpose of this research project was to develop and pilot test a set of currently missing hardware and software elements that will enable multiple vendors to provide Solar+ technology that can serve the fast-changing needs of the California grid.

The project had several key goals:

- Produce a hardware design toolkit with simplified, standardized switchgear
- Develop open-source automation software that integrates and controls devices, including flexible loads managed with advanced controls
- Advance the understanding of how to target public investment in microgrids on targeted sites with high values

These goals are important for ratepayers because they advance state-of-the-art technologies and ultimately drive down the costs of fully featured, efficient microgrids, making these technologies and their benefits more widely accessible to everyone.

Target audiences expected to use these results include microgrid developers and vendors, building automation software developers, critical facility operators and planners, utility personnel who focus on distribution system safety and interconnections, and staffers at both utilities and state agencies who are addressing wildfire risks.

Project Approach

A talented and diverse project team was brought together to achieve the project goals. The Schatz Energy Research Center at Humboldt State University served as prime contractor and led the design and engineering, construction management, market analysis, and coordination of the overall project. Serraga Energy and the Blue Lake Rancheria Tribe served as site host and construction contractor. Lawrence Berkeley National Laboratory focused on the development and integration of advanced buildings and automation software. The project team also engaged with contractor and vendor partners, including PG&E, Tesla, Colburn Electric, Randy Cox Electric, McKeever Electric, C.K. Johnson, Schweitzer Engineering Labs, Eaton, and SunPower.

The research team's approach was to use a challenging but achievable pilot installation as an organizing and motivating framework for technology research and development. The real-world challenges and contexts of a pilot project helped to clarify and shape the development of hardware, software, and market-scaling knowledge. The pilot project was located at a gas station and convenience store owned and operated by the Blue Lake Rancheria Tribe in northwest California. This site is adjacent to a Red Cross certified emergency evacuation center and provides critical emergency services.

Table 1 describes key technical and non-technical challenges the team faced and how they were addressed.

Table 1: Summary of Key High-Level Challenges and Solutions

Challenge	Solution
Lack of standardized and pre-approved hardware designed for microgrid interconnection	Developed, tested, permitted, and interconnected a custom-designed switchgear and controls system that is more suitable for replication and manufacturability
Limited photovoltaic capacity compared to site loads during fall and winter outages, due to constrained physical hosting capacity, constrained budget, and net metering rules	Utilized high-efficiency solar photovoltaic modules to maximize power density. Worked to reduce the cost of PV deployment with dedicated installation contractors. Kept deep backup fuel-based generation in place to firm-up power supply.
Challenging software integration across diverse control system interfaces, firmware algorithms and setpoint configurations, and poorly defined physical response characteristics from connected systems	Built on and extended a scalable, open-source framework to coordinate control of diverse connected systems. Developed and tested software drivers to connect equipment.
Utility interconnection processes geared toward highly customized and engineered systems, leading to high fixed costs	Worked through the interconnection process and identified opportunities to standardize and streamline future work

Source: Schatz Center

This study also identified market scaling and cost factors to understand more fully the potential of Solar+ microgrid technology. The research team conducted a market survey of nearly 12,000 convenience stores in California to identify their preferences and potential for energy system upgrades. The project had higher costs than anticipated, so the team also developed a cost estimation framework for Solar+ microgrids that includes future cost projections once the technology is established and widely deployed.

The performance of Solar+ microgrids requires multiple metrics to capture theoretical use cases and value streams. Researchers measured and assessed system performances in a range of dimensions, including utility bill savings, peak load management, energy shifting, resilience potential, and zero-carbon solar photovoltaic production. A technical advisory committee made up of representatives from many agencies and organizations also guided the project.

Project Results

Overall, this project achieved its major goals. The project team designed, constructed, and operated a Solar+ microgrid that provides clean, resilient, cost-effective energy at the Blue Lake Rancheria. The progress made by this research project included breakthroughs and advances in hardware standardization, software framework design, and market scaling insights.

One of the most challenging phases of the project was in the construction and commissioning of the microgrid. As with many first-time projects, vendors and equipment suppliers often do not get it right the first time. There were several delays in the construction schedule, and commissioning issues required unanticipated attention. Numerous lessons learned were documented and informed researchers' recommendations for standardized designs to avoid these issues in the future (see Appendix F).

In the cost analysis of microgrids, researchers concluded that major barriers to their adoption are the "soft" costs of planning, design, permitting, engineering, programming, and setup. These account for between 20 percent and 30 percent of the total costs with status-quo approaches. Based on experience from this project, researchers determined that these soft costs can be significantly reduced, perhaps by as much as 80 percent, through continued technology standardization and deployment.

It is challenging to put a price on the value of maintaining electric service to communities with high wildfire risk. Utility bill savings may be an important factor for supporting Solar+ technology, but ultimately bill savings are secondary to facility safety and system reliability. Leadership from policymakers is needed to enable the deployment of clean energy microgrids to critical sites, and supporting these microgrids can lead to a more commercially viable and sustainable market for widespread scaling.

Advancing the Research to Market

The most promising near-term market for Solar+ microgrids is at community-serving sites facing wildfire threats. The pilot system at a rural gas station and convenience store chosen for this project is but a single example; there are nearly 12,000 gas stations across the state that could replicate it (National Association of Convenience Stores, 2021). Grocery stores, public safety facilities, hospitals, community centers, and schools would also benefit from this technology.

Benefits to California

Solar+ microgrids are important for California ratepayers because they are a pathway for both climate mitigation and resilience. These are vital priorities as California works to address the compelling and acute needs to decarbonize the state's energy system and respond to emerging threats, including wildfire.

The technology developments supported by this project are instrumental for advancing toward a commercially viable Solar+ microgrid market. This includes advances in developing a standardized piece of integrated switchgear for simple microgrid applications like those found in small- and medium-sized commercial buildings. This standardization can bring about cost reductions in switchgear hardware, microgrid controls, and soft costs such as engineering design, interconnection and permitting.

The potential reduction of emissions from Solar+ microgrids are mainly tied to distributed solar deployment. Since California has a binding statewide mandate for decarbonization, it is important to note that Solar+ microgrids will change the location of solar generation. With widespread microgrids, solar photovoltaics deployed in the state could do double duty and also provide local resilience.

Another key benefit of Solar+ storage is the ability of these systems to provide grid services that can benefit all ratepayers. These grid services, such as load shedding, load shifting and energy storage, and optimized dispatch, can help enable the transition to a 100-percent renewable electric grid. Solar+ storage systems can help address the "duck curve" problem, where there is too much power in the middle of the day before a steep ramp-up in the early evening.

Direct project benefits include energy and demand cost savings, greenhouse gas emission reductions, direct job creation, and increased low carbon resilience. Rooftop solar and behind-the-meter batteries clearly hold the promise to decarbonize and add resilience to the electric system, though they face significant cost and complexity barriers, especially in the small-commercial-building market. This project shines a light on a potential pathway toward widespread deployment of distributed Solar+ systems.

CHAPTER 1:
Introduction

The Importance of Solar+

As California works to create a 100-percent renewable electric grid, the state must develop cost-effective ways to utilize more variable renewable energy resources like solar. Solar+, also referred to as "Solar plus" (O'Shaughnessy et al., 2017) or "Solar Plus X" (United States Department of Energy [DOE]), refers to the integrated and optimized deployment of building-level solar photovoltaic (PV) technology with energy storage, controllable loads, and optimized control software. Solar+ technologies allow customers to strategically shift certain loads or use battery storage to better match available solar power with both onsite and electric grid loads. This can lower customer utility bills and deliver grid services that benefit all ratepayers while increasing onsite resilience by providing a backup energy source.

By aligning renewable resources with demand, Solar+ technologies can help California reach its renewable energy goals and mitigate climate change. In addition, adding microgrid controls to the portfolio of Solar+ technologies can provide resilience to critical facilities in California's communities and help counter the ongoing effects of climate change.

Project Objectives

The key objectives of this project were to develop a set of site targeting guidelines, hardware design practices, and dynamic, open-source control software for Solar+ technologies that could be deployed at scale in the small- and medium-sized building sector, with a special focus on convenience stores and fueling stations. A key challenge for Solar+ technologies is that they need to be well integrated and optimized to realize their full benefits. If these technologies are procured separately, without coordination, there will be lost opportunities for optimization and cost savings. In addition, to be cost-effective in the small- and medium-sized building sector, it is important that these technologies become integrated, standardized, and streamlined, rather than relying on custom engineering and design.

The objective of this project was to design, implement, operate, and evaluate a Solar+ system in a pilot-scale application for a combined convenience store and gas station, and to use this experience and the resulting lessons learned to inform deliverables in three key areas needed for technology scale-up: hardware design guidelines, integrated open-source software, and site targeting tools.

Project Team

The project team included several key partners:

- Schatz Energy Research Center (Schatz Center): prime contractor, owner's engineer, and lead system designer and integrator

- Blue Lake Rancheria (BLR) and Serraga Energy, LLC (Serraga): site host and installation contractor (Serraga is the project development and management entity for the Blue Lake Rancheria.)
- Lawrence Berkeley National Laboratory (LBNL): optimization software developer
- McKeever Energy and Electric (ME&E): PV contractor for system design and procurement

Report Structure

This report describes project activities and presents project results and deliverables. Chapters 2 and 3 focus on the design, procurement, installation, and commissioning of the pilot Solar+ project at the Blue Lake Rancheria Play Station 777 in Blue Lake, California, located in Humboldt County near the cities of Eureka and Arcata. This work was accomplished over a two-and-a-half-year period between January 2018 and July 2020. Chapter 4 describes the development and testing of the Solar+ Optimizer software developed by the team from LBNL, as well as the islanding controls developed by the Schatz Center. Development, commissioning, and testing of the software elements occurred in parallel with the design, procurement, installation, and commissioning of the project hardware. System operation and performance were evaluated in various phases between August 2020 and July 2021. Performance monitoring is discussed in Chapter 5. A key objective of this project was to produce deliverables that would lead to deployment at scale for Solar+ technologies in the small and medium building sector. Chapter 6 describes the market replication tools and information that were developed. Finally, chapters 7 through 9 discuss project knowledge transfer activities, project conclusions, lessons learned, and ratepayer benefits. A robust set of appendices provides detailed information on many of the topics discussed in this report.

CHAPTER 2:
Solar+ Design and Permitting

Chapter 2 describes the design, engineering, and permitting of the Solar+ pilot project located at the Blue Lake Rancheria Play Station 777 gas station and convenience store (C-store) located in Humboldt County near the cities of Eureka and Arcata. The Solar+ system combines a solar PV system with battery energy storage and advanced controls to create a building energy system that optimizes the generation and consumption of electricity at the site. In addition, an islanding controller with related switchgear and protection was integrated into the system to provide islanding capabilities. This qualifies the system as a microgrid.

This system was designed to meet the needs of small- and medium-sized commercial buildings. To succeed in this market, a system must be cost-effective. This requires that a system be largely standardized, have a streamlined interconnection process, and facilitate the integration of system components. The Solar+ pilot system was designed with these parameters in mind. A design memo included in Appendix A provides additional detail. Note also that a Hardware Design Toolkit document was prepared to present general lessons learned throughout the Solar+ design process; this document is included in Appendix F.

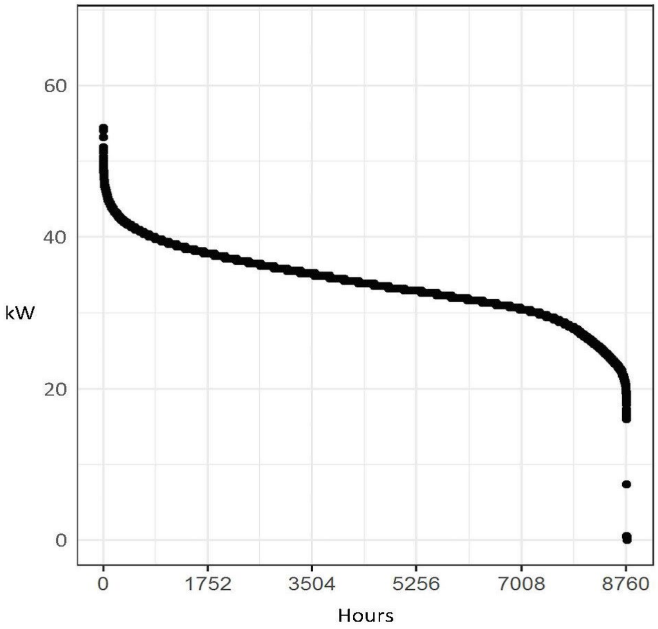
System Design

The design of the Solar+ system involved: load assessment; PV array sizing and siting; battery sizing and siting; islanding switchgear design; integration into the existing facility; heating, ventilating, air conditioning, and refrigeration (HVAC&R) controls hardware; integrated system controls hardware; and network and communications supervisory control and data acquisition (SCADA) design.

Load Analysis

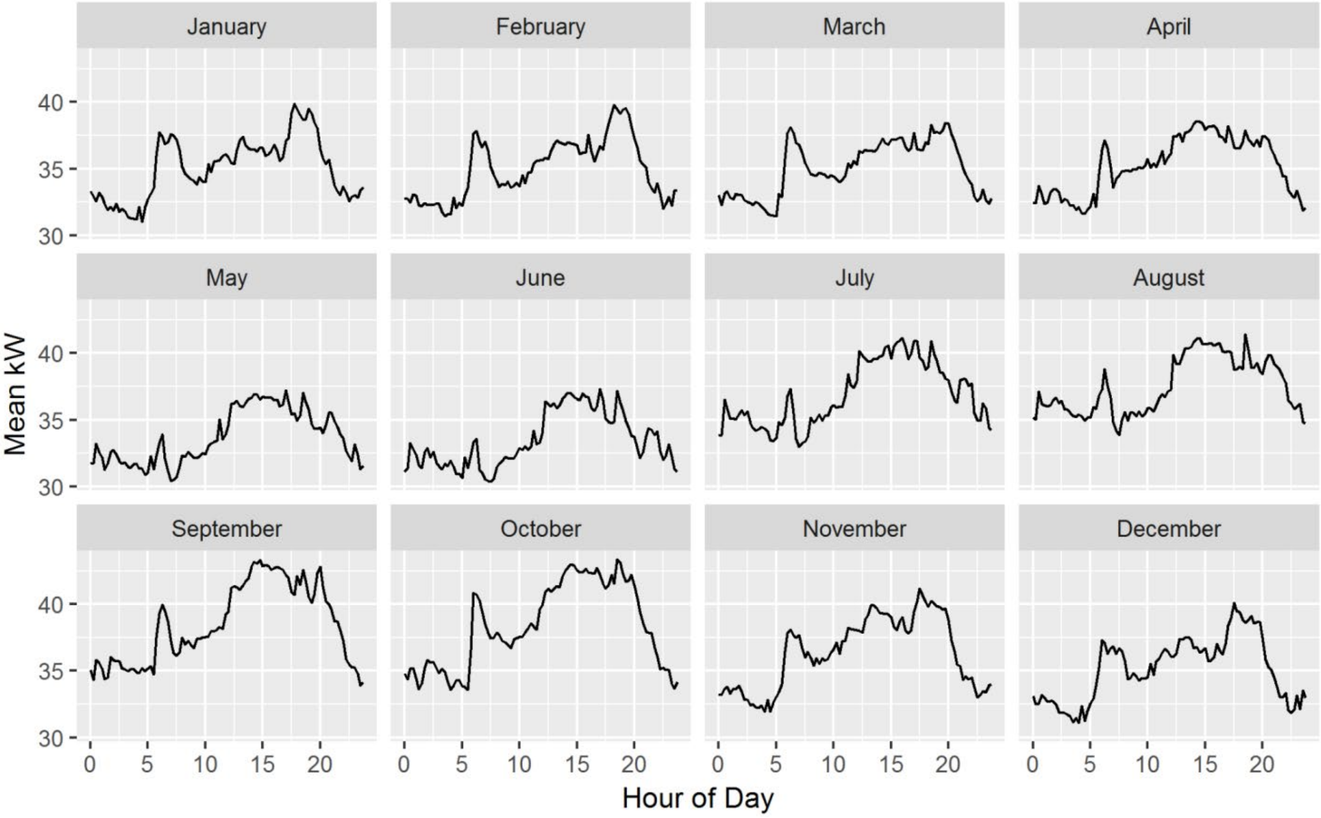
Fifteen-minute electricity consumption data were collected for the facility for approximately three years prior to design (September 2014 through September 2017). Due to load decreases over this time period from energy efficiency, the most representative complete year in this series was 2016. These data showed average annual consumption in 2016 of about 293,000 kilowatt-hours per year (kWh/yr), with an average demand of 34 kW. Since the facility is located in a mild, coastal climate, there were only modest seasonal impacts to the load profile. The hourly variation in load was also modest. The facility operates around the clock every day and features 77 gaming machines. This accounts for a large baseload of approximately 20 kW and a stable load profile. For nearly the entire year of 2016, the load varied between about 20 kW and 50 kW (as illustrated by the 2016 load duration curve for the facility in Figure 2), with the majority of hours, roughly 75 percent, falling between 30 kW and 40 kW (as seen in Figure 3, which shows hourly load profiles by month for an approximate 3-year period).

