Smart Home Panels and Modular Batteries for Capacity Management, Load Control, and Grid Resilience in Affordable Housing

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ABSTRACT

This study addresses critical barriers to residential electrification in power-constrained affordable multifamily housing through an integrated smart panel and modular battery solution. The system enables building electrification without costly electrical service upgrades while providing advanced load management, demand response capabilities, and grid resilience during outages. The smart panel system features 12 circuits with expandable capacity up to 90 kWh and 21.6 kW output, accommodating peak loads from heat pumps, induction stoves, and electric dryers without service upgrades. Key innovations include automated circuit-level load management, rapid grid-to-battery switchover, storm guarding for enhanced resilience, and time-of-use optimization for demand response. The system integrates with existing rooftop PV arrays to enable unit-level islanding during outages while minimizing recharging costs. Direct benefits include reduced smart home panel installation costs incurred from electrician's billed labor hours from 8-12 hours to 4 hours, while the modular plug-in batteries require no additional labor hours. The proposed solution could save approximately $942 per installation of one set of smart home panels and batteries. Performance metrics include (1) avoided electrical infrastructure upgrade cost, (2) customer bill savings, (3) revenues from grid services, and (4) reduced cost of downtime for critical loads. Preliminary field results indicate that a 6-kWh battery system can offer annual bill savings of $12–24 per kWh of storage capacity. Across the field units, it sustains critical-tier circuits for 10–49 h and critical-plus-essential load for 2–44 h, depending on each unit's load profile.

Introduction

Extreme weather events, such as storms, flooding, wildfires, and heatwaves, have been become more frequent in recent years, which lead to more power outages and Public Safety Power Shutoffs (PSPS) events (CPUC 2025). Energy resiliency is crucial for California's well-being during weather-related outages as critical services, such as heating, cooling, refrigeration, air purification, and communication, depend on electricity. Due to the increased frequency, intensity, and duration of power outages caused by extreme weather events, the demand for home backup power systems has significantly grown (CEC 2025). Ensuring clean, affordable backup power solutions is imperative to meet California's environmental justice goals as power outages disproportionately impact low-income, rural, and disadvantaged communities (Domier 2026). According to the U.S. Energy Information Administration's 2020 Residential Energy Consumption Survey, California has a total of 13.18 million housing units, with approximately 69.9% of households built before 1980, and only 8% being all-electric households (EIA 2020). 17% of households have experienced a power outage lasting 24 hours or more. Of the housing units in California, 29% are apartments, which comprise 50% or more of housing built every year in California since 2009 (McGrath 2023). Electrical service capacity in older multifamily housing buildings is undersized for current decarbonization goals. Units built in the 1970s-2000s often provided only 60A service at each unit, meaning the currently needed minimum 100A service is rarely in place (EPRI 2022, Fournier 2024).

Electrical service retrofits that accompany building electrification are inherently expensive and conservative. In addition, converting natural gas furnaces, clothes dryers and boilers to heat pump technology, gas stovetops and ranges to induction, and even adding an EV charger, represent large but intermittent additional loads to a residence. Further, electrification of multifamily developments represent significant electrical demand increases which may stress available grid capacity, especially during times of peak use (Murphy 2024). One promising alternative to costly capacity expansion is to manage these new loads intelligently so that they operate within the electrical service a building already has, but existing approaches each fall short in scalability or functionality. Recent studies (Kim 2016, Sridhar 2024, Sparn 2024) applied flexible load controllers to dynamically prioritize and curtail controllable loads, holding a building below a demand limit or responding to dynamic electricity prices. However, this approach only holds load within the existing service capacity and depends on per-site control logic that is difficult to scale across many units. Dynamic load-management devices and smart breaker panels can accommodate heavy loads by sharing power between them or switching off designated circuits to prevent overloading the main breaker (Crawford 2023, Walker 2024). The limitation of this approach is that the customer can operate only one heavy load at a time. This raises the central research question: how can hardware such as smart panels and load-sharing switches be integrated with software-defined controllers to manage service capacity without costly panel or service upgrades? How can an all-electric home maintain essential services during a power outage?

To address barriers mentioned above, this study utilizes scalable "plug-and-play" batteries to enable electrification and decarbonization of such buildings, as well as provide automated grid services and resilience-preserving essential services during power outages and managing peak demand versus maximum service capacity by islanding battery-powered subpanels, dynamic pricing or grid events. This study also tackles the economic barriers of high upfront cost of battery energy storage systems and potential electrical service upgrades and technical barriers of load management of selective circuits and use of batteries for backup power. Apartment units will also have the capability to disconnect from the grid/building and operate islanded plug-in batteries and solar PV generation through the smart home panel, powering only essential circuits.

Technical Framework

In this study, we designed a central controller that manages high-level decisions (e.g., designated load shed capacity for each participating customer or dispatch of stored energy from the battery to temporarily support more load than the grid electric and local PV service can provide) due to limited existing capacity or during specific grid situations. Site controllers enable residents at each unit to adjust their own behaviors to coordinate operations between selected circuit loads, flexible loads, and the connected batteries to manage simultaneous peak loads.