Figure 2: Play Station 777, 2016 Load Duration Curve



Source: Schatz Center

Figure 3: Play Station 777 Average Monthly Load Profiles



Monthly load profile based on data from September 2014 through September 2017

Source: Schatz Center

PV Array Sizing and Siting

The roof space of the gas station fueling island canopy was the preferred location for the solar PV array. To maximize array size within the usable space, the modules were arranged in a single plane, as opposed to multiple rows with spacing between the rows. With the PV array in a single plane, however, the highest point of the array could become excessively tall, depending on the array's tilt angle. The optimal tilt angle for a PV array in Humboldt County is approximately 30 degrees from the horizontal; however, a 60-kW single-plane array sloped at 30 degrees would have a maximum height of 18 feet, which would be aesthetically undesirable and create an excessive wind loading atop the gas station canopy. After considering several options, an 8-degree tilt was chosen, resulting in a PV array maximum height of 5 feet and an estimated 6-percent reduction in energy generation relative to a 30-degree tilt. The project team estimated that the PV array would meet nearly 25 percent of the annual load for the facility. The design for the PV array also needed to fit within structural and seismic loading limits for the canopy structure. A licensed civil engineer at SEE Engineering completed a structural engineering assessment for the PV array installation and found that the seismic loading was the limiting criterion. The PV array size was maximized within the constraints of this seismic loading limit.

Battery Sizing and Siting

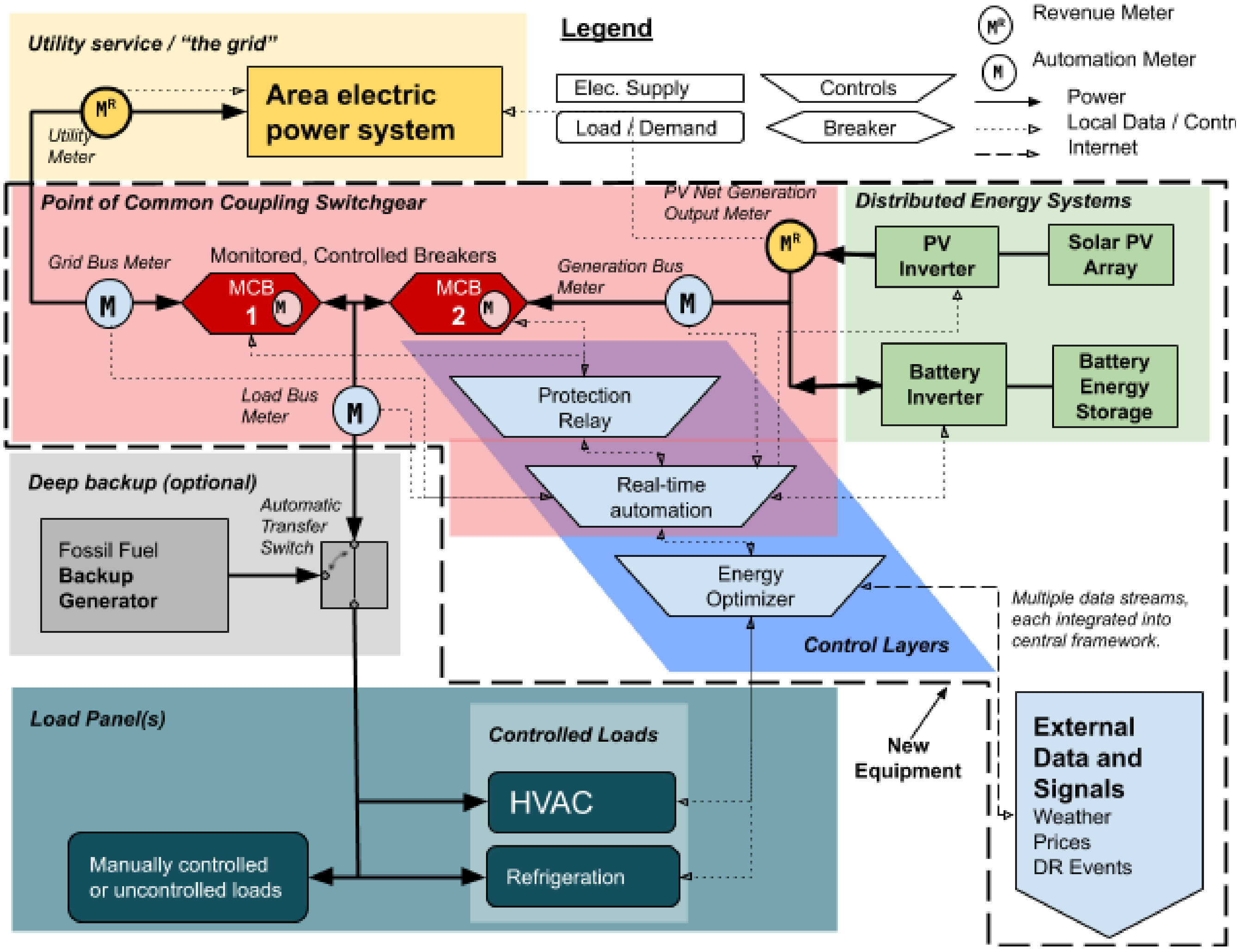
A 174-kWh, 109-kW battery energy storage system (BESS) was chosen based on the site's approximate 30-50 kW load over a typical day and the expected output of the PV array. The battery is expected to provide a minimum of 1 to 2 hours and as much as 4 to 6 hours of islanded runtime during a grid outage under most circumstances. The battery would also be used for energy arbitrage, to store solar power generated during the middle of the day when prices are low and dispatched in the evening when prices are higher. Assuming that up to 75 percent of the battery capacity is used for this purpose, the team estimated that the battery would provide roughly 2.6 hours of storage for PV generation at peak output. The estimated annual average peak sun hours for the array at this site is about 4.4 hours per day, so the battery can store about 60 percent of the PV energy generated, on average. The battery and islanding switchgear were located behind the facility near the PG&E meter and electrical service and were placed on a single concrete pad.

System Architecture and Switchgear Design

The design team specified and procured custom switchgear for this project. The switchgear integrates the new PV generation and battery energy storage into the site's existing electrical infrastructure and also provides the ability to disconnect from the bulk electric grid to operate in island mode. It is referred to throughout this document as *islanding switchgear or point of common coupling* (PCC) switchgear. Key components integrated into the switchgear included: monitored controlled breakers, protection relays, and real-time microgrid controls. While the switchgear and controls were custom designed, an islanding switchgear product such as this could become a standardized and listed product that could even be pre-approved by electric utilities for this type of solar-plus battery application. This would significantly reduce the cost of the islanding switchgear, reduce required design engineering, simplify the interconnection and permitting process, and reduce the costs for custom programming for protection relays and microgrid controls.

Note that the system was designed so that power from the pre-existing, 175-kW standby diesel generator (DG) would not flow through the new switchgear. The DG will continue to function according to its original design. The DG will provide power only when the facility is islanded, and the battery and PV cannot supply enough power for the loads. In this way the DG is relegated to deep backup. The isochronous DG will continue to be interconnected via the existing automatic transfer switch (ATS) so it can never operate in parallel with the PG&E grid. Figure 4 provides a simplified single line diagram of the electrical design, in addition to a simplified conceptual drawing of the controls architecture.

Figure 4: Single Line Diagram of Solar+ System With Controls



Source: Schatz Center

Network, Communications, and Controls Hardware

As shown in Figure 4, the Solar+ control system consists of three control layers. The protection controls are at the most foundational level. This functionality is provided by a pair of redundant intertie protection relays that control the motorized breakers: MCB1 and MCB2. Note that the second relay in the pair is required by PG&E as a backup. The second layer of control is the real-time automation layer that controls the islanding features of the system. These controls consist of a custom programmed real-time automation controller (RTAC), a battery system controller, and the intertie protection relays. These first two control layers are discussed further in chapters 3 and 4, as well as in Appendix F.

The third level of control is the energy optimization layer. This layer, discussed in greater detail in Chapter 4, operates at a much slower rate and utilizes energy and weather forecast data, as well as utility pricing data (energy and demand charges, by period), to determine management of the battery storage resource, as well as of the thermal loads, both HVAC and refrigeration. The optimization controls included the Solar+ Optimizer software, battery dispatch software, and refrigeration and HVAC controls. The optimization control layer is particularly important for managing the blue sky operation of the system while minimizing energy costs. It can also manage the thermal loads during an islanding event in an effort to extend the islanded runtime on PV and battery power.

All three of these control layers were implemented and tested in this research project. Solar+ Optimizer controlled thermal loads and battery dispatch,[1] while the battery dispatch software controlled only battery dispatch. Control of battery dispatch by these two control methods is assessed in Chapter 5, Performance Monitoring. For long-term operation, only the battery dispatch software will be used for optimal battery dispatch. This is because the Solar+ Optimizer software is developmental. It is not an off-the-shelf product and there is no product support service available for it. For these reasons, the Solar+ Optimizer software will be decommissioned at the pilot site at the end of the research period. However, it is important to note that the Solar+ Optimizer software is available as open-source software on GitHub (see Chapter 7) and that development of this software continues under a spin-off project called "HP-flex," another California Energy Commission (CEC)-sponsored program.

Appendix B includes a list of the controls and communications hardware procured for this Solar+ project.

Refrigeration and HVAC Controls

The existing refrigeration and HVAC controls could not be controlled by an energy management system, so they had to be replaced. New digital, network-compatible refrigeration controllers and HVAC thermostats were purchased so they could communicate with and be controlled by an external source. More information about the newly purchased refrigeration and HVAC controls is provided in Appendix B.

Network and Communications Engineering

The Schatz Center, in collaboration with LBNL and with review by Serraga, created network structure and data-flow diagrams showing each device's role in the Solar+ communications, control, and electric power systems. Networked equipment included: Solar+ Optimizer control

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[1] During pilot project testing, Solar+ Optimizer controlled an emulated battery rather than the actual battery. See the performance evaluation section of the report, Chapter 5, Performance Monitoring, for more information about this testing.

platform, refrigeration and HVAC controls, external weather forecast data, power meters, protection relays, microgrid controller, PV inverter, battery site controller, human machine interface panels, firewalls, gateways, and network switches. Together, the diagrams show the signal paths and data flow paths used for communication and control between all devices. The network diagram was included as part of the electrical plan. Network structure details are considered confidential and are not included in this report.

A cybersecurity assessment was conducted by BLR as part of the network and communications design process. BLR Information Technology (IT) staff is trained in cybersecurity analysis and protection methods, ensuring that the Solar+ network and communications design meet cybersecurity requirements.

Permitting and Interconnection

The BLR, as a Native American sovereign nation, had jurisdiction over this project. BLR reviewed the construction plans, conducted construction inspections, approved construction upon completion, and provided the final permit inspection certificate.

The Schatz Center handled the interconnection process to connect the PV generation and battery storage to PG&E's distribution grid. The process involved approval of an interconnection application, a pre-parallel inspection (PPI), and obtaining permission to operate (PTO) after passing the PPI.

The project's interconnection included several notable points.

- The PG&E interconnection was via the Net Energy Metering 2.0 (NEM2) Tariff under the NEM2 Multiple Tariff Sub-Schedule. The metering configuration was a net generation output meter (NGOM) on the PV system that ensured that any export was credited as NEM-eligible only if it was from the PV generator; the battery was considered non-export.
- The site's operating mode was parallel with reverse power protection. The site interconnects and operates in parallel with PG&E. A SEL 7000 GT+ relay acts as the reverse-power protection device; it will trip to prevent generation from exceeding an agreed-upon limit of 50 kW. The PV inverter produces a maximum of 50 kW.
- The microgrid design included a 600-amp, 480-volt, 3-phase, visible, manually operated, lockable AC disconnect switch that can disconnect the entire facility load and generation from PG&E.

Materials sent to PG&E prior to scheduling the PPI included a final permit inspection certificate, a completed PG&E basic information form, a completed PG&E generation PPI G5-1 form, as-built system single-line and 3-line diagrams, system DC schematic, protection relay test results, relay backup power plan, AC disconnect specification sheet, NGOM cabinet specification sheet, and transformer specification sheet.

Notable points related to the project’s pre-PPI paperwork follow.

- An uninterruptable power supply (UPS) served as backup power for the protection relay, as opposed to a battery with a charging system. This was accepted because the tripping source was reliable and independent from the power system AC source; the system’s fail safe ensures that a loss of the tripping source trips the main breaker at the PCC.
- The system employed a generation breaker in addition to the PCC breaker. The system’s design opens the generation breaker when the BESS state of charge is low during an islanding event. This allows the battery to recharge while the backup DG carries the convenience store loads. PG&E requested that this second breaker’s protection settings be included in the G5-1 form, along with the relay test results.

During the PPI, PG&E inspected the system’s construction and witnessed the protection relay’s function. Since the system’s design did not at that time allow PG&E to witness its anti-islanding function, PG&E granted conditional permission to operate (cPTO) for testing purposes only. Under cPTO, the project team was able to complete commissioning of the BESS and run through necessary testing to confirm the system’s anti-islanding capability. PG&E returned to witness the system’s anti-islanding capability, the system was granted full permission to operate, and PG&E installed the NGOM.

CHAPTER 3: Procurement, Installation, and Commissioning

Chapter 3 discusses the procurement, installation, and commissioning of the Solar+ system installed at the Blue Lake Rancheria Play Station 777 gas station and convenience store in Northern California's Humboldt County.

Procurement

Hardware procured for the Solar+ system broadly consisted of a PV system, a BESS, islanding switchgear, and controls and communications equipment. The main PV hardware consisted of the PV modules, PV array racking, and PV inverter. The BESS included the battery storage, battery inverter, and battery site master controller. The main islanding equipment consisted of a custom switchgear, protection relays, an RTAC islanding controller, and power meters. The thermal controls consisted of the refrigeration controllers and programmable thermostats. Solar+ Optimizer control hardware included a small-form factor computer, a network switch, and a building automation and control network (BACnet) gateway. Appendix B provides a list of the procured hardware, including manufacturers and model numbers.

Installation

Installation activities were divided into six categories. A timeline and a summary of installation activities are provided in this section:

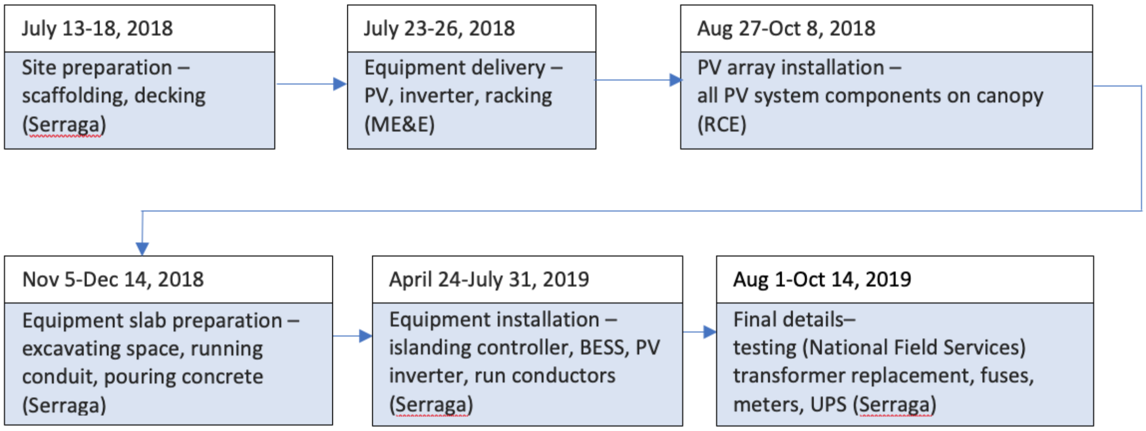
- Site Preparation
- Equipment Delivery
- PV Array Installation
- Equipment Slab Preparation
- Equipment Installation
- Final Details

The entities involved in the installation of the Solar+ pilot project at the Blue Lake Rancheria Play Station 777 included:

- Serraga at the Blue Lake Rancheria: Serraga was the project development and management entity for the BLR. Serraga also deployed its own construction crews and electricians to support project deployment.
- McKeever Energy & Electric (ME&E): ME&E provided PV system design and system procurement services.
- Robert Colburn Electric (RCE): RCE provided PV array installation services.
- Schatz Energy Research Center at Humboldt State University (Schatz Center): the Schatz Center was the prime award recipient for this project and served as the BLR owner's engineer.

Figure 5 provides a construction timeline for the project.

Figure 5: Blue Lake Rancheria Solar+ Project Construction Timeline



Source: Schatz Center

Serraga began site preparation on July 13, 2018. Serraga established a laydown yard to secure equipment and tools, ordered scaffolding for easy canopy access, and built a deck platform atop the canopy with a guardrail to create a safe work environment and prevent damage to the canopy.

PV array installation began on August 27, 2018. RCE followed the PV plan developed by ME&E and its engineering firm. RCE first installed the racking substructure by lifting steel tube verticals to the canopy via telehandler and mounting them to the existing canopy I-beams. Next, RCE installed the IronRidge racking to the substructure and secured the PV modules to the racking (Figure 6). The "homeruns," the positive and negative ends of the PV array's 13 strings, were pulled through existing underground conduits between the canopy and the convenience store electrical gutter.

Figure 6: PV Array Installation

Image on the left shows PV array racking substructure and on the right installed PV modules on the racking structure.

Source: Schatz Center

Serraga prepared the equipment slabs in November and December of 2018. The main equipment slab is roughly 5′ x 24.5′ and holds the PCC and battery energy storage system. A second equipment slab is 5.5′ x 3′ and holds the PV inverter. Serraga ran conduits from the convenience store, beneath the slab locations, to the appropriate locations within the slabs where the equipment would eventually sit (Figure 7). Once the conduit positions were set, concrete was poured to form the slabs (Figure 8).

Figure 7: Switchgear Site Preparation

Conduits shown in place beneath slabs.

Source: Schatz Center

Figure 8: Switchgear Pad Concrete Pour

Staff pouring concrete for the main equipment slab.

Source: Schatz Center

Serraga began to place equipment on April 23, 2019. Using a forklift, the five sections of the islanding switchgear, the battery, and the battery inverter on the slab (Figure 9) were all installed. All equipment fit perfectly over the positioned conduits. On May 29, 2019, Serraga pulled conductors between the islanding controller and the store (Figure 9). One run connects the islanding controller to the AC disconnect switch (PG&E’s point of connection) and the other run connects the islanding controller with the existing ATS.

Figure 9: Placing Switchgear and Battery and Pulling Wire

Staff placing the BESS inverter and pulling conductors from inside the C-store to the islanding switchgear.

Source: Schatz Center

Serraga completed final placement of the equipment in July 2019. Figure 10 shows the equipment area with the PCC switchgear, BESS, PV inverter, BESS site controller, and NGOM cabinet.

Figure 10: Nearly Completed Switchgear Installation

Complete equipment lineup, shown on equipment slabs

Source: Schatz Center

Hardware Commissioning

This section discusses the commissioning of the Solar+ hardware installed at the C-store. Detailed commissioning results are included in Appendix C. Commissioning of the software associated with the project is discussed in Chapter 4.

Refrigeration and HVAC Controllers

The commissioning steps for the refrigeration and HVAC controllers are provided in Appendix C.

Islanding Switchgear

Commissioning of the islanding switchgear consisted of acceptance testing of the switchgear, as well as relay testing of the SEL-700GT+ protection relays contained within the islanding switchgear. National Field Services, a third-party testing agency, performed the acceptance and relay tests (Figure 11).

Two mobilizations (site visits by the test engineer) were required: the first to complete acceptance testing of the islanding switchgear and initial relay testing, and the second to repeat the relay testing while PG&E witnessed the pre-parallel inspection.

Figure 11: Switchgear Testing

The team testing the monitored, controlled, motorized breaker.

Source: Schatz Center

The switchgear testing revealed an insulation resistance deficiency in the 225-kVA transformer where the neutral bus bar contacted the base of the frame and shorted to ground. As a result, a new transformer was manufactured and replaced by the switchgear vendor. The replacement transformer was tested and passed inspection. All other testing of the switchgear and protection relays was found to be acceptable per National Electrical Testing Association (NETA) and National Electrical Code (NEC) standards. The full test report is included in Appendix C.

Solar Photovoltaics

The solar PV commissioning examined the PV array, inverter, and cables. String voltages were measured at each of the three combiner boxes on the canopy roof. All PV module strings registered acceptable open-circuit voltages when compared with the expected open-circuit voltage, which was calculated based on the number of modules in series in the string and on the module's temperature.

Insulation resistance testing was performed on the cables from the PV combiner boxes to the switchgear. All cables exhibited adequate resistance to ground.

The PV inverters were commissioned following instructions provided in the SMA Core 1 Installation Manual. The inverter startup procedure was followed, and the inverter passed all commissioning tests.

SunPower Corporation conducted commissioning and acceptance tests according to its protocols. The system passed these tests.

Battery Energy Storage System (BESS)

The BESS commissioning included two main steps:

1. The installer completed the BESS construction checklist with support from a Schatz Center engineer.
2. The BESS manufacturer, Tesla, Inc., performed additional commissioning.

The BESS construction checklist included:

- A record of general site information.
- Inspection of civil work (for example, anchor bolt torque, pad dimensions, grade).
- Inspection of electrical work (for example, conductor lug torque, connections, large conductor insulation tests).
- Meter documentation and inspection of current transducer placement.
- Energization testing.
- Photo documentation.

A manufacturer's representative commissioned the BESS, including communications and system startup. Functionality testing included grid-parallel operation with battery dispatch, and islanding and grid forming capabilities. Schatz Center and Serraga personnel were onsite to witness the BESS commissioning tests. Following multiple tests interspersed with trouble-shooting and subsequent modifications, the BESS system passed all commissioning tests. Numerous troubleshooting activities also took place after initial commissioning was completed.

Power Meters

Three power meters monitored the load, PV, and BESS. Commissioning included visual inspections and confirmed accurate readings against other measurement devices.

Real-Time Automation Controller

After the PV, power meters, and BESS were commissioned, the system’s basic islanding controls were tested. The islanding controls test required that both the BESS and the intertie protection relay perform as intended. Commissioning the islanding controls required that the system be live and connected to PG&E. Consequently, this commissioning process was completed after PG&E conducted a site visit and witnessed proper functionality of the intertie protection relay settings and provided temporary permission to operate for testing purposes.

The basic islanding controls test included two steps: forcing an intentional island using an emulator to change the islanding control setting, and physically opening the utility AC disconnect to simulate a grid outage. The islanding control features of the Solar+ system successfully passed the commissioning tests. The full commissioning steps and results for the RTAC and islanding controls are included in Appendix C.

CHAPTER 4:
Software Development and Testing

Chapter 4 discusses the development, testing, and deployment of software for the Solar+ system at the Blue Lake Rancheria Play Station 777 gas station and convenience store. The software developed for this project covered an array of functions, as shown in Table 2. The Solar+ Optimizer software and eXtensible Building Operating System (XBOS) were developmental software deployed for research and testing purposes only in this project; they will not be used for long-term operation at the pilot site. However, it is important to note that, if the Solar+ Optimizer software were deployed for long-term operation, it could both replace the battery dispatch software and handle optimal battery dispatch management. In addition, work will continue via other projects on the development and deployment of Solar+ Optimizer and associated Model Predictive Control software.

Table 2: Software Functions and Long-Term Disposition

Function	Software	Long-term Disposition
Optimal management of loads, generation, and battery storage1 to minimize costs during blue sky operation, human machine interface (HMI) and data historian	LBNL Solar+ Optimizer and XBOS building operating system	Deployed for research and testing only
Optimal management of battery storage to minimize costs during blue sky operation	Battery dispatch software	Deployed for long-term operation
Microgrid islanding capabilities, supporting HMI and data historian	SEL-3505-3 custom logic	Deployed for long-term operation
Electrical protection	SEL-700GT Intertie Protection Relay settings	Deployed for long-term operation

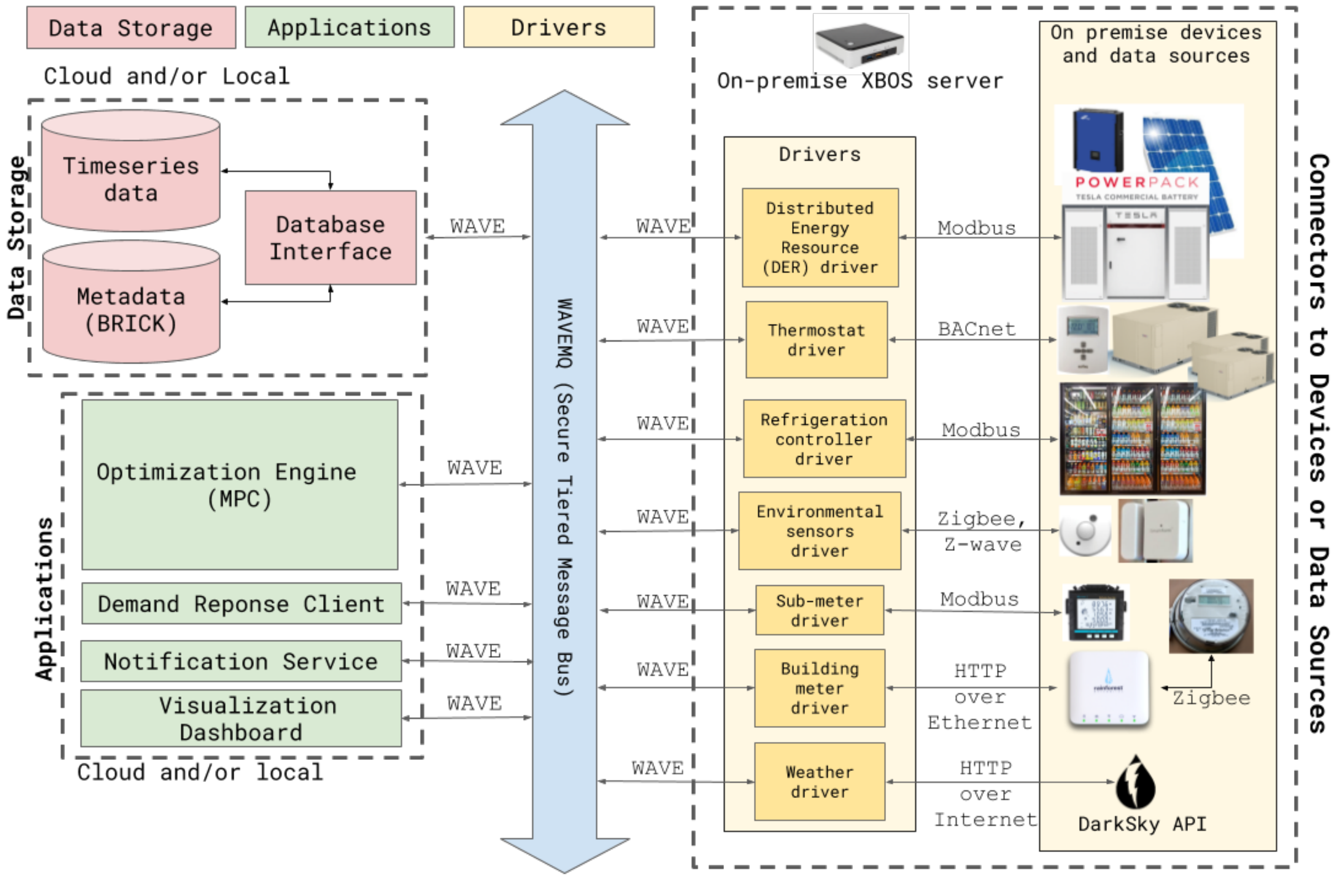
1 Note: The battery storage system monitored and controlled by the Solar+ Optimizer software was an emulated battery system that was used for research purposes.

Source: Schatz Center

Solar+ Optimizer Model Predictive Control Software

To integrate sensors, controllers and advanced control sequences for building systems and distributed energy resources (DER), the Solar+ Optimizer software solution was developed by the LBNL team. It supports integration across multiple devices and protocols, as illustrated in Figure 12. Through support for several communication protocols and application programming interfaces (API), Solar+ Optimizer allows integration of systems typical for small and medium commercial buildings. Leveraging the ability to host applications, advanced controllers can also be deployed for the Solar+ Optimizer. This project used Model Predictive Control (MPC) based optimization to generate the best setpoints for equipment in the convenience store. MPC is a powerful optimization technology because it can adjust to real-time conditions of the day and dynamically find the best combination of setpoints for the overall integrated system. MPC allows different systems to work together toward the goals of the optimization. Solar+ Optimizer can additionally operate within a local network but can be configured to operate in tandem with Cloud-based resources.

Figure 12: Software Architecture Diagram of the Solar+ Optimizer System



Source: LBNL

XBOS

To coordinate the numerous heterogeneous connected devices and controllers within a building, robust network communication is a key requirement. Most commercial and academic solutions use middleware (software that resides between the hardware devices and other sources that produce data and the applications that use the data). Solar+ Optimizer uses XBOS, an open-source building operating system developed for real-time data acquisition from sensors and control of building actuators (Fierro, n.d.). XBOS consists of several components (see Figure 12).

- **WAVE and WAVEMQ:** WAVE is an authentication engine that handles permissions and access control. WAVEMQ is a multi-tier publish-subscribe message bus that allows the exchange of data and control signals.

- **Drivers:** Drivers are connectors to real devices and other data sources (for example, web-based services, emulated devices). A driver both gathers data from a device and controls the device in response to requests from an external controller. With the required permissions, a driver can publish and subscribe to messages on WAVEMQ.
- **Data Storage:** Both operational and configuration data are stored on dedicated databases. There are separate data stores for the building metadata represented using the Brick schema (Balaji et al., 2016) and for continuous real-time data collected by the drivers.
- **Applications:** Developers can write applications on the XBOS platform using real-time data published on the message bus (for example, notification service, visualization dashboard) or historical data that has been stored in the database (for example, MPC-based optimization engine, fault detection tools). Applications can publish control signals for the devices on WAVEMQ and can trigger a change in operation mode.

Model Predictive Control (MPC) Optimization Engine

Existing solutions often use proprietary platforms and site-specific specifications for generating and sending control signals to devices. The open-source package MPCPy (Blum and Wetter, 2019) was used to implement MPC-based optimization in an open-source framework. Solar+ Optimizer integrates MPCPy as an XBOS application, extending its capabilities to interact with real-time systems. This application, labeled the optimization engine, identifies historical data and future forecasts from the data store, solves the optimization problem using the MPCPy framework, and publishes control signals to devices through WAVEMQ. Through this process, Solar+ Optimizer provides a scalable, protocol- and manufacturer-independent solution for implementing advanced building controls. This section describes the components of this optimization engine.

MPCPy utilizes models defined in the Modelica language (Mattsson and Elmqvist, 1997), an equation-based multi-domain language that models complex physical systems, including mechanical, electrical, and deterministic control systems. These models can predict future system behavior to support linked simulation-optimization problem solving approaches.

Using the MPCPy framework, the Solar+ Optimizer optimization engine employs models of the building systems (HVAC, refrigerator, freezer, battery storage, PV system) and minimizes the cost of building operations, subject to various demand response (DR) scenarios or grid price signals. Fundamentally, Solar+ Optimizer reduces electricity bills for buildings subject to time-of-use (TOU) tariffs that contain both energy and demand charges. Other modes of operation for responding to grid signals include real-time pricing, demand limiting, load shedding, load shifting, and load tracking (the objectives of these signals are described in Table 5). The optimization engine is structured in a flexible way so that the various responses to grid signals can be easily configured and swapped. This is achieved by formulating the objective function in a generic way that captures both the energy and demand portions of an electricity bill and load limits in a DR event. Grid signals are translated into components of the parameterized objective function or constraints of the optimization problem. Various operating modes are stored in variables of a configuration file to allow easy switching between modes.

Solar+ Optimizer Software Deployment and Testing

The Solar+ Optimizer software, data infrastructure, and applications were developed and tested at LBNL before they were installed at the convenience store. The software development and testing included: the XBOS platform, drivers that connect to each of the hardware devices and software services, model development (in Modelica), development of the optimization engine, and the data storage system. Preliminary driver development also involved procuring and evaluating multiple options for each controller and sensor (for example, thermostats, power meters) before finalizing the devices deployed at the convenience store.

During the deployment, a local XBOS server was set up at the convenience store and a Cloud server was set up virtually at LBNL. The local server communicated with: the HVAC thermostats over BACnet/IP, the refrigerator controllers and the power meters over Modbus/serial, the RTAC over Modbus/TCP, and the DarkSky weather API over HTTP.

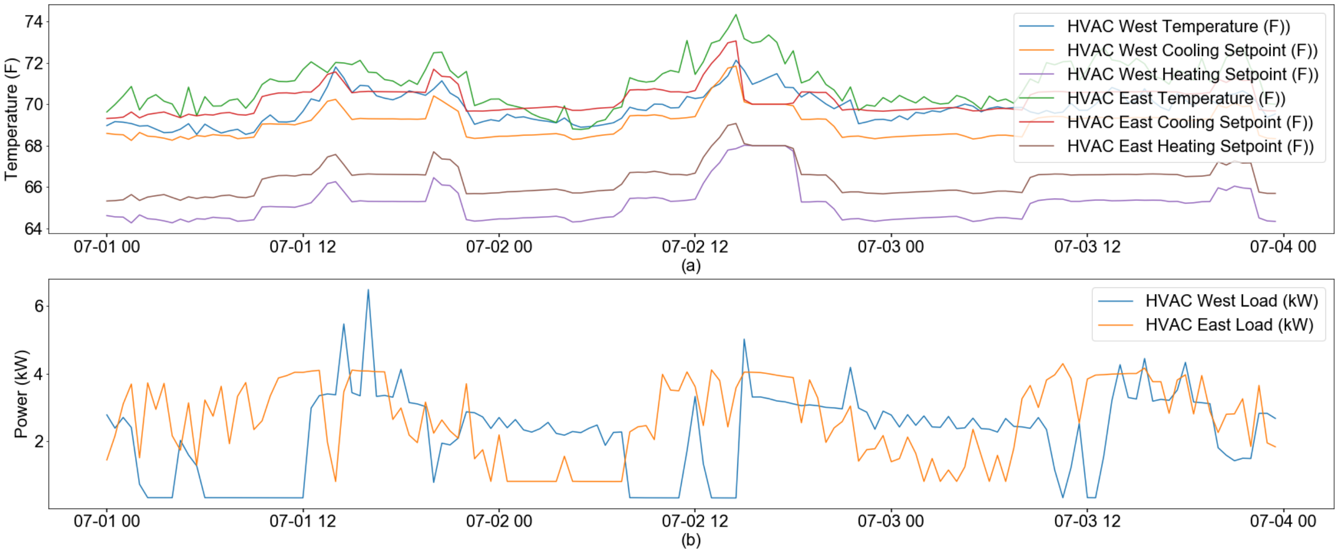
Leveraging the ability of Solar+ Optimizer to operate in a local network and also in a Cloud environment, two databases were set up: one on the local server and one at LBNL. The local server holds only recent data relevant to the MPC optimization, allowing optimal controls even when the connection to the Cloud database fails. The Cloud database allows data querying, analytics, visualization, and other non-critical applications without overwhelming the local server.