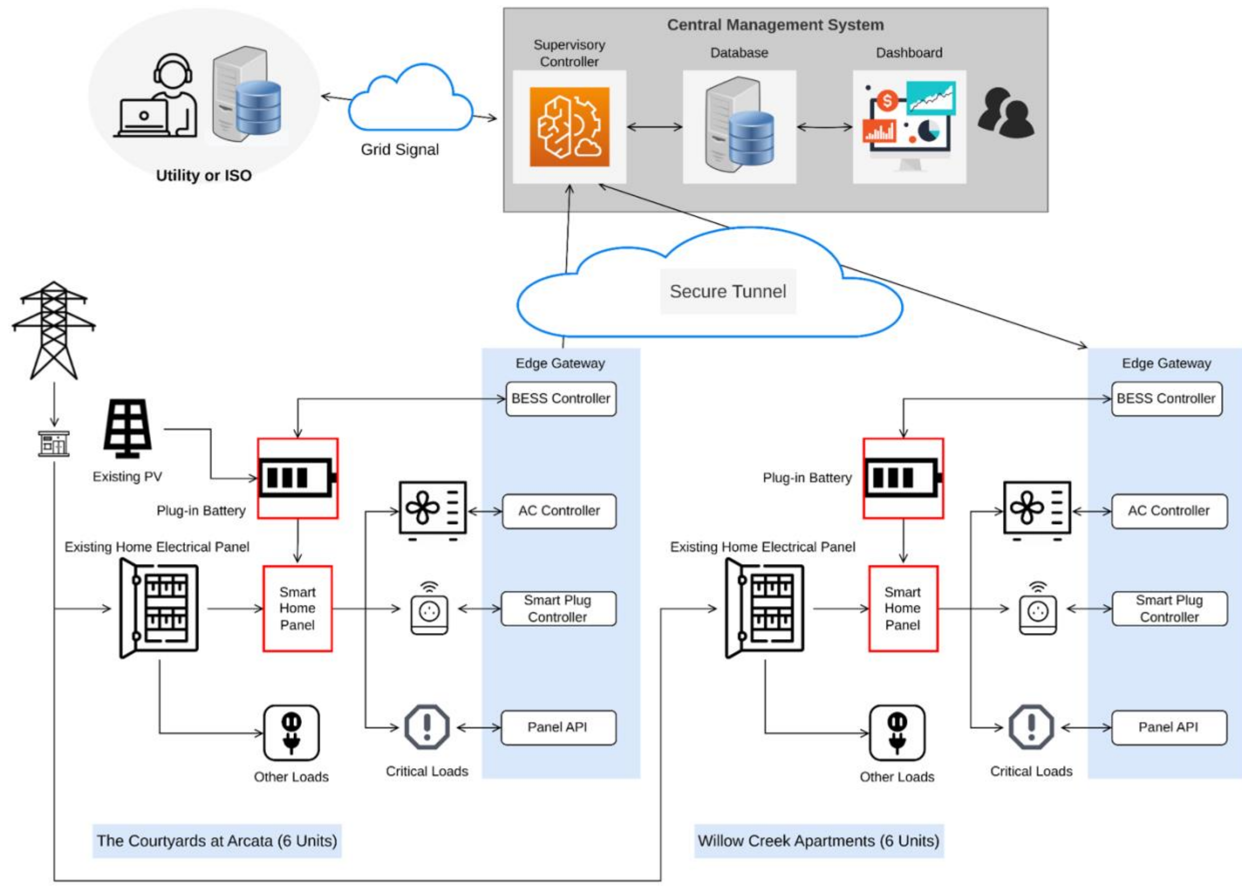

Figure 1. Conceptual diagram of centrally coordinated smart panels, BTM batteries, building flexible loads, and grid

Table 1 and Figure 1 present key components include a smart home panel, modular plug-in batteries, and an edge computing gateway. The smart home panel can be installed alongside and connects easily to existing breaker panels, allowing for the tailored load management of selective circuits, short-term loads, or maintaining essential services during extreme weather events or power outages. The Smart Home Panel is equipped with 12 circuits and can be expanded to a capacity of up to 90 kWh with a 21.6 kW output and can receive a maximum solar input of 16.8 kW. Modular batteries are designed to integrate with these panels, effectively expanding available capacity at the apartment. Additionally, the smart panel includes enhanced features such as pre-charging plug-in batteries in the event of grid emergencies or natural disasters, and a Time of Use (TOU) functionality to help save electric energy costs by automatically switching from grid to backup power during high-rate periods.

Table 1. Key Components in the Proposed Solution

Key Components	Plug-and-Play Features
Smart home panel	Modular design panel equipped with 12 circuits, 20 milliseconds auto switchover, up to 3 plug-and-play inverters, app control output
Inverter	7.2kW-21.6kW output with up to 3 inverters, 5.6kW-16.8kW solar input with up to 3 inverters

Key Components	Plug-and-Play Features
	Cloud service supports IEEE 2030.5-2018
Modular plug-in batteries	Portable and scalable, modular plug-in batteries can be expanded to a capacity of up to 90 kWh and 21.6kW (limitations of current module)
Edge computing gateway	Equipped for edge computing, the gateway supports standard communication protocols such as OpenADR and IEEE 2030.5, SunSpec Modbus, interfaces with control protocols like BACnet and Modbus for managing flexible loads and uses APIs to integrate with smart home panels.