The Solar+ Optimizer software was developed, deployed, and commissioned at the convenience store in the following phases by running short, one- to two-hour-long tests for each:

1. **Data Storage, Query, and Device Optimization** (read only): Continuously collects data from all devices (thermostats, refrigeration controllers, battery, power meters, and weather API); queries the data and runs the MPC optimization engine in "shadow mode" (open loop, controlling no devices).
2. **Thermostat Control:** Runs the MPC optimization and changes the thermostat heating and cooling setpoints.
3. **Refrigeration Control:** Runs the MPC optimization and changes the refrigerator and freezer cooling setpoints.
4. **Battery Control:** Runs the MPC optimization and changes the emulated battery charge/discharge rate setpoints.
5. **Grid Signals:** Publishes signals to notify Solar+ Optimizer about upcoming DR events and the ability of Solar+ Optimizer (and MPC optimization engine) to glean details from the event.
6. **DR:** Verifies that the Solar+ Optimizer software can respond to different grid signals (for example, prices, demand limiting, load shedding, load shifting and load tracking) by changing the setpoints of different devices in the store.
7. **Islanded Mode:** Ensures that MPC can change the thermostat behavior when the building operates in grid-disconnected mode.

An illustration of how changing the thermostat setpoints resulted in a change to both indoor temperatures and net load is shown in Figure 13. Figure 14 shows the results of Phase 6. Demand response testing showed how the Solar+ Optimizer software controlled the building devices to vary the net load in response to different signals. Additional details regarding Solar+ Optimizer commissioning tests are provided in Appendix C.

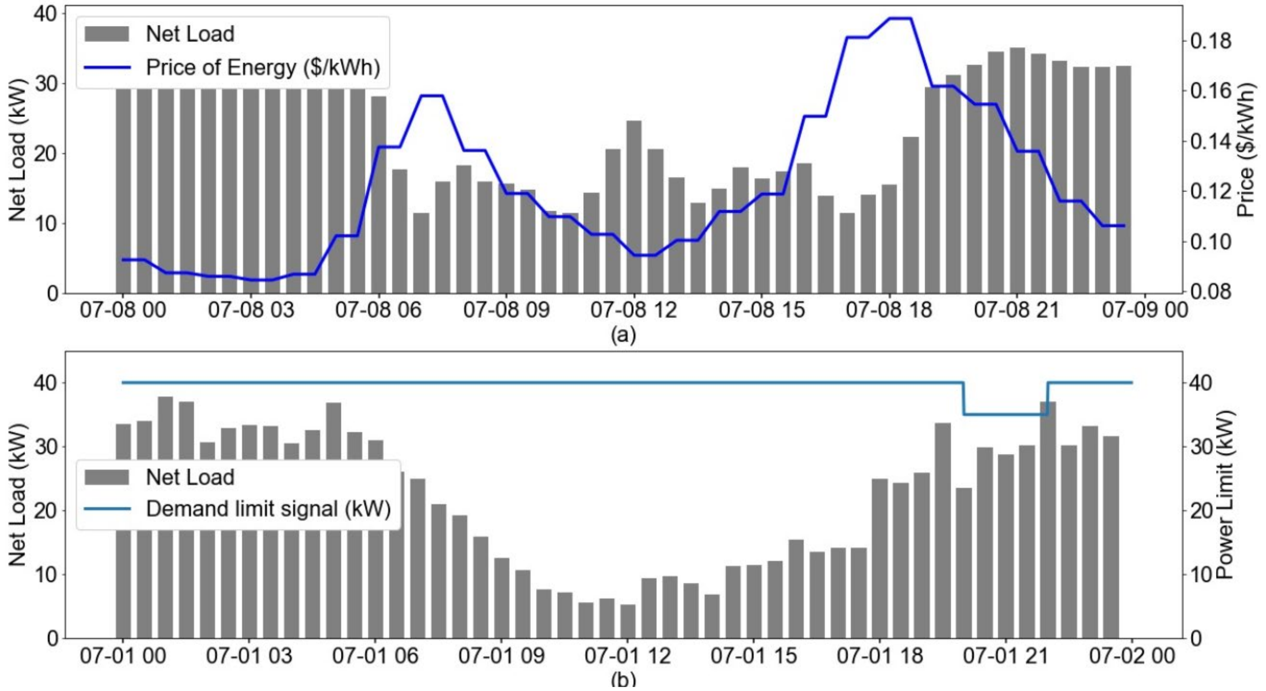
Figure 13: HVAC Response Testing Results

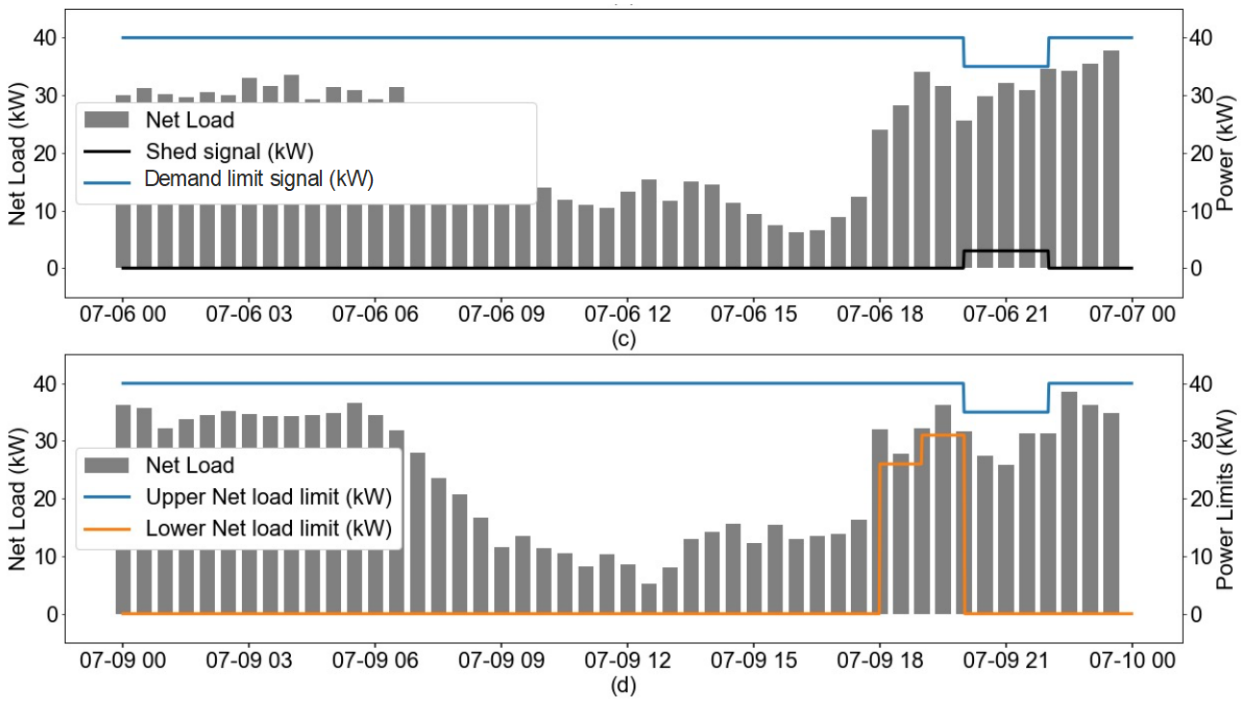


A three-day test where the Solar+ controller changed the setpoints of both the thermostats: (a) changing HVAC setpoints and zone temperatures over time, (b) corresponding changes in power consumption of both the HVAC units.

Source: Lawrence Berkeley National Laboratory

Figure 14: Overview of Building Control Responses





Charts showing how the Solar+ controller controls the building to respond to different grid signals: (a) 24-hour varying prices, (b) demand limiting signal of 35 kW from 6 p.m. to 8 p.m., (c) load shedding signal of 3 kW and the corresponding demand limiting signal from 6 p.m. to 8 p.m., (d) load shifting signal to consume a minimum of 26 kW from 6 p.m. to 7 p.m., 31 kW from 7 p.m. to 8 p.m., and a maximum of 35 kW from 8 p.m. to 10 p.m.

Source: LBNL

Battery Dispatch Optimization Software

One key aspect of a Solar+ energy system is optimal management of the battery energy storage resource to minimize energy costs. This can include charging the battery when power is cheap and discharging it when prices are high, or reducing the peak demand seen at the utility revenue meter to reduce demand charges. As mentioned above, the Solar+ Optimizer software was deployed at the pilot site for testing purposes only and will not be utilized there over the long term after the project concludes. Therefore, an alternate battery management software was needed.

The Schatz Center team obtained off-the-shelf battery management software from the project's battery vendor. The team provided the vendor with information about the applicable utility tariffs, rate schedules and billing cycles, as well as historic load data and estimated solar PV production data. The information provided to the vendor also specified a 50-kW export limit and noted a desire to maintain a minimum 25 percent state of charge on the battery at all times for resilience purposes. The vendor used this information to configure the battery management software. Because the software employs machine learning algorithms, it allows a brief period to fine-tune its operation. Once the software was fully operational, the researchers monitored its performance, detected a problem due to a software configuration error, and resolved the problem with the vendor.

Controls for Islanded Operation

The Schatz Center team developed the controls for the islanding controller. The main functions of the islanding controller are to provide fault protection for internal and external power system faults and to provide islanding capabilities and required protection for interconnecting with the utility's electric power grid.

The Solar+ system's two main operational modes are:

1. **Normal Operation:** When parallel with the grid
2. **Islanded Operation:** When separated from the grid during an outage

The following sections provide technical descriptions of these two operational modes. Proper operation of these modes, and of the transitions between them, requires proper integration, networked communication, and operation of the SEL-700GT+ protection relay, SEL-3505-3 RTAC-based islanding controller, and BESS site master controller.

Grid-Connected Operation

While the microgrid is connected to the PG&E grid, the BESS inverter is in grid-following mode, so anti-islanding functions are active per UL1741/IEEE1547 standards. At any given time, the BESS may be charging, discharging, or idle, depending on the optimal dispatch schedule (as determined by the battery dispatch software). In the event of a PG&E grid outage, the BESS inverter goes offline and the SEL-700GT+ relay at the point of common coupling (PCC) opens the PCC circuit breaker.

Islanded Operation

In the event of a PG&E grid outage, both inverters (for the PV system and for the BESS) go offline per the anti-islanding requirements of UL1741/IEEE1547. The PV and BESS inverters are certified as meeting the UL1741 standard. The SEL-700GT+ relay at the PCC also senses the grid outage and opens the PCC circuit breaker, isolating the microgrid from the PG&E grid. In all cases during an unplanned outage of the PG&E grid, the microgrid is de-energized momentarily. This momentary outage can be fast enough to mimic a seamless transition or, in some cases, the outage can last a maximum of approximately four seconds.

Power to the SEL-700GT+, SEL RTAC-based controller, and BESS site master controller is maintained at all times via a UPS. In the event of a UPS failure, both the PCC MCB1 and MCB2 circuit breakers fail-safe to an open position (via the AC holding coil function), disconnecting both the PV and the BESS.

Once the microgrid is disconnected from the PG&E grid, if the BESS and renewable generation can meet onsite loads, the BESS acts as the grid-forming generator. The existing 175-kW DG acts as the grid-forming generator only if the automatic transfer switch senses that the BESS and renewable generation cannot meet onsite loads.

Since the BESS provides power before the DG detects a grid outage, the generator remains off while the BESS inverter is grid forming. In grid-forming mode, the BESS provides voltage and frequency support to the microgrid as needed to maintain stability. The battery charges and discharges in this mode, as needed, to balance loads and renewable generation output.

If the diesel generator is grid forming, then the BESS does not discharge power; the SEL-700GT+ relay and RTAC-based controller at the PCC sense that the BESS and renewable generation cannot meet onsite loads and open the BESS/PV circuit breaker, isolating the BESS/PV bus from the rest of the system. This allows the PV system to charge the BESS if solar power is available. If the BESS state of charge reaches an upper threshold, the SEL-700GT+ closes the BESS/PV circuit breaker, the DG disconnects and turns off, and the BESS inverter becomes grid forming.

Commissioning the islanding controls required the Solar+ system to be live and connected to PG&E. Consequently, the commissioning process for the islanding controls was completed after PG&E's PPI and subsequent receipt from PG&E of cPTO for testing purposes. The basic islanding controls test included two steps: (1) forcing an intentional island using Modbus Poll, a Modbus master simulator, to change the islanding control setting in the BESS controller, and (2) physically opening the utility AC disconnect to simulate a grid outage. These commissioning tests were conducted successfully, and the simulated grid outage test was successfully demonstrated for PG&E during the final onsite inspection. Additional information regarding commissioning of the islanding controls appears in Appendix C.

CHAPTER 5: Performance Monitoring

This chapter discusses the performance of the Solar+ pilot project located at the Blue Lake Rancheria Play Station 777 gas station and convenience store. The dates by which key Solar+ system components were fully operational (that is, installation and commissioning were complete) are shown in Table 3.

Table 3: Full Operation Dates for Solar+ System Components

Solar+ Component	Start of Full Operation
Solar PV system	January 2020
Storage battery	June 2020 (grid-connected) August 2020 (island mode)
Islanding controller	August 2020
Solar+ Optimizer software	August 2020
Vendor supplied battery dispatch software	June 2020

Source: Schatz Center

Following the full installation and commissioning of these key components, a series of tests was conducted and operational data were collected to assess the performance of both the individual components and the fully integrated system. The following sections describe the testing and performance monitoring results, which included:

- PV System Performance Monitoring.
- Battery and PV Performance Monitoring.
- Solar+ Optimizer Capability Testing.
- Solar+ Optimizer Performance Monitoring.
- Solar+ Island Performance Monitoring.
- Solar+ Battery Dispatch Comparison.

Note that additional details regarding capability testing and performance monitoring are included in appendices D and E, respectively.

PV System Performance Monitoring

PV system output was assessed over a period longer than four months. The team compared the actual system with simulated system output, using the National Renewable Energy Laboratory (NREL) System Advisor Model (SAM). The solar radiation data used in the SAM for this analysis were primary solar radiation data collected at a nearby solar monitoring site during the study period. During the study period of August 1, 2020 through December 17, 2020, the Solar+ PV system generated 105 percent of what was expected, based on the SAM simulation (25,386 kWh versus 24,156 kWh).

Battery and PV Performance Monitoring

Battery system performance was assessed over a period of approximately five months, from mid-August through mid-January of 2021. Power-flow data for the study period were collected at 15-minute intervals for the BESS, PV system, and site load. Battery state-of-charge and capacity were tracked using the battery's internal monitoring system. The battery system employed its own optimization routine to minimize the convenience store's electricity bills. During this period, the convenience store was on the PG&E E-19 TOU rate, a 25-percent minimum battery state-of-charge ensured resilience during unexpected macrogrid disruptions, and a 94-percent maximum state-of-charge provided the control system sufficient time to curtail PV generation in an excess-generation condition during islanding.

Battery behavior during this period was driven by the TOU rate. The highest prices occurred during the summer season (May through October) on weekdays between noon and 6 p.m. On weekends and during the winter months, there was little price difference between different time periods, so the system tended to discharge the BESS during the summer high-price period and recharge it when prices were lowest, late at night. However, during the winter period and on weekends, there was very little cycling of the battery. Table 4 shows the battery use characteristics during the summer and winter periods, as well as the annual average. Also shown are the estimated electricity bill savings and greenhouse gas (GHG) emission reductions attributed to the PV and BESS systems during this period.

Table 4: Battery and PV Performance Characteristics

Parameter	Summer	Winter	Annual Average
Battery utilization (cycles per day)	0.52	0.07	0.30
Battery efficiency[1] (%)	87.2	46.7[a]	82.1
Electric bill savings (%)	31.6	26.3	29.7
Greenhouse gas emissions reduction (%)	22.0	10.2	16.3

1 Note: Battery system efficiency was relatively low in the winter months due to a combination of reduced inverter efficiency at low loads and parasitic loads making up a much greater fraction of the overall energy.