Demonstration Use Cases

The project team demonstrated three smart home panel use cases with plug-in batteries. These use cases can be used to model and provide design frameworks for a broader range of scenarios to help address capacity constraints.

Use Case #1: Capacity Management

Figure 2 details the smart home panel use case that demonstrates the capacity management of the panel and plug-in batteries. The panel and plug-in battery increase the existing panel capacity by 50%, increasing the total capacity to 90A. When the demand from the unit exceeds the maximum capacity of the existing system, the smart panel uses the plug-in battery as an additional energy source to ensure the capacity needs of the home are being met.

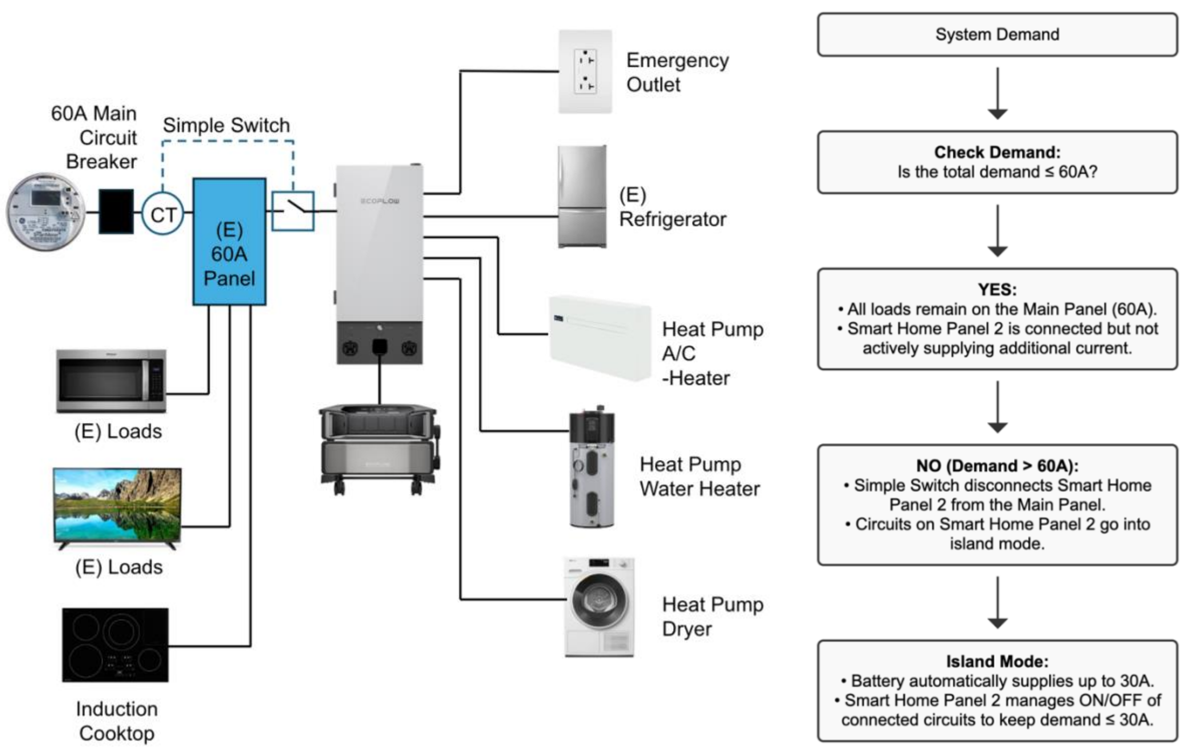

Figure 2. Conceptual diagram of capacity management of smart home panel with plug-in batteries, building flexible loads, and interruptible circuit loads

Use Case #2: Load Management

Figure 3 depicts the use of plug-in batteries and load flexibility for optimizing home energy usage in response to utility tariffs or dynamic pricing, with the gateway accessing real-time and forecasted grid data to minimize utility bill and CO2 emissions (CEC 2026). Battery operation is paired with heavy loads like induction stoves to avoid upgrading electrical services. Depending on battery capacity and the load distribution across periods, the battery discharges primarily during on-peak hours and can extend into part-peak periods.