Source: Schatz Center

Solar+ Optimizer Capability Testing

Following the deployment, commissioning, and functional testing of the Solar+ Optimizer software, the research team put the system through a series of capability tests. The team designed these tests to assess the Solar+ Optimizer's performance while in different operating modes and to determine its ability to provide grid services such as demand limiting, load shedding, load shifting, and load tracking. During this testing, the emulated battery was shrunk to 27 kWh and 14 kW capacity. This reduced how heavily the optimization engine would rely on readily available electrochemical energy storage for demand flexibility services, allowing the team to better evaluate how flexible HVAC&R loads would affect these services. A data-driven baseline model was created to compare against the Solar+ Optimizer-controlled building.

Details of the baseline model and the test setup are presented in Appendix D. Table 5 summarizes the capability test results. Three modes were tested.

- **Blue Sky:** Covered "normal" grid operation without any demand response events. The team evaluated the bill savings that the Solar+ Optimizer software would generate under two different tariffs: Redwood Coast Energy Authority (RCEA) E19 and PG&E B19. Both tariffs had TOU energy and demand charges.
- **Grid Response:** The team generated different types of grid signals that were published to the Solar+ Optimizer system a day in advance. This included a real-time price forecast, demand limiting and load shedding signals (requesting the building to reduce net demand), a load shifting event (a period of increased consumption, followed by a load shed) and a load tracking signal (requesting the building to follow a reference power signal). Because the objectives of each of the signals were different, the team evaluated the performance of Solar+ Optimizer using different metrics for each one (as shown in the Metric Descriptions column in Table 5).
- **Island:** In this mode, since it was not possible to turn off power to the actual building, the team simulated an island event and analyzed how the Solar+ Optimizer software managed building loads.

Table 5: Summary of the Solar+ Optimizer System Capability Testing

Mode	Test Case	Test Objective	Test Duration	Metric Descriptions	Metric Values
Blue sky	RCEA E-19 tariff	Minimize TOU energy and demand cost.	1 day	1) Estimated change in monthly bill (%)	1) -8.21% (cost savings)
Blue sky	PG&E B-19 tariff	Minimize TOU energy and demand cost.	1 day	1) Estimated change in monthly bill (%)	1) 2.22% (cost increase)
Grid response	Real-time pricing	Minimize energy cost.	2 days	1) Change in cost over testing period (%)	1) -1.62%
Grid response	Demand limiting	Minimize energy cost. Keep the net load below a 26-kW limit 15:00-18:00.	1 day	1) Time in violation of demand limit (%) 2) Estimated change in monthly bill (%)	1) 0% 2) -11.4%
Grid response	Load shedding	Minimize energy cost. Reduce net load by 3 kW 15:00-18:00.	1 day	1) Average demand reduction during the load shedding period (%)	1) 59.4%
Grid response	Load shifting	Minimize energy cost. Increase net load by 3 kW 12:00-15:00, then decrease net load by 3 kW 15:00-18:00.	1 day	1) Average demand reduction during the demand decrease period (%) 2) Average demand increase during the demand increase period (%)	1) 9.01% 2) 29.9%

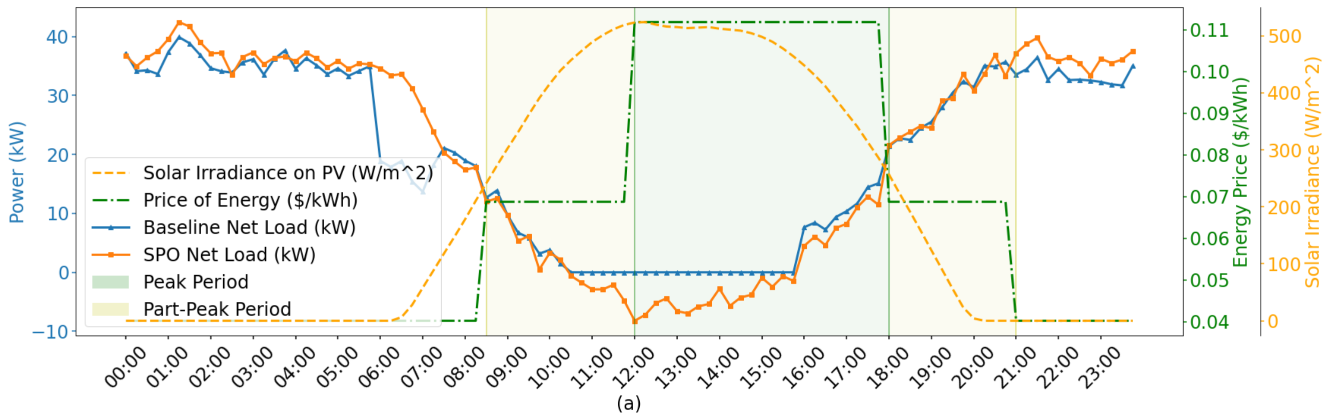
Mode	Test Case	Test Objective	Test Duration	Metric Descriptions	Metric Values
Grid response	Load tracking	Minimize time and net load outside of a reference power signal.	1 day	1) Percent difference of time in violation vs baseline (%) 2) Percent difference of energy in violation vs baseline (%)	1) 19.2% 2) 18.1%
Island	Simulated islanding event	Reduce energy use 14:00-18:00.	1 day	1) Extended operation hours (%)	1) 43.8%

Source: LBNL

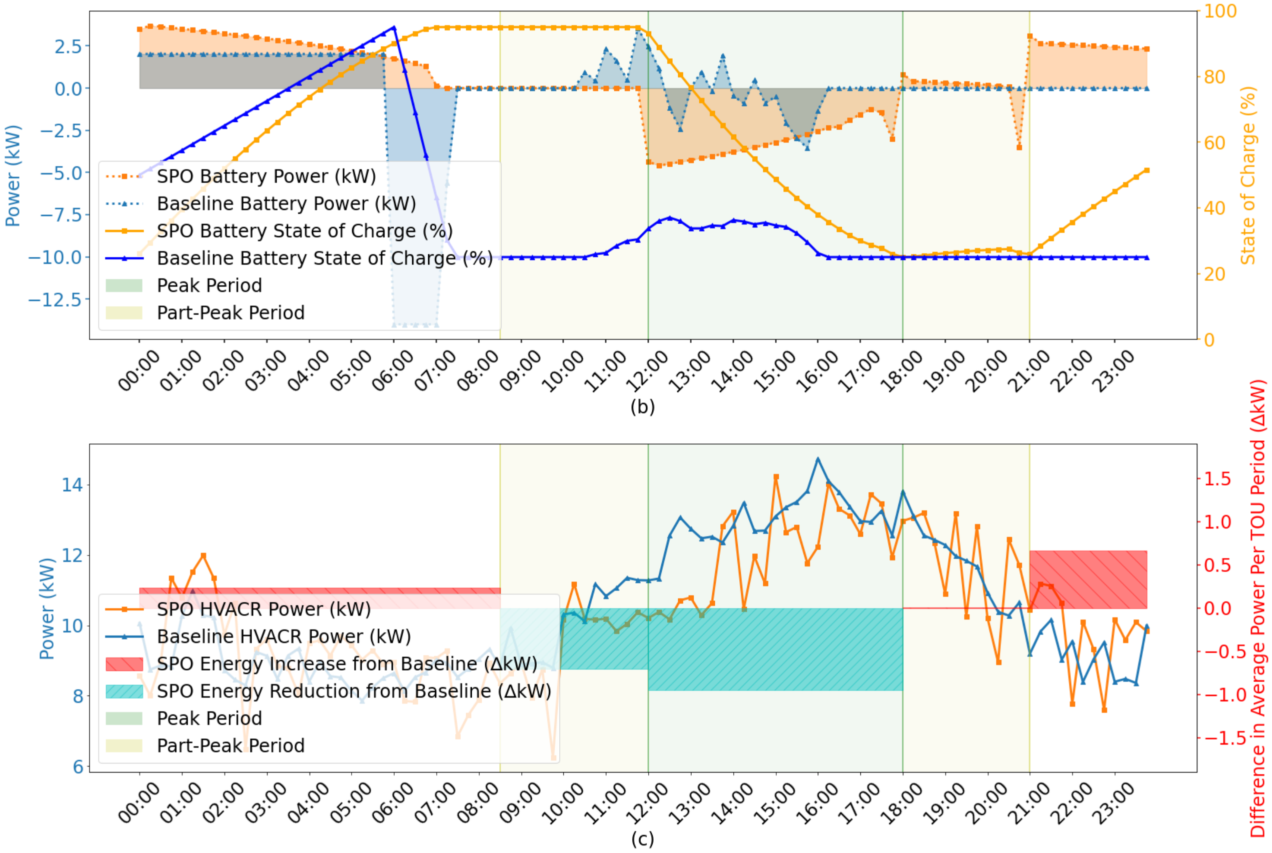
Figure 15, Figure 16, and Figure 17 show how Solar+ Optimizer performs under the RCEA E19 tariff, under a load-shed signal, and in island mode. The figures show both the external conditions (the solar irradiance on the PV, the price of energy, and the different TOU periods), and the internal equipment behavior (net load, HVAC&R power, battery power, battery state of charge) for both Solar+ Optimizer and the baseline model.

For both the RCEA E19 tariff and the load-shedding scenarios, the baseline battery discharged once it was fully charged (causing a dip in morning demand), where Solar+ Optimizer gradually charged the battery during the morning, then discharged it during peak hours or load-shed periods to reduce the net load. In Figure 16c, after the battery discharged completely (around 4 p.m.), Solar+ Optimizer reduced the HVAC&R load to meet the requested shed amount. Figure 17 shows that, during the islanding event (4 p.m. to 10 p.m.), Solar+ Optimizer idled the HVAC, resulting in an increased indoor temperature but reduced electrical demand. This allowed the building to operate for longer periods off the battery. Refrigeration operation was not changed, due to strict health and safety regulations regarding food storage.

Figure 15: Baseline System Operation in Response to Status-Quo Tariff



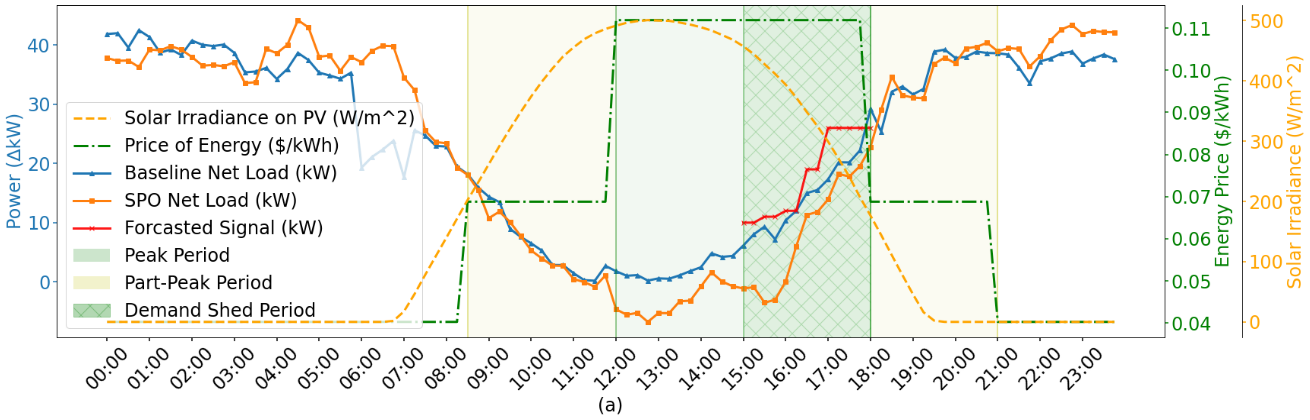
(a)

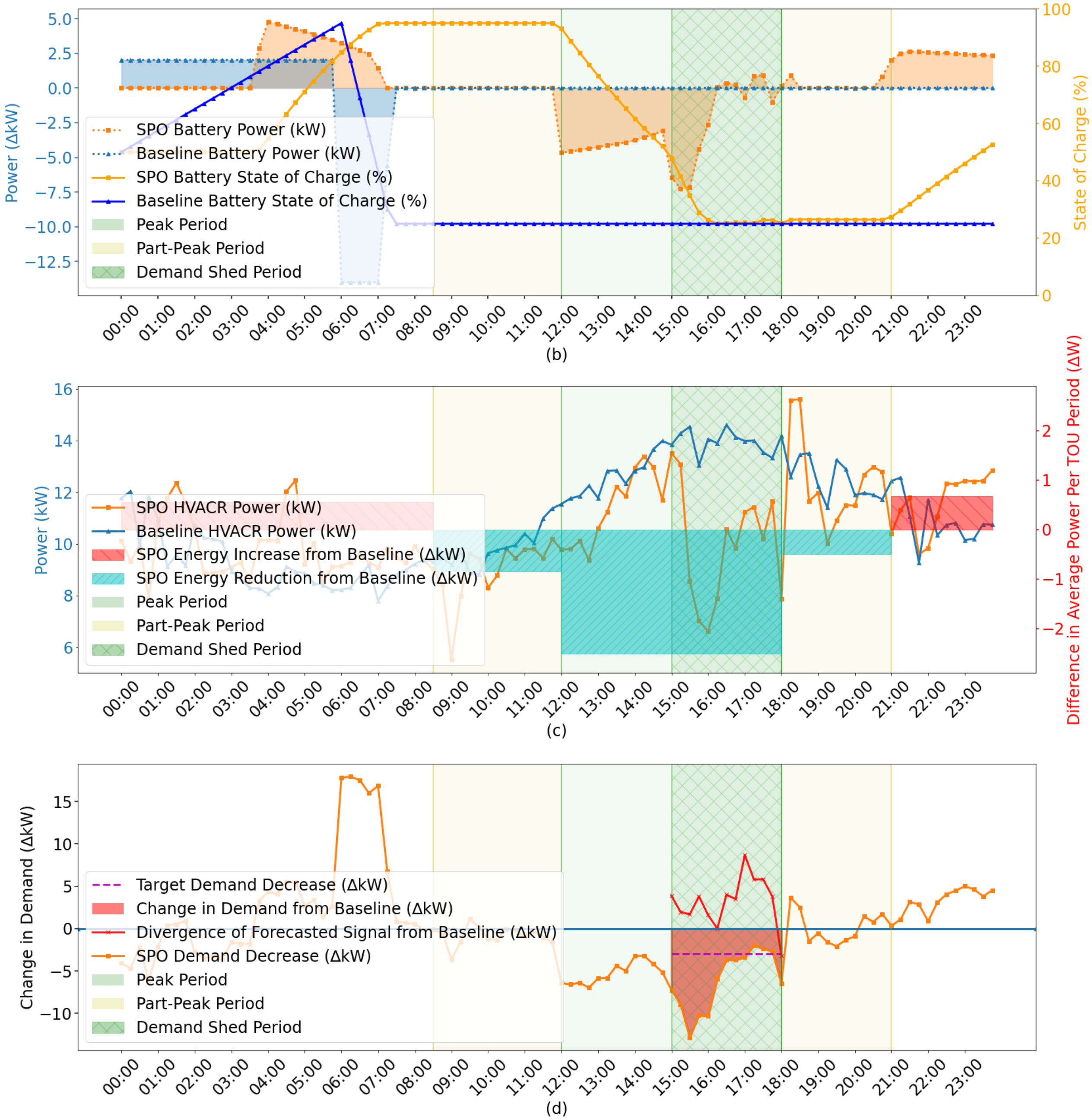


Blue Sky Operation Under RCEA E19: (a) Solar+ Optimizer (referred to as SPO within the figure) and baseline net power profiles plotted with solar irradiance and energy prices for the day, (b) battery state of charge and power for baseline and Solar+ Optimizer batteries (charging is positive power, discharging is negative), (c) HVAC&R power use: shaded bars show the difference between the Solar+ Optimizer average and the baseline average HVAC&R power (the area of the red bars shows how much more energy Solar+ Optimizer used, the area of the blue bars shows how much less).