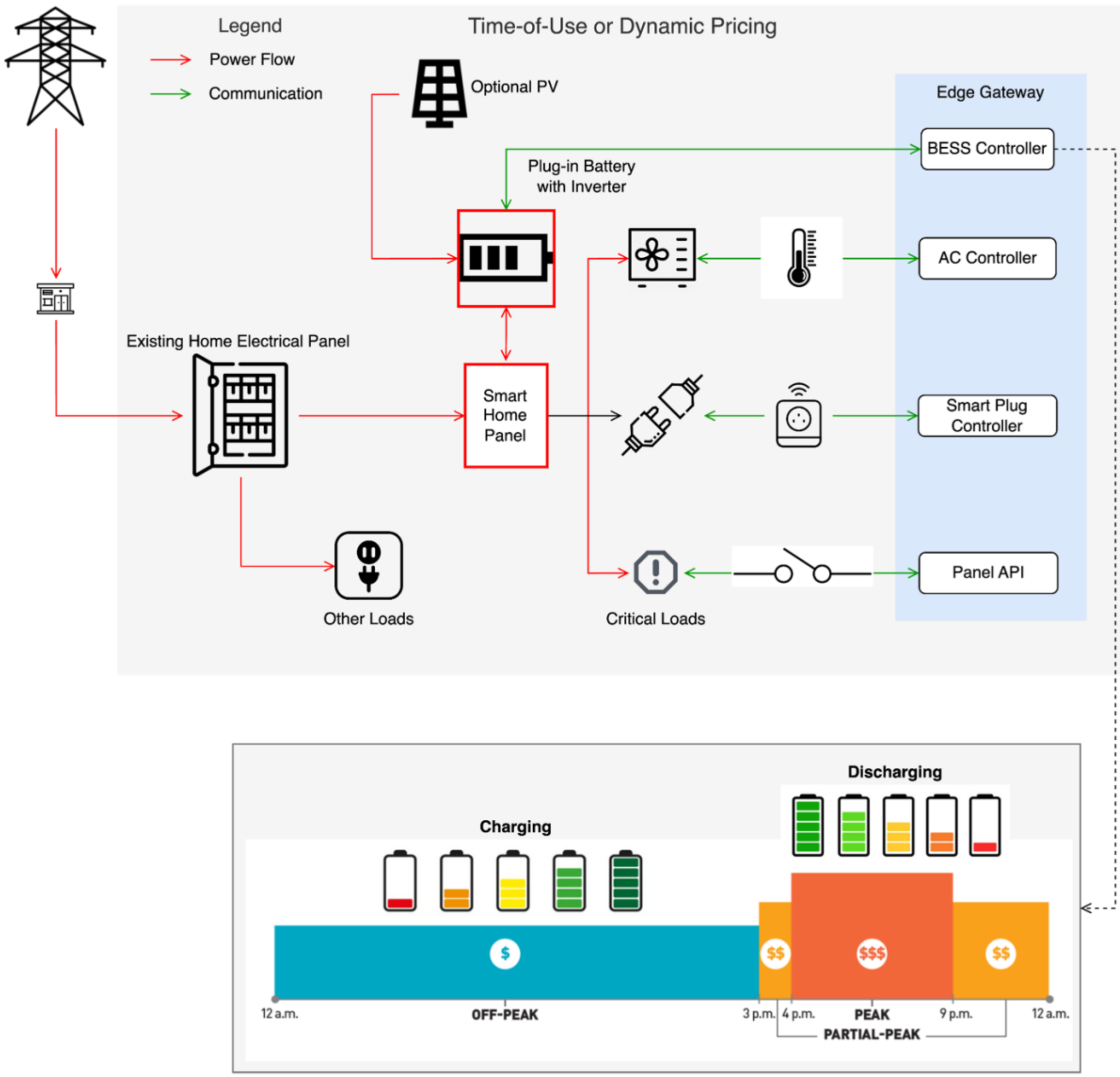

Figure 3. Conceptual diagram of off-grid operation of smart home panel with plug-in batteries, building flexible loads, and interruptible circuit loads

Use Case #3: Grid Resilience

Figure 4 details off-grid operation during power outages, where the panel automatically switches to off-grid mode and powers critical circuits with batteries (optionally supplemented by solar PV), managing energy consumption by lowering power usage of flexible loads (e.g., raise the thermostat setpoint of the air-conditioning unit). The testing determines the longest off-grid time the system can withstand.

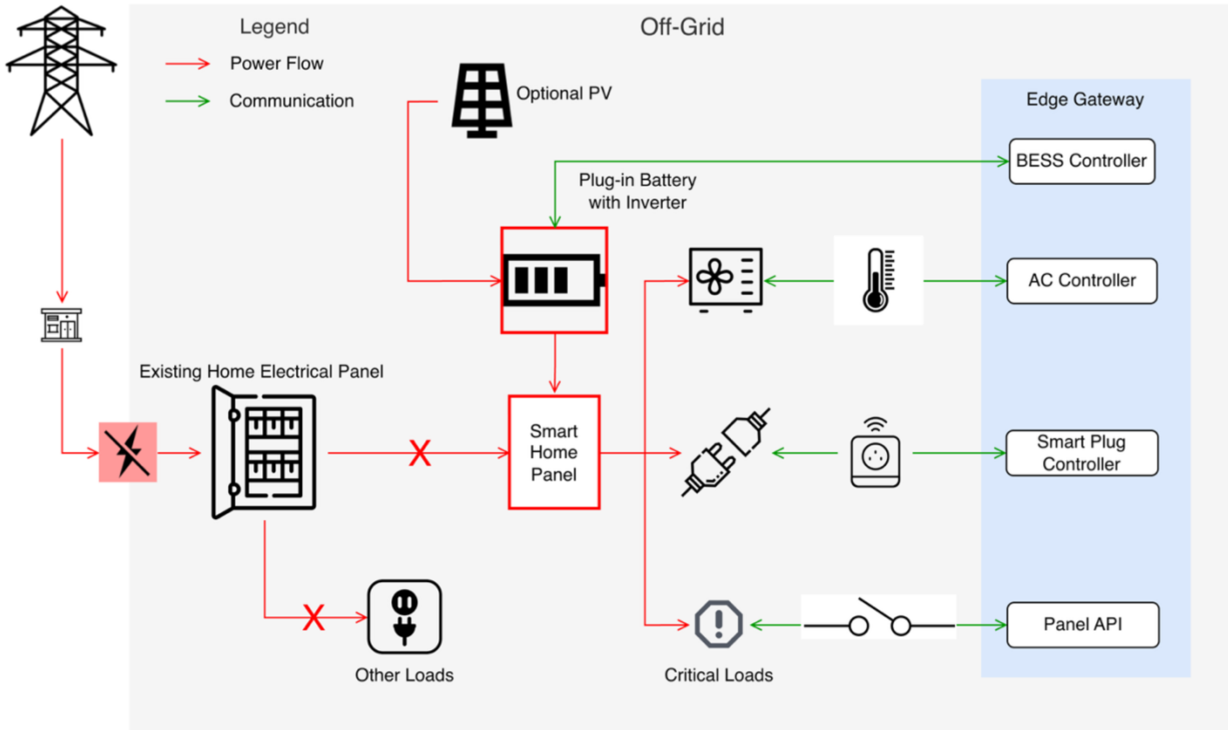

Figure 4. Conceptual diagram of off-grid operation of smart home panel with plug-in batteries, building flexible loads, and interruptible circuit loads

Site Demonstration

Since January 2026, the project team has been demonstrating this solution at two multifamily apartment sites in northern California (California Climate Zone 1), as shown in Figure 5. The project team installed above-described equipment (smart home panel with modular batteries), edge-computing gateways with built-in control algorithms, and retrofitted heat pumps, induction stoves, and electric dryers, to demonstrate and validate the solution. Testing has been conducted on a range of units at each location clustered in buildings where possible – two 1BR units and a building of four 4BR units at Arcata, CA, and a building of three 2BR and three 3BR units at Willow Creek, CA.

Figure 5. Site demonstration at The Courtyards at Arcata (left) and The Willow Creek Apartments (right)

Circuit Load Priorities

By June 2026, load priority data were collected through on-site engagement with tenants at five apartment units – as part of the smart home panel deployment in this project. Each tenant ranked home loads into four tiers – Critical, Essential, Moderate, and Non-Essential — to define which circuits should be sustained by the plug-in battery system during grid outage events or demand response dispatch periods. The results indicate a strong consensus on core critical and essential loads, with mixed priority for HVAC and health-specific appliances. Table 2 summarizes residential load priorities across all surveyed units as follows:

- Tier 1 – Critical Loads. Refrigerator and freezer were the top-ranked loads in every unit, driven by food safety concerns. Two units also include an additional standalone freezer (hallway and dining room, respectively), which inherit the same Critical tier. Wi-Fi router and modem was designated Critical by all units due to its role as the communications (access utility alerts, contact emergency services, and coordinate with family) during emergencies. Essential lighting was Critical in all units, though the specific circuit varied. This load is very low-wattage and supports all other in-unit activities during an outage. Cell phone and laptop charging was universally ranked Critical for emergency communication. These devices often share a circuit with the Wi-Fi router and few small plug loads.
- Tier 2 – Essential Loads (Common across most units). Electric water heater was rated Essential in all units, with two units noting "limited use" as intermittent or scheduled operation during an outage. Microwave and small cooking appliances were rated Critical in most units.
- Tier 3 – Unit-Specific Loads. Clothes washer and dryer (high-draw appliances) was rated Essential in one unit, and most units consider air-drying as acceptable solution. HEPA air filter was rated Critical for one unit with occupant respiratory needs. Entertainment devices were labeled as critical/essential for 2 units and non-essential for 3 units.
- Tier 4 – Non-Essential Loads. Electric oven and stove, dishwasher, and non-essential lighting were rated non-essential by most or all tenants. Small appliances were preferred over high power draw appliances to extend the power backup hours using the battery.

Table 2. Residential load priorities for load management

Load Category	Selection Rate (# of units)	Consensus Priority Tier	Notes
Critical – All 5 units			
Refrigerator & Freezer	100%	★ Critical	Prevent food spoilage; food safety risk during extended outage.
Wi-Fi Router & Modem	100%	★ Critical	Maintain emergency communication.
Essential Lighting (kitchen/living room)	100%	★ Critical	Basic habitability and safety; supports all in-unit activities.

Cell Phone & Laptop Charging	100%	★ Critical	Emergency communication; often shares circuit with Wi-Fi router.
Essential – majority of units			
Electric Water Heater	100%	◆ Essential	Noted as "limited use" – intermittent/scheduled operation acceptable.
Microwave / Small Cooking Appliances	80%	◆ Essential	Basic food preparation during outage; preferred over full oven/stove.
Additional Freezer (where present)	60%	★ Critical (if present)	Prevent food spoilage for units with supplemental freezer.
Unit-Specific or Mixed Priority			
HVAC	60%	◇ Mixed	Thermal resilience for occupants with comfort sensitivity.
HEPA Air Filter / Air Purifier	20%	★ Critical (one unit only)	Health and indoor air quality for occupant with respiratory needs.
Clothes Washer / Dryer	20%	◆ Essential (one unit only)	In-unit laundry access requested by tenant.
Essential Outlets – Bedroom (circuit)	50%	◆ Essential (circuit-based)	General-purpose charging and device access via bedroom circuit.
Entertainment Devices (TV, etc.)	20%	◇ Mixed	Non-essential for 3, critical/essential for 2 units
Non-Essential – Most or all units			
Electric Oven & Stove	20%	○ Non-Essential	High power draw; small appliances preferred by 4 of 5 units.
Dishwasher	0%	○ Non-Essential	Low urgency; hand-washing acceptable during outage.
Non-Essential Lighting & Decorative Fixtures	0%	○ Non-Essential	Supplemental; no safety function.