Source: LBNL

Figure 16: System Operation in Response to Load Shed Signal

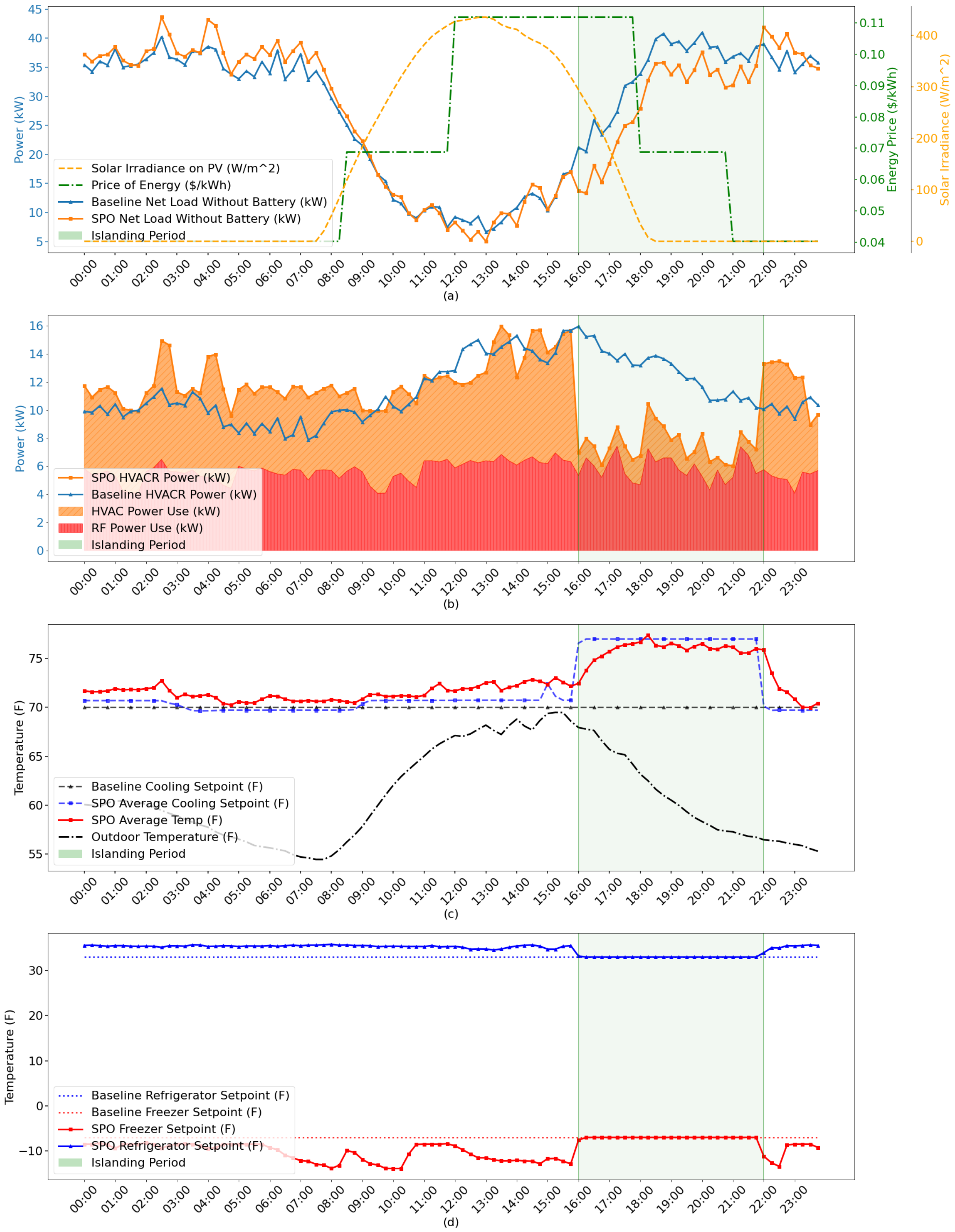




Load Shed Test Power Profiles: (a) Solar+ Optimizer, baseline, and forecasted net power profiles, (b) battery state of charge and power for baseline and Solar+ Optimizer batteries (charging is positive power, discharging is negative), (c) HVAC&R power use: shaded bars show the difference between the Solar+ Optimizer and baseline averages, (d) change in demand from baseline, indicating the amount of demand increase.

Source: LBNL

Figure 17: System Operation During Island Event



Islanding Test Data: (a) Solar+ Optimizer and baseline net power profiles, (b) Solar+ Optimizer HVAC&R power plotted against baseline HVAC&R power: shaded portions show the amount of power contributed by HVAC (orange) and by refrigeration (red), (c) Solar+ Optimizer HVAC setpoints and indoor temperature plotted with baseline setpoints, (d) Solar+ Optimizer refrigerator and freezer setpoints vs. baseline.

Source: LBNL

Solar+ Optimizer Performance Monitoring

A key goal of this project was to show that the operational value of distributed solar energy systems can be significantly increased by using key technologies like energy storage, smart inverters, controllable loads, improved forecasting, and optimization algorithms. These technologies, when integrated and optimized, allow distributed resources to serve customer needs (for example, bill savings, improved power reliability, and critical facility resilience) without creating problems on the distribution system (such as oversupply). These Solar+ systems also provide distribution grid services.

The research team developed a measurement and verification plan to assess the performance of the Solar+ system. The team also ran the Solar+ system for an extended period to collect operational data. During this operational period, the team conducted short-term tests to assess the performance of specific Solar+ Optimizer functions. Researchers then evaluated this operational data to assess the performance of the Solar+ system.

In terms of overall system performance, the Solar+ system met most of the performance goals that were established at the start of the project. Table 6 shows the stated performance goals and the resulting performance metrics for the Solar+ system. Additional information regarding the performance testing is provided in Appendix E.

Table 6: Summary of Solar+ Performance Goals and Accomplishments

Goal	Metric Description	Data Sources and Systems	Result
Decrease in solar intermittency[1] compared to a traditional fixed-tilt PV system	The standard deviation of Solar+ system output[2] compared to the standard deviation of a PV system output over solar-producing hours (~ 7 a.m. to 4 p.m.).	Actual site load, modeled PV,[3] emulated 174 kWh 109 kW BESS,[4] Solar+ Optimizer in load tracking mode[5] for a day during winter 2020 testing period[6]	Metric Goal: 10% Metric Achieved: 22.6%
Increase in energy generated over the course of an average day compared to that of a standalone solar PV system + standalone battery storage system	Potential avoided solar generation curtailment[7] based on a realistic base level of curtailment[8]	Actual site load, modeled PV, emulated 174 kWh 109 kW capacity BESS, Solar+ Optimizer in blue sky mode under PG&E B19 over 20 days during winter 2020 testing period	Metric Goal: 10% Metric Achieved: 13.5%
Increase in overall system capacity factor compared to a traditional fixed-tilt PV system	The increase in energy generated from potential avoided curtailment, relative to the given PV capacity	Actual site load, modeled PV, emulated 174 kWh 109 kW capacity BESS, Solar+ Optimizer in blue sky mode under PG&E B19 over 20 days during winter 2020 testing period	Metric Goal: 10% Metric Achieved: 13.5%

Goal	Metric Description	Data Sources and Systems	Result
Improved ability to provide energy later into the evening compared to a traditional fixed-tilt PV system	The percent of solar shifted to the evening, measured as the total Solar+ system output from 4-9 p.m. as a percent of the total solar PV generation	Actual site load, modeled PV, modeled 174 kWh 109 kW capacity BESS, Solar+ Optimizer in blue sky mode under PG&E B19 over 20 days during winter 2020 testing period	Metric Goal: N/A Metric Achieved 48.5%
Ability to provide distribution grid services	The ability of Solar+ Optimizer to shift and shed site demand, judged by several metrics including average load reduction and response time	Actual site load, modeled PV, emulated 27 kWh 14.5 kW capacity BESS, Solar+ Optimizer in demand shifting mode for one day and demand shedding mode for one day during the capability testing period, summer 2020	Yes, the Solar+ system can provide *shed* and *shift* DR services
Solar module efficiency	The overall efficiency of the solar PV system compared to the average panel conversion efficiency	Actual PV generation data, site ambient temperature, nearby solar insolation data, SAM results for data collected August 1 to December 17, 2020	Goal: ≥ 21% Achieved: 22.2%*
Energy storage round-trip efficiency	The total round-trip efficiency of the actual BESS, including parasitic loads	Actual BESS (109 kW, 174 kWh), PV (60 kW-DC) and site load power flow data collected from August 18, 2020 to January 15, 2021	Goal: ≥ 80% Achieved: 82.1%
Expected system lifetime	How long the system will last (with periodic routine maintenance) How long the system will last until it drops below 80% capacity)	All actual systems	Goal: ≥ 10 yrs Achieved: Expected to last > 10 yrs
Cost reduction compared to the cost of a standalone solar PV system + standalone battery storage system	System installed cost	Actual system costs, estimated actual system benefits and emulated system benefits	Goal: 10% Achieved: Not determined

1 The Solar+ system output was controlled to decrease its standard deviation over the daytime; it was not smoothed on a moment-to-moment basis, meaning the intermittency was not decreased at shorter time scales. This is fully described in Appendix E.

2 The Solar+ system output is the sum of modeled solar, emulated battery, and HVAC&R load reduction.

3 The modeled PV was created using design parameters for the PV array, along with a conversion efficiency factor based on actual PV generation data. It is fully described in Appendix E.

4 The emulated battery system is a simulated battery functional mock-up unit using two primary parameters in its model: peak power (kW) and energy capacity (kWh). It is fully described in Appendix E.
5 During load tracking mode, Solar+ Optimizer attempts to make the site net load follow a reference load signal.
6 The winter testing period ran from November 21, 2020 to December 22, 2020. In this period, the emulated BESS size was adjusted to the actual BESS size.
7 Based on the duck curve phenomenon, there will be curtailment of solar PV generation in the middle of the day. This means that, if more solar power is produced in the middle of the day, there will be more curtailment. Therefore, the ability to shift the dispatch of solar power from midday to evening hours can eliminate curtailment and increase the effective output from the Solar+ PV system. This is explained further in Appendix E.
8 The curtailment factor curve was created based on the modeled curtailment of variable generation on March 29th, 2020; it is described in NREL's report, *Overgeneration from Solar Power in California: A Field Guide to the Duck Chart* (Denholm et al., 2015).

Source: LBNL

Solar+ Island Performance Monitoring

During the summer and fall in much of California, high temperatures lead to higher energy consumption from air conditioning demand. This spike in demand, if not well managed, can put a strain on the grid and cause blackouts. To prevent this, the California Independent System Operator (California ISO) issues Flex Alerts requesting consumers to either reduce or shift their energy use. The BLR responded to a 4-day August 2020 Flex Alert by islanding its Solar+ microgrid during the afternoon-evening peaks and reconnecting to the grid at night. Table 7 provides statistics regarding Solar+ system behavior during these islanding events, including the breakdown between the load covered by the solar PV and battery system versus that covered by the existing back-up DG. On average, the PV + BESS system met over 80 percent of the load and covered over 75 percent of the runtime hours.

Table 7: Battery and PV Performance Characteristics

Parameter	17-Aug	18-Aug	19-Aug	20-Aug	Overall
Islanded hours (hrs.)	9.78	7.57	7.12	6.40	30.87
Average site load (kW)	30	35	35	36	34
% hours on PV+BESS	57%	71%	100%	89%	77%
% hours on diesel gen	43%	29%	0%	11%	23%
% load met by PV	30%	41%	54%	45%	42%
% load met by BESS	33%	36%	46%	45%	39%
% load met by diesel gen	37%	23%	0%	10%	19%

Source: Schatz Center

Solar+ Battery Dispatch Comparison

The research team tested Solar+ Optimizer's ability to optimize electricity bill savings alongside the installed off-the-shelf optimization software,[2] for comparison purposes. This testing took place over 18 non-sequential days between June and August 2021 under the PG&E B-19 tariff. The Solar+ optimized emulated battery and the commercially optimized installed battery

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[2] Tesla Opticaster software is being used (https://www.tesla.com/support/energy/tesla-software/opticaster).

operated simultaneously so that the exact conditions and building energy use would affect the bill savings calculation for each software type. The bill savings generated by the Solar+ Optimizer-controlled emulated battery and the commercial battery are shown in Table 8.

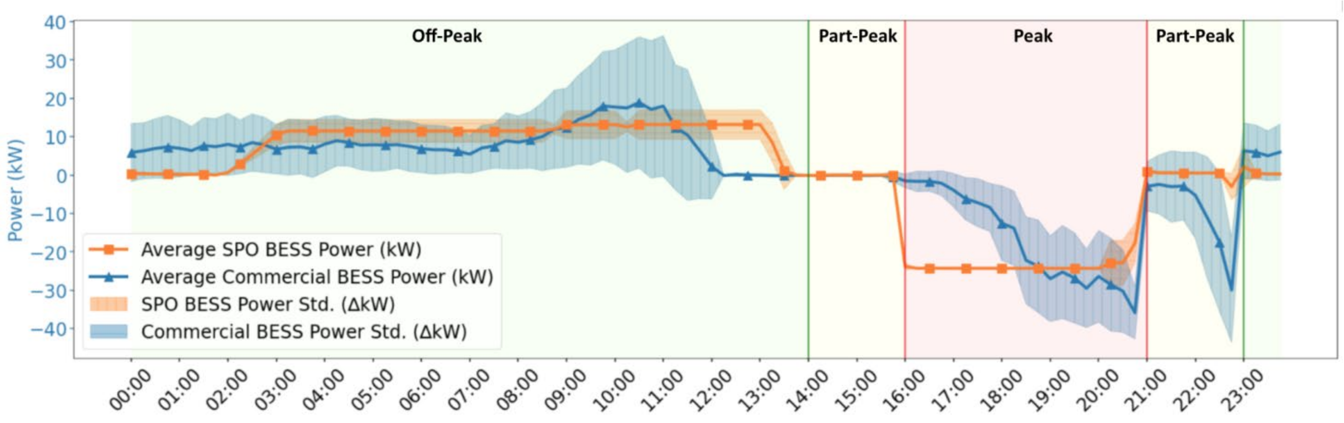
Table 8: Solar+ Optimization and Commercial Battery Optimization Bill Savings

Scenario	Total Bill	Energy Cost	Demand Cost
No battery	$3,767	$2,232	$1,535
Commercial software	$3,396	$2,148	$1,248
Commercial software (% savings)	9.8%	3.8%	19%
Solar+ Optimizer	$3,560	$2,095	$1,464
Solar+ Optimizer (% savings)	5.5%	6.1%	4.6%

Source: LBNL

By prioritizing reductions in demand costs, the commercial software saved 4.3 percent more on the total electricity bill than Solar+ Optimizer; Solar+ Optimizer generated most of its savings by reducing energy costs. Figure 18 shows the battery charge/discharge curves and the differences between the two.

Figure 18: Comparison of Solar+ Optimizer to Commercial Dispatch Algorithm



Commercial BESS and Solar+ Optimizer controlled emulated BESS charge/discharge power averaged to a single day with standard deviation. Charging is positive; discharging is negative.

Source: LBNL

The average Solar+ Optimizer BESS power shows how highly Solar+ Optimizer weights TOU energy prices. Because Solar+ Optimizer energy costs are the same every day, the battery is performing essentially the same every day. This is shown in the small standard deviation (the shaded orange region). The battery also charges at a flat rate for most of the off-peak period, and it discharges at a flat rate during the peak period, which has less impact on demand charges in each period. The commercial battery performance has a much larger standard deviation since it is operating more actively day-to-day to decrease the demand charge. This is because a demand charge is set during the highest power use at any time within the billing period. Different days will have different net-load curves and, thus, different charge/discharge requirements for the battery.

Note that, beyond the comparison between dispatch optimization and bill savings, Solar+ Optimizer can control loads of any suitable device via a driver tailored to each device (for example, HVAC, refrigeration, and electric vehicle [EV] charging loads). Solar+ Optimizer is therefore a much more powerful tool for adding substantial value through grid services and associated revenue streams.

CHAPTER 6:
Market Replication Tools and Information

The goals of the Solar+ project were to develop, deploy, test, and monitor a Solar+ installation at a gas station and convenience store and, based on that experience, develop standardized design guidelines, advanced building control algorithms, and siting tools that promote the deployment of replicable Solar+ installations in small- to medium-sized commercial buildings. These Solar+ systems benefit both individual building owners and the larger electric distribution grid. This chapter outlines the outcomes and information developed to achieve the market replication and scaling goals.

Hardware Design Toolkit

The Solar+ Hardware Design Toolkit was designed for microgrid systems that serve small- to medium-sized commercial buildings. Microgrids for this building sector must keep costs down while providing desired basic services — the "blue-sky" bill savings and back-up power when electricity from the utility grid is unavailable. The Solar+ Hardware Design Toolkit documents some best practices and lessons learned for the design of small- to medium-sized Solar+ microgrids. Key topics covered in the toolkit include:

- Controls for a minimum viable microgrid: Key control layers include protection, automation, and optimization.
- Islanding switchgear, which controls the interconnection of the microgrid and the onsite distributed generators.
- Protection relays and monitored, controlled breakers, which are key components of islanding switchgear.
- AC-coupled versus DC-coupled solar PV plus battery storage systems.
- The importance of solar PV smart inverter functions.
- Battery storage system sizing and inverter capacity decisions.
- Recommendations on the integration of a backup, fuel-fired generator.
- Interconnection and net metering processes and requirements.
- Commissioning and testing requirements.

The complete Solar+ Hardware Design Toolkit is included in Appendix F.

Site Targeting Tools

Reducing the cost of Solar+ microgrids and achieving commercially sustainable and widespread application require innovations in technology that can be fueled by additional deployments. The Schatz Center team conducted surveys of sites that could be near-future adopters of microgrids (for example, convenience stores), developed an estimation framework for the cost of microgrids, and developed a set of recommended site targeting guidelines to guide near-term deployment.

Convenience Store Surveys

To better understand the gas station/convenience store building sector and opportunities for deployment of Solar+ technology, the team conducted a series of surveys. These included a geo-spatial survey, an online survey, a phone survey, and an in-person survey; each successive survey built upon the previous survey results.

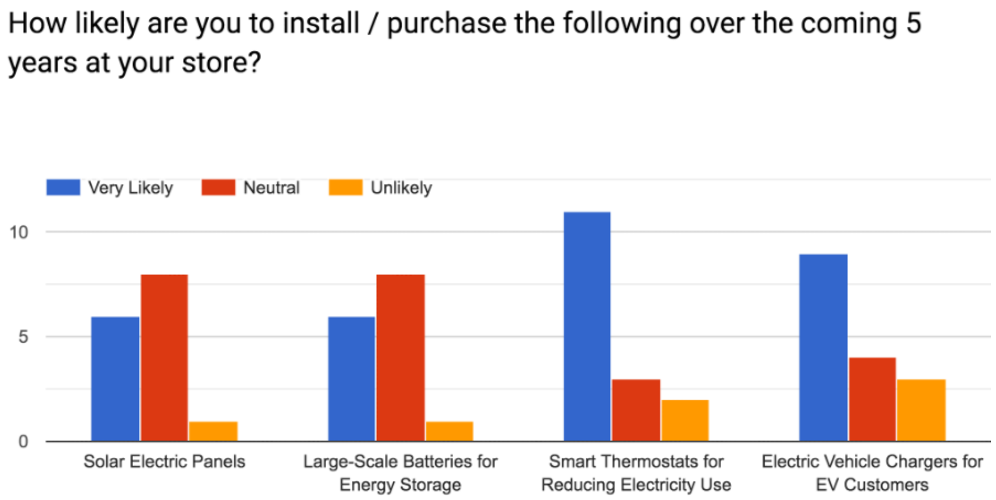
The first survey was a geo-spatial survey using Google Earth to gather information about 83 gas station/convenience stores throughout California. The survey assessed site layouts and available space on canopies and convenience store roofs for solar photovoltaic arrays. This work informed remaining survey work.

The second survey was online and sent to California convenience store owners with the support of two industry associations: the National Association for Convenience and Fuel Retailing and the California Independent Oil Marketers Association (now the California Fuels & Convenience Alliance). This survey was completed by 16 participants. The goal of the survey was to gain a better understanding of the importance of electrical service to gas stations and convenience stores in California, and to gauge the interest that site owners have in solar electricity, energy storage, energy efficiency, and EV charging.

The third survey involved calling convenience store owners who completed the online survey and agreed to a phone interview. In this way, convenience store owners could freely express their opinions of the Solar+ package and explain their main concerns about electricity at their locations. Lastly, from those who participated in the phone interview, the team selected 12 sites for onsite surveys. All onsite surveys were conducted in Northern California and consisted of brief conversations with the site manager or owner and a walk around the site to collect data. Information collected included the characteristics of existing electrical infrastructure (for example, electric loads and appliances, electric service panels) and information about fueling island canopies and convenience store roofs and their ability to support solar PV installations.

The results of the survey work indicated strong potential for the deployment of Solar+ technology in the gas station/convenience store building sector. As the following figures indicate, the online survey results showed a strong interest in: Solar+ technologies (Figure 19), the ability to keep stores functional during natural disasters (Figure 20), and electricity costs (Figure 21). However, the results of these surveys cannot be generalized to the overall gas station/convenience store building sector because the survey sample was not a representative random sample and was likely influenced by self-selection bias, since all online, phone, and onsite survey participants self-selected to participate. It is likely that participants chose to participate because of an existing interest in the topic area. Nonetheless, the information collected in these surveys does provide useful information regarding the potential for deploying Solar+ technology in this building sector. Additional information about the Solar+ surveys is included in Appendix G.

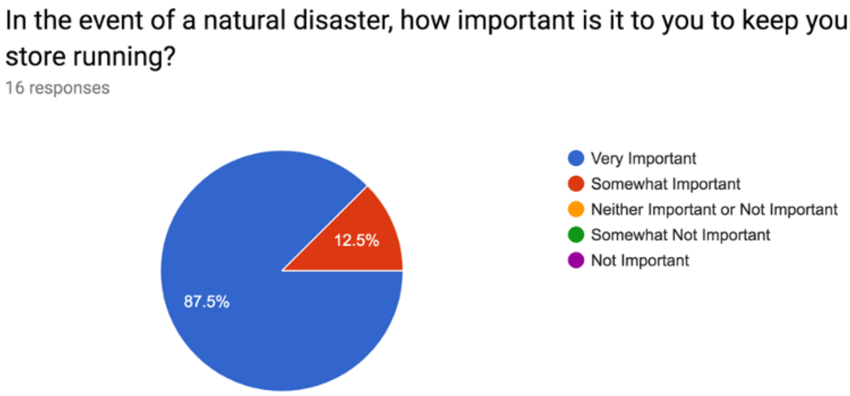
Figure 19: Level of Interest in Solar+ Technologies



Summary survey responses from N=16 convenience store owners / operators in California

Source: Schatz Center

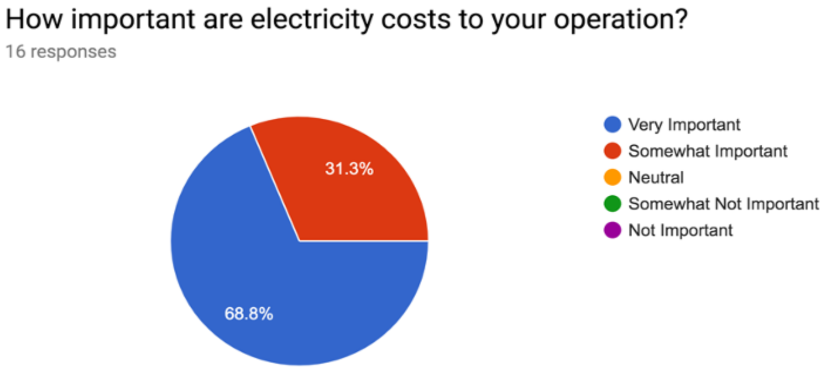
Figure 20: Importance of Keeping Store Running During a Natural Disaster



Summary survey responses from N=16 convenience store owners / operators in California

Source: Schatz Center

Figure 21: Importance of Electricity Costs



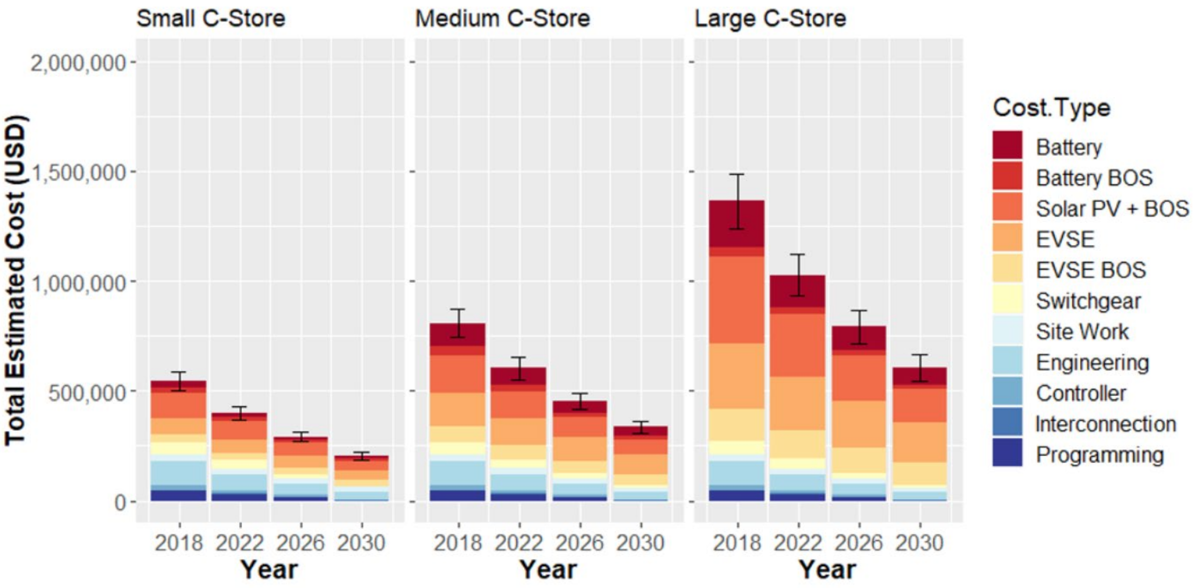
Summary survey responses from N=16 convenience store owners / operators in California

Source: Schatz Center

Cost Estimation Model

The Schatz Center team developed a cost estimation timeline model that estimated the cost of Solar+ microgrid projects out to the year 2030. This work was summarized in detail by Thalia Quinn, a graduate student research assistant at the Schatz Center, in her master's thesis (Quinn, 2019). Capital cost estimates were developed for battery storage, solar PV, EV chargers, system controls (including blue sky optimization and islanding capabilities), switchgear, site work and installation labor, and soft costs such as permitting and engineering. A range of Solar+ system design scenarios was evaluated (from small to large facilities, as well as facilities with extra resilience), and dollar-per-watt estimates were developed for each scenario for a range of future dates (Figure 22). Decreases in future costs were estimated using learning curve techniques and publicly available industry cost-projection data.

Figure 22: Projected Solar+ Costs by Year for Three Scenarios



Estimated cost for Solar+ microgrids at convenience stores, including PV, battery, EV chargers (electric vehicle supply equipment or EVSE), balance-of-system (BOS) costs, and microgrid-specific equipment and engineering and programming services

Source: Schatz Center

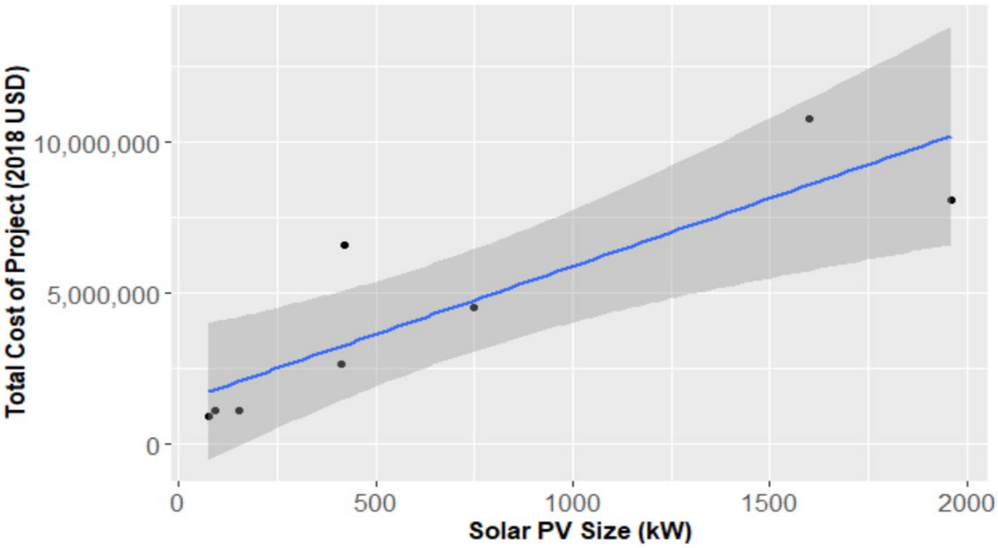
When considering the costs of clean energy microgrids, there are two core categories: equipment for energy generation, storage, and utilization; and microgrid-specific equipment and engineering services. The first category, which includes installation of solar PV systems, batteries, and additional elements like EV chargers, is largely commercial off-the-shelf equipment. These mass market elements will benefit from ongoing cost reductions as a broader consumer market grows.

Microgrid-specific elements are required to integrate energy services with building and power systems to ensure safe and reliable operation of the microgrid. Custom switchgear costs $50,000 to $250,000 per system and requires more than $10,000 in professional work to prepare the site and support installation and commissioning. The soft costs of designing the microgrid controls, managing the interconnection permitting process, programming controls, and overall integration of software systems total about $100,000 per site, depending on individual details. Overall microgrid-specific costs currently add up to between 20 percent and 50 percent of total project costs for small and medium sites.

This project worked to address these two significant microgrid cost areas by developing standardized and scalable approaches to the design and engineering of hardware and software. If these costs can be cut significantly, together with ongoing cost reductions in energy services equipment, it could lead to more widespread deployment of Solar+ microgrids.

The team benchmarked the cost estimation model against eight recent microgrid installations. These were evaluated and a cost curve was developed for estimating the total cost of a Solar+ microgrid project in 2018 as a function of the solar PV array size (Figure 23). The eight microgrid projects evaluated had battery storage systems with power capacities ranging from 20 percent to 270 percent of the PV system capacity and with storage capacities ranging from one to eight hours. PV array sizes ranged from 90 kW to almost 2 MW. Additional details regarding the cost estimation model work are summarized in Appendix H.

Figure 23: Reported Solar+ Microgrid Cost as a Function of PV Array Size



Total project cost of microgrids versus the solar PV installed capacity (circa 2018)

Source: Schatz Center

Site Targeting Toolkit

The methodology for choosing sites for microgrids is simultaneously simple and complex. In simple terms, microgrids should be targeted for sites where benefits outweigh the costs. Yet there remains considerable uncertainty when predicting the benefits of microgrids. The biggest factor is the often hard-to-measure value of resilience, particularly at sites that provide critical services to communities responding to wildfires and other threats to the safety and continuity of electricity service.

There are relatively high costs for microgrids compared with simply installing solar PV and energy storage for lower bills. These costs are related to higher-capacity needs for batteries and additional costs for switchgear, integration, and interconnection setups. A high value for resilience points to candidate sites that are critical for lifeline sectors and continuity of social services. These include hospitals, first responder stations, grocery stores, and others. At these sites the additional cost of the hardware, software, and integration engineering required for microgrids is balanced by the benefits of resilience and reliability.

Based on the overall Solar+ project findings, along with other work related to the economics of solar and storage, the research team recommends a multi-criteria approach to identifying sites for prioritizing microgrid investment. These criteria are described in Table 9.

The most important sites for targeting microgrid deployment are those with multiple layers of need and opportunity. For example, a hospital or disaster shelter in a rural and low-income community facing elevated wildfire risk would gain significant benefits from a Solar+ microgrid due to the high value of serving load during outages and a high frequency of expected outages. The complete Site Targeting Toolkit, including additional supporting information and discussion, appears in Appendix I.

Table 9: Criteria for Microgrid Targeting

Criterion	Why This Matters	Example Sites/ Locations
Bill Savings: Favorable solar PV and energy storage economics for bill savings (for example, coincidence of load with solar, availability of NEM tariffs, "peaky" loads with demand charges to be managed with batteries)	Sites where bill savings are higher from solar PV and energy storage projects would fare better	This is a site-specific issue and depends on the utility billing structure. Most commercial buildings in California will have favorable economics for solar and batteries as the costs fall.
Distribution System: Target locations on the distribution system require microgrids to unlock the hosting capacity.	Constrained distribution circuits can limit deployment of DER. Microgrids (with appropriate engineering) can overcome these interconnection constraints.	Locations with "over-subscribed" circuits, or rural locations with inadequate infrastructure
Critical facilities: Facilities that provide high-value services to communities	These sites provide significant societal value in continued operation during blackouts, with a high "value of serving lost load."	Grocery stores, community meeting buildings, schools
Disaster response facilities: A special category of critical facility, including sites that are instrumental for supporting disaster response	These sites have particularly high values from continued service, and they directly avoid loss of life during disaster response.	Hospitals, public safety facilities, gas stations, community shelters

Criterion	Why This Matters	Example Sites/ Locations
Facilities in outage-prone locations: Sites in locations that experience frequent power outages	These sites will experience more frequent power outages, amplifying the resilience value from microgrids that are called into action.	Wildfire prone regions, outlying rural areas facing natural hazards
Facilities serving vulnerable communities: Sites that provide service to vulnerable communities	Under-resourced communities are more vulnerable to disaster and may face more significant hazards from loss of service due to an inability to access alternatives.	Indigenous communities, low-income communities, and other historically underserved communities

Source: Schatz Center

CHAPTER 7: Technology/Knowledge/Market Transfer Activities

In an effort to promote the advancement and deployment of Solar+ technologies, the team engaged in numerous technology and knowledge transfer activities. A technology and knowledge transfer plan was developed. This chapter summarizes the efforts that carried out that plan.

Technical Advisory Committee Meetings

A technical advisory committee (TAC) was assembled, and four meetings were held. The TAC consisted of participants with broad backgrounds. The organizations represented included: investor-owned utilities, a community choice aggregator, state regulatory agencies (California Public Utilities Commission, California Independent Service Operator), research entities (LBNL, Electric Power Research Institute), emergency services (California Governor's Office of Emergency Services), industry associations (National Association for Convenience and Fuel Retailing, California Independent Oil Marketers Association), the grocery/retail sector (Target), and clean-energy industry vendors and associations (SunPower, Emerson Commercial & Residential Solutions, Siemens Building Technologies, McKeever Energy & Electric, California Solar and Storage Association). Key topics during these TAC meetings included general project overviews, DR strategies and pricing signals, survey results, and discussions on the value of resilience. The purpose of the TAC was to provide guidance and support for the project and to spread knowledge and lessons learned. Other key benefits from the TAC included:

- Access to fueling station and convenience store owners and operators via professional industry association leaders. This allowed us to field a three-part survey (online, by phone, and in person) in order to gain information about the needs, desires, and perceptions of store owners and operators and assess the market potential for Solar+ technologies in this building sector.
- Assistance with the development of the market survey.
- Insight into the value of resilience for the fueling station and convenience store and, more broadly, small- and medium-sized commercial buildings.
- Sharing knowledge and lessons learned from this Solar+ research project.

Outreach Activities

Outreach activities were conducted throughout the project and are summarized here.