Figure 6 presents the per-tier peak power for the three load-priority tiers across the five apartment units. The values shown are non-coincident sums: each tier's total demand is the sum of the peak power of its labeled circuits, which do not occur simultaneously. The aggregate peak ranged from approximately 10.2 kW (Unit #5) to 15.4 kW (Unit #2). The coincident peak monitored at each unit's service panel is substantially lower than this non-coincident power due to temporal diversity among circuits. During an outage, the battery operates in EPS (emergency power supply) mode. Its 7.2 kW output per battery inverter covers each unit's critical-tier peak, and the stored energy sustains the critical load for at least three hours in Units #1 and #3, and one to two hours in Unit #2 (whose critical peak is roughly double). Because critical loads draw their peak only intermittently, realized backup duration is typically longer.

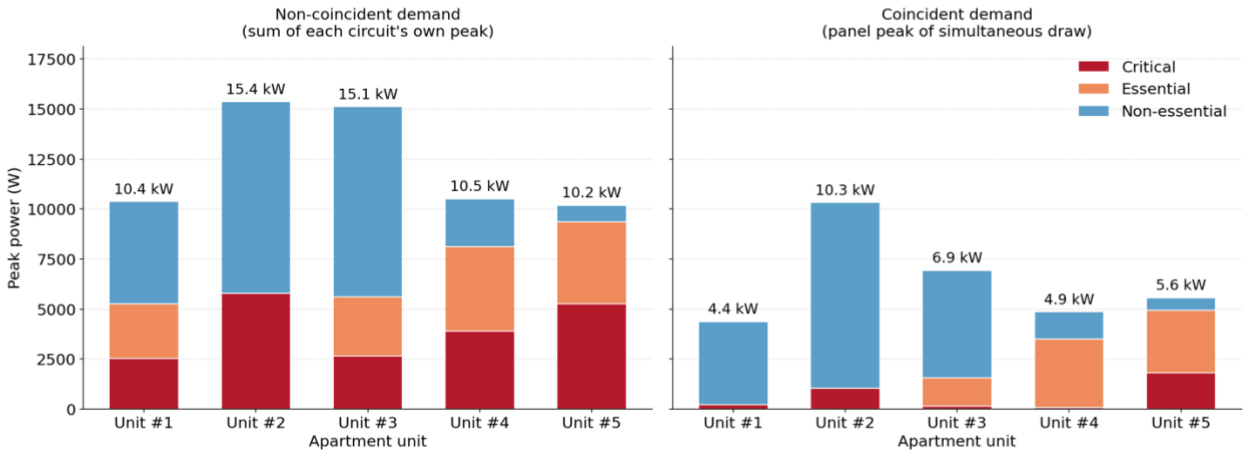

Figure 6. Circuit peak power non-coincident demand (left) and coincident demand (right)

Example Apartment Unit

Figure 7 shows the retrofit configuration in which the existing 100A, 240V single-phase electrical panel is replaced with a 100A, 240V single-phase EcoFlow panel. All new and existing circuits were reconnected to the EcoFlow panel. By the National Electrical Code (NEC) for energy storage systems, batteries and inverters were installed in an enclosure with a power connection box to the smart home panel inside the apartment.

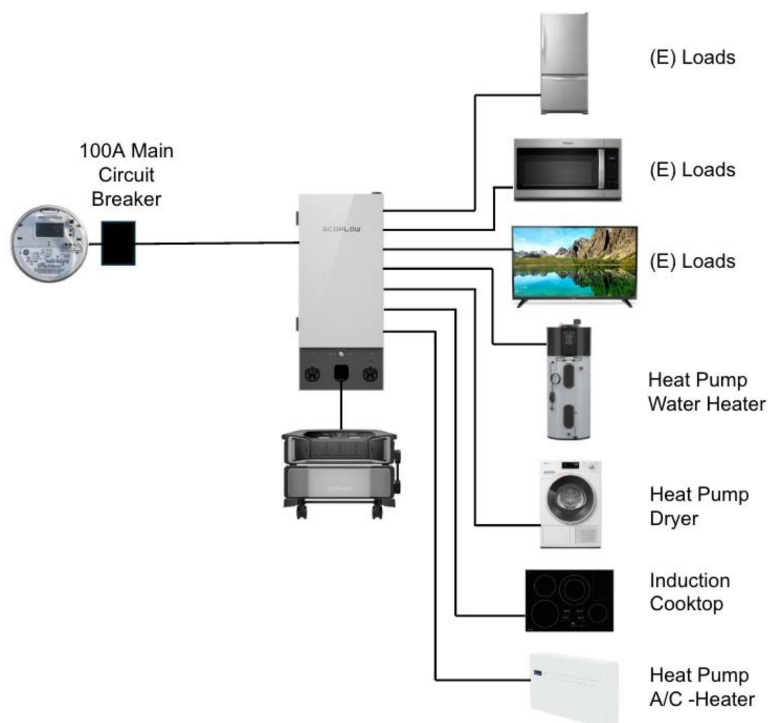

Figure 7. Design configuration #1 - 240V, 1 ph., 100A service, installed new smart home panel, and plug-in batteries (inverter and batteries installed in an enclosure)

Operation and Benefit Analysis

As of June 2026, the testing unit had experienced only one real power outage event. Testing is ongoing, and we will conduct controlled outage experiments onsite through the summer of 2026.