Publicity

Publicity included press releases, fact sheets, blog posts, and other products:

- News updates and blog posts were published via the Schatz Center newsletter and website.
- A project fact sheet was developed and shared when informing others about the project.
- A project webpage was developed on the Schatz Center's website
- Numerous public tours of the Solar+ project site in various stages of construction and operation were hosted by BLR for diverse audiences, including schoolchildren, state and federal policymakers, and regional officials.

Webinars/Presentations

The following webinars and presentations were delivered on behalf of the Solar+ project. Project results and lessons learned could not be presented at in-person conferences during the project time frame due to COVID-19 restrictions.

1. Solar+ for Small and Medium Commercial Buildings presentation, CEC EPIC Symposium, February 19, 2019
2. Solar+ Optimizer: A Model Predictive Control Optimization Platform for Grid Responsive and Resilient Building Microgrids, webinar presentation to UC Berkeley CIEE, CITRIS, and ECRN, July 21, 2020

Publications

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Industry Outreach

Trade Associations

The project team reached out to a number of industry associations to engage them in project activities. Representatives from the National Association for Convenience and Fuel Retailing and the California Independent Oil Marketers Association responded favorably to this request and became strong collaborators as a result. In addition to their participation on the TAC, they supported efforts to conduct a Solar+ survey of their members. They reviewed the team's surveys and outreach messages and provided feedback and guidance. Once the team finalized materials that everyone supported, trade representatives sent out the online survey request to their membership to encourage participation. This was a big reason for the successful engagement and strong response to the online survey and subsequent phone and in-person surveys.

Companion EPIC Projects, Utilities, and Regulators

The Solar+ project team engaged and collaborated with a number of other CEC EPIC-funded projects. These engagements included:

- Advances in interconnection hardware and switchgear from this Solar+ project are being used to inform development of microgrids at new buildings on the BLR. These advances are also informing the development of the Redwood Coast Airport Microgrid (also funded by the CEC under the EPIC Program). Design principles from this Solar+ project also helped inform PG&E's Community Microgrid Technical Best Practices Guide.
- The software advances in this project contributed key features to LBNL's eXtensible Building Operating System (XBOS) software related to controlling PV and battery systems and adding model-predictive control features. These are being carried forward into a follow-up project called "HP-flex" (also funded by the CEC under the EPIC Program), which will continue refining the model predictive control approach for heat pumps that are critical for decarbonization.
- This project collaborated with the project team from E3 on its EPC-17-004 Solar+ Storage Tool. E3 developed a tool for assessing the potential benefits associated with Solar+ storage projects, including transmission and distribution system benefits and energy efficiency benefits. The E3 team used this Solar+ project as a case study to test its tool. Key sensitivities that were examined showed that a case where the customer really values high reliability (using a very high value of lost load) has a big impact on cost effectiveness, as does a case where there is a large transmission and distribution value associated with the project, and where the project is appropriately compensated for grid services.
- The Solar+ project team engaged with other EPIC-funded Solar+ projects, CEC staff, and investor-owned utility (IOU) staff to share information from the CEC-funded Solar+ projects regarding how behind-the-meter storage is dispatched and how that relates to current methods used by the CEC and the IOUs for forecasting behind-the-meter storage.

Open-Source Software

The Solar+ Optimizer software was built on top of publicly available, open source software such as XBOS (https://github.com/gtfierro/xboswave) and MPCPy (https://github.com/lbl-srg/MPCPy). The Solar+ Optimizer software will soon be available under a modified BSD-3 license at https://github.com/LBNL-ETA/SolarPlus-Optimizer.

CHAPTER 8: Conclusions and Recommendations

This chapter provides a review of key conclusions and lessons learned from the Solar+ project, followed by a list of suggested areas for future research.

Conclusions and Lessons Learned

The Scaling Solar+ for Small and Medium Commercial Buildings project was a strong success and met most project goals and objectives. Following is a list of lessons learned.

Demonstrated Abilities of a Solar+ System

The Solar+ system at the Play Station 777 demonstrated the following benefits:

- Decrease in solar intermittency compared with a traditional fixed-tilt solar PV system
- Shifts in dispatch of power, avoiding the curtailment of other renewable sources on the grid and increasing the total renewable energy generated
- Shift generation to later in the evening, providing generation that can be used to mitigate the steep demand ramp-up in the early evening hours
- Distribution grid services, such as load shift and load shed
- Reduced energy and demand costs
- Reduced GHG emissions
- Increased resilience and decreased reliance on backup fossil-fueled generators

Design Lessons Learned

- Defined a set of controls and control layers needed for a minimally viable microgrid. This is critical to developing a standardized, cost-effective Solar+ microgrid system that can be replicated across the small- and medium-sized building sector.
- Developed a design for the islanding switchgear that could be optimized and then standardized for mass production.
- Developed a design that can incorporate an existing backup generator, without complications.
- Developed a simplified system that requires little to no interaction and provides a simple interface, as well as a simple data historian able to track system performance and spot performance issues.

Solar+ Optimizer Lessons Learned

- The team proved that it is technically feasible to develop and implement an open-source software system that integrates diverse technology vendor systems within a high-performance automation framework.
- The choices of distributed control hardware are critical for ensuring compatibility with microgrid automation; many thermostats and mass-market energy control systems require continuous and robust connections to the internet that rely on Cloud-based systems for communication. It is important to identify hardware with local control and communications options that ensure resilience against internet and regional communication system outages.
- The team successfully deployed model-predictive control optimizations that manage thermal loads within the constraints of comfort and utility. However, fine tuning of model-predictive control parameters is critical for ensuring that algorithms are beneficial, and at the current stage of development model tuning requires expert intervention.

Operations and Maintenance Lessons Learned

- For Solar+ systems to be practical in the small- to medium-sized building sector, they must be low maintenance and operate unattended. This poses a challenge because the optimized, integrated controls on these systems can require tuning and upkeep. When these systems are first installed, it is critical that their performance be monitored and verified and, if the system is not performing according to specifications, further commissioning be conducted. In addition, any time a change is made to software (for example, a firmware update is uploaded or a new rate tariff is updated in the software settings), it is important to confirm that the new firmware or software settings are performing as expected. If the system is not performing as expected, then troubleshooting must be performed and the system repaired.

Replication and Site Targeting Lessons Learned

- The Solar+ project team assembled for this project could replicate the design developed here much more quickly and cheaply in a second iteration, since there were many lessons learned and software tools developed that would make deployment much faster the second time around. In addition, additional cost savings could be captured via value engineering.
- This project made progress toward developing a simple microgrid islanding controller and associated switchgear configuration that could be standardized, pre-approved by distribution system operators, and mass produced. This would substantially bring down the capital costs of the controls and switchgear and would significantly reduce engineering design and permitting costs. This platform could be designed to be plug-and-play across a wide range of distributed energy system vendors and manufacturers and could feature a simple user HMI and a historian.

Potential Areas for Future Research

Public funding is crucial to support the first movers whose projects plow new ground, because the cost to engineer and install novel systems often outweigh site-specific benefits. The advances that are made, however, can lead to spillover gains across a range of projects and applications. Specific next steps to advance Solar+ microgrids through technology development include:

- Continued refinement in simplified and cost-effective interconnection hardware (switchgear). This project made important advances that have informed subsequent designs. Continued support for deployment is important to improve these vital pieces of microgrid hardware.
- Certifying a pre-approved switchgear design and controls setpoint framework to streamline interconnection processes.
- Continued development and support for open-source software frameworks to integrate DER and microgrids. This project, starting at Technology Readiness Level 6, made advances and proved the concept of an open-source framework but did not result in a commercially viable and stable framework. The status quo of fragmented and proprietary controls remains in place. The team now rates the technology at Technology Readiness Level 7.
- Scaling model-predictive control at mass market sites will require additional research and development (R&D) to avoid or reduce the need for expert setup and tuning. Basic and applied R&D that focuses on artificial intelligence for robust and useful model-predictive control setup and tuning is a promising frontier for reducing barriers to broader use of model-predictive control.
- Target support for early market deployment of microgrids at critical facilities in wildfire-prone regions, which will have mutually beneficial outcomes in public health and longer-term technology R&D. Microgrids could be supported with block grants and incentives to meet needs in wildfire-prone communities, particularly historically underserved communities (including indigenous communities) in rural and outlying areas that face significant risks and have little access to resources. Learning by doing in these communities will lead to important and valuable community benefits, with spillover gains through technology to help bring down costs.

Several opportunities for policy innovation and public-interest R&D should be considered. These could unlock significant value and support more widespread deployment.

- Consider whether utility-owned switchgear, with costs recovered through a special rate for microgrid sites, may be more appropriate than site-owned switchgear. Utility-owned switchgear may enable more widespread standardization since utilities could develop and deploy a set of in-house standardized designs across their service territories. This would also de-risk this portion of the project for sites, which would pay for resilience service through a cost-recovery tariff. While this may be a promising future direction, this project did not study the financial or policy implications.

- Consider special support for standards-based, machine-readable, local communication (without requiring Cloud-based services) between DER controls that would support future open-source development and integration of DER in high-resilience microgrids.
- Consider supporting a publicly available and free solar energy forecasting service based on weather forecasts. There are proprietary solar forecasts available that are costly for single sites, presenting barriers to optimum operations.

CHAPTER 9: Benefits to Ratepayers

The benefits associated with this Solar+ project include both direct benefits associated with the pilot project and potential benefits of opportunities for replication and scale-up.

Direct Project Benefits

Direct project benefits are those that directly accrue from the pilot project at the Blue Lake Rancheria Play Station 777. These benefits include energy and demand cost savings, GHG emission reductions, direct job creation, support of Tribal energy sovereignty, sustainable energy, and lower carbon resilience for the facility. Following is a brief accounting of the direct benefits associated with the Solar+ pilot project.

- Energy and demand costs were an estimated 32 percent lower in summer and 26 percent lower in winter under E-19 rates. Summer savings under B-19 rates were estimated to be 36 percent ($1,370 per month).
- GHG emissions were estimated to be 16 percent lower.
- An estimated 2.5 full-time jobs were created as a result of the project.
- The project provided increased low or zero carbon resilience that allowed the facility to decrease its diesel consumption by approximately 80 percent over 31 hours of islanded runtime over a four-day period.
- The project demonstrated the ability to provide demand response grid services. With appropriate rate structures and compensation programs, the project could provide grid services.
- The project host has also installed EV charging infrastructure at their facility. While this EV charging infrastructure was not directly part of the Solar+ project, it will benefit from the added resilience and energy and demand savings features of the Solar+ project. In addition, the Solar+ project concept includes the integration of EV charging, and the subsequent installation of this infrastructure at the facility serves to demonstrate this concept.

Potential Project Benefits via Replication and Scale-Up

A key objective of this project was to provide lessons learned to promote deployment of Solar+ projects at scale in the small- to medium-sized building sector, with a special focus on convenience stores/fueling stations. There are nearly 12,000 convenience stores/fueling stations in California, and these buildings share unique characteristics that could lead to standardized designs. In addition, these facilities offer the potential to help meet the need for increased EV charging infrastructure and provide important services (food, ice, refrigeration, and fuel) during natural disasters and power outages (Quinn, 2019). With increased deployment of Solar+ systems, there would be a multiplier effect of benefits to ratepayers in the areas of energy and demand cost savings, GHG emission reductions, job creation, increased low-carbon resilience in the electricity sector, and grid services, including load shedding and shifting.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
AC	Alternating current
AC-coupled	Refers to the connection of battery energy storage and solar electric generators on the common AC electric bus of their respective inverters.
Anti-islanding	A feature of grid-tied inverters that ensures they do not try to form an island while connected to the bulk electric grid if the bulk electric grid loses power.
API	Application programming interface: a software interface that allows two software applications to talk to each other.
ATS	Automatic transfer switch
BACnet	A standardized communication protocol for Building Automation and Control networks
BESS	Battery energy storage system
BLR	Blue Lake Rancheria
BOS	Balance-of-system costs include all components required for installing and integrating solar photovoltaic and battery energy storage systems.
Blue sky mode	This refers to the operation of a microgrid when it is connected in parallel with the bulk electric grid.
CEC	California Energy Commission
CIEE	California Institute for Energy and Environment
CITRIS	Center for Information Technology Research in the Interest of Society
cPTO	Conditional permission to operate
CPUC	California Public Utilities Commission
C-store	Convenience store
DC	Direct current
DC-coupled	Refers to the connection of battery energy storage and solar electric generators on the DC electric bus of a shared inverter.
Demand limiting	A demand response strategy that aims to keep the electrical load below a pre-defined quantity.
DER	Distributed energy resources
DG	Diesel generator
Duck curve	The “duck curve” refers to a characteristic curve showing the gross electrical load, the cumulative solar generation, and the net electrical load, especially in California or other regions where there is a large volume of solar generation. Because there is so much solar power

Term	Definition
	generated in the middle of the day, the net load curve dives to zero or even negative values. Then, when solar tails off in the evening and people return home from work and turn on their appliances, the net load ramps up very rapidly. The shape of the net load curve over a typical 24-hour period on a weekday, especially in the spring time, looks like the shape of a duck's body.
DR	Demand response: the ability to shed electrical load when needed to provide services to the grid.
ECRN	Environmental Change Research Network
EPIC	Electric Program Investment Charge
EV	Electric vehicle
EVSE	Electric vehicle supply equipment, also known as electric vehicle chargers
GHG	Greenhouse gas
HMI	Human machine interface
HTTP	Hypertext transfer protocol: an application layer protocol that facilitates communication over the Internet.
HVAC	Heating, ventilating, and air conditioning
HVAC&R, HVACR	Heating, ventilating, air conditioning, and refrigeration
Islanded operation	This refers to the operation of a microgrid system when it is disconnected from the main electric grid and operating in isolation.
ISO	Independent System Operator
LBNL	Lawrence Berkeley National Laboratories
Load shedding	Load shedding refers to the process of reducing an electric load by turning an electrical appliance down or off so that it does not consume as much power.
Load shifting	Load shifting refers to the process of reducing an electric load during one time period but shifting the usage to another time period rather than forgoing it altogether.
Load tracking	Load tracking tries to manage an electric load and keep the power consumption within pre-defined bounds.
MCB	Monitored and controlled breaker
ME&E	McKeever Energy and Electric
Megger testing	A method of electrical testing that uses an insulation tester resistance meter to verify the condition of electrical insulation and help prevent short circuits from occurring.

Term	Definition
Modbus	A data communications protocol for connecting industrial electronic devices.
Modbus Poll	A Modbus master simulator that allows testing and simulation of the Modbus protocol.
Modbus/serial	The use of the Modbus protocol over serial communication lines.
Modbus/TCP	Modbus-TCP or Modbus-TCP/IP is the use of the Modbus protocol with a TCP interface that runs on the Internet.
Model Predictive Control (MPC)	An advanced method of process control that relies on dynamic models of the process and allows the current time slot to be optimized while anticipating future system behavior.
MPCPy	An open-source software platform for Model Predictive Control in buildings scripted in the Python programming language.
NACS	National Association of Convenience Stores
NEC	National Electrical Code
NEM	Net energy metering
NETA	National Electrical Testing Association
NGOM	Net generation output meter
NREL	National Renewable Energy Laboratory
NUC	Next Unit of Computing: a bare bones mini personal computer from Intel.
PCC	Point of common coupling, where a distributed generator connects to the utility distribution system.
PG&E	Pacific Gas and Electric Company
PPI	Pre-parallel inspection
PTO	Permission to operate
PV	Solar photovoltaics: the most common technology for solar electricity generation.
RCE	Robert Colburn Electric
RCEA	Redwood Coast Energy Authority: the community choice aggregator in Humboldt County.
RTAC	Real-time automation controller
RTP	Real-time pricing
R&D	Research and development
SAM	System Advisor Model: a renewable energy simulation model available from NREL.
SCADA	Supervisory control and data acquisition

Term	Definition
Schatz Center	Schatz Energy Research Center at Humboldt State University
SEL	Schweitzer Engineering Laboratories
Serraga	Serraga is the project development and management entity for the BLR.
SMA	A solar technology company headquartered in Germany that manufactures inverters for distributed energy systems.
Solar+	A system combining solar, batteries, and potentially other energy services equipment, such as demand response controls.
Solar+ Optimizer, SPO	Model predictive control software written in MPCPy that uses an XBOS platform to optimize the control of solar electric generation, energy storage, and demand response controls in order to optimize benefits and costs.
Switchgear	Switches, circuit breakers and other electrical components that are used to interconnect electrical generators, energy storage and electrical loads.
TAC	Technical Advisory Committee
TCP	Transmission Control Protocol: the standard communication protocol for communicating over the Internet.
Technology Readiness Level	Technology Readiness Level (TRL) is a metric that describes the maturity level of technologies and was developed at NASA in the 1970s. TRLs are based on a scale of 1 to 9, with 9 being the most mature.
TOU	Time-of-use: with time-of-use electric rates, the price changes depending on the time of day and the time of year.
UPS	Uninterruptible power supply
WAVE	An authentication engine that handles permission and access control between applications and devices on a secure tiered message bus.
WAVEMQ	A multi-tier publish-subscribe message bus that allows exchange of data and control signals.
XBOS	eXtensible Building Operating System, an open-source building operating system developed for real-time data acquisition from sensors and control of building actuators.

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