We evaluated the backup duration that the installed 6-kWh battery operating in EPS (island) mode provides to each unit's critical and essential loads, assuming the battery is fully charged at the outage onset and a 95% discharge efficiency. Critical and essential circuits were considered under two demand cases: an “average-load” case using each unit's mean aggregate load, and a “worse case” driven by the measured time-series load on the unit's peak-consumption day (the local day with the highest energy use of the corresponding circuits. Using the peak-day profile rather than an instantaneous peak yields a physically realistic worst case in which demand remains within the inverter rating capacity 7.2 kW. Under the average-load case the critical tier is sustained for 21–71 h across the six units (median ≈ 2.5 days), decreasing to 5–59 h once essential loads are added. On the peak day, critical-tier circuits can be sustained over 10–49 h and critical + essential is 2–44 h (Figure 8). The average-to-peak-day reduction is largest for HVAC-dominated units: Unit #5, whose peak-day essential demand averages ≈3.2 kW of near-continuous air conditioning, sustains only 2.0 h of combined critical + essential backup versus 17 h for its critical tier alone, whereas units with no essential load on record (Unit #2) are unaffected by tier. Note that every unit retains at least 10 h of critical-load backup even on its worst day—and most exceed a full day.

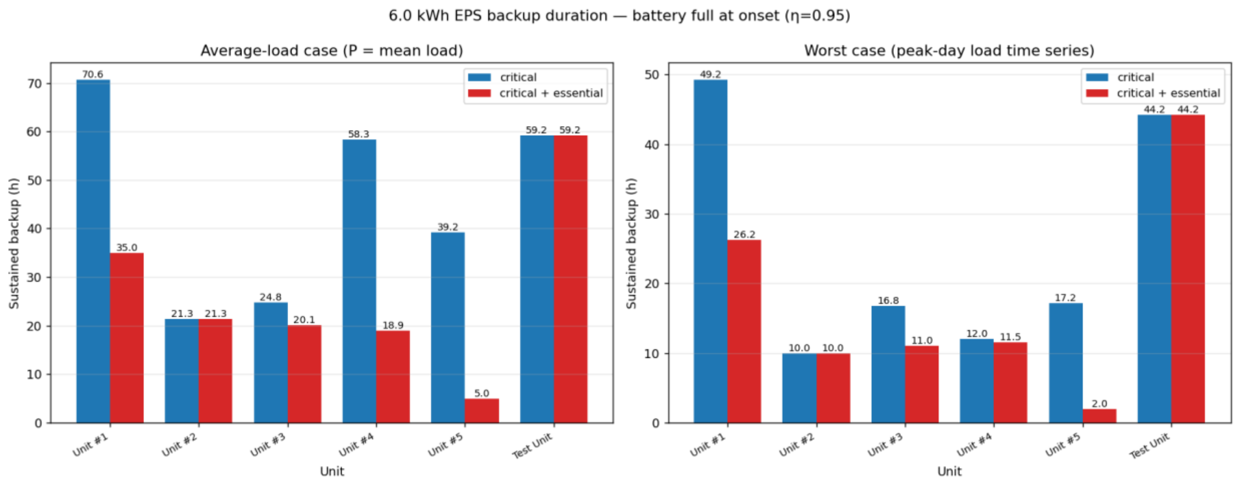

Figure 8. Probability of Surviving Grid Outage with Outage of Different Durations

Direct benefits to customers include reduced smart home panel installation costs incurred from electrician's billed labor hours from 8-12 hours to 4 hours. On the other hand, modular plug-in batteries feature a plug-and-play design that does not require additional labor hours. The proposed solution could save approximately $942 per installation of one set of smart home panels and batteries. This compares to a typical 5-kW/12.5-kWh battery storage system, which provides about 2.5 hours of backup at rated power. Beyond resilience, the system delivers energy-arbitrage savings under the time-of-use (TOU) rate and sustains critical loads during outages through the plug-in battery storage. During the 4–9 p.m. on-peak window, the on-peak energy use of these units ranges from 3.06 to 10.25 kWh. For a 6-kWh battery, shifting that consumption out of the on-peak window yields an estimated utility-bill savings of $6 to $12 per month. Figure 9 depicts battery dispatch operation at TOU mode during a representative week.

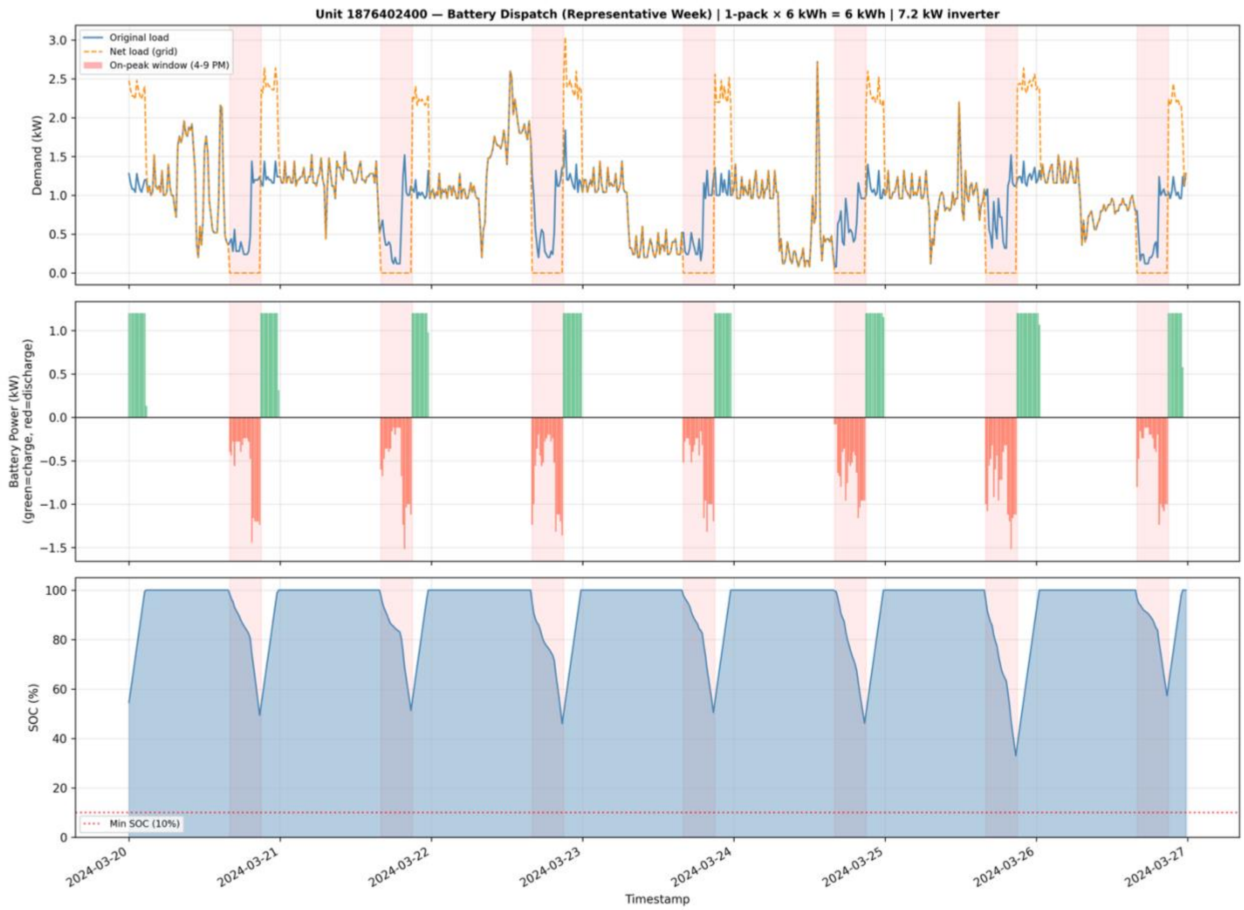

Figure 9. Battery dispatch operations during a representative week

Conclusions

Costs for upgrades to electrical panels and wiring to support additional electric appliances can be prohibitive and cause owners to continue using gas-fueled appliances. The cost of the upgrades necessary for electrification retrofits is a barrier if the owner or tenant carries the cost. Multifamily buildings may require utility service upgrades to power lines and transformers in areas where distribution infrastructure is inadequate to serve the building's increased demand. This can be expensive if the property owners are required to cover the costs of service upgrades themselves, increasing costs by thousands of dollars per apartment unit. Affordable housing complexes operate on tight budgets, meaning electrification upgrades can be prohibitively expensive. This study demonstrated an innovative solution: an integrated smart home panel and modular plug-in battery system, coordinated by a central controller, that adds capacity and resilience behind the meter without service or panel upgrades. The solution has been deployed since January 2026 at two northern California affordable housing sites.

Preliminary analysis yielded several quantitative results. The smart panel cut electrician-billed installation labor from 8–12 hours to about 4 hours, and the plug-and-play batteries added none, saving roughly $942 per installed set. Tenant surveys showed strong consensus on the loads that must ride through an outage — refrigeration, Wi-Fi, essential lighting, and device charging were ranked Critical by every household — while HVAC and health-specific appliances varied by unit. A single 7.2 kW inverter covered each unit's critical-tier peak, and a fully charged 6-kWh battery in EPS mode sustained critical loads for 21–71 hours under average demand (median ≈ 2.5 days) and at least 10 hours even on each unit's worst-case day. Shifting the 4–9 p.m. on-peak energy (3.06–10.25 kWh per unit) off-peak saved an estimated $12–24 per kWh of installed capacity per year. These results show that modular behind-the-meter storage paired with circuit-level smart-panel control can enable electrification while delivering outage resilience, peak-demand management, and TOU bill savings – a combination especially valuable for the low-income, rural, and disadvantaged communities most exposed to PSPS and weather-driven outages. Field testing is underway across three scenarios — load and capacity management, time-of-use operation, solar PV integration, demand response, and power outage. Future demonstration will quantify grid-services revenue and extend the solution across additional units to assess scalability and aggregate grid impact.

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