Laboratory Evaluation of Residential Smart Panels

Final Report

ET24SWE0039

Prepared by:

Keith Graeber PE CLTC

Andrew Harper PE CLTC

Jonathan Bryant EIT CLTC

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Acknowledgements

The research team gratefully acknowledges the contributions of VEIC, who led the market research and stakeholder engagement activities, including outreach to electrical contractors, installers and local city inspectors. Their work provided valuable insights into the market readiness of smart panel technologies and the opportunities and barriers to broader adoption.

Abbreviations and Acronyms

Acronym	Meaning
AC	Alternating current
A	Amp
CCT	Correlated color temperature
CLTC	California Lighting Technology Center
CT	Current transformer
kW	Kilowatt
M&V	Measurement and verification
OEM	Original equipment manufacturer
SUA	Service upgrade avoidance
TBD	To be determined
UL	Underwriters Laboratories
VEIC	Vermont Energy Investment Corporation
W	Watt

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Executive Summary

The transition to widespread building electrification has revealed a critical infrastructure barrier: many residential homes lack sufficient electrical service capacity to support high-demand electric appliances such as heat pumps, electric vehicle chargers, and electric dryers. Conventional service upgrades are costly, complex, and often inaccessible to homeowners. Smart electrical panels provide an alternative pathway by dynamically managing circuit-level loads to prevent overcurrent conditions and defer upgrades.

This final report presents the results of laboratory testing and stakeholder engagement conducted by the California Lighting Technology Center at the University of California, Davis in collaboration with Vermont Energy Investment Corporation. The research team evaluated three commercially available systems, each representing a distinct architecture: a full smart panel replacement with integrated intelligent breakers, a downstream relay-based smart subpanel, and a retrofit system using smart breakers. All three demonstrated the ability to limit current draw below breaker trip levels and confirm the technical feasibility of service upgrade avoidance. The panel replacement system employed adaptive overload-dependent response times and staggered recovery logic, reducing nuisance cycling while maintaining protective function. The smart subpanel operated with strict adherence to its defined threshold and rapid shedding at approximately four seconds, but used fixed re-enable timers that produced more frequent cycling under sustained overloads. The smart breaker system relied on user-defined operating “scenes,” providing limited autonomous protection and depending heavily on accurate configuration.

Across all systems, energy reporting proved accurate, within five watts of laboratory reference meters. This level of precision is sufficient for household decision-making but not revenue-grade. Advanced features commonly referenced in product literature—including demand response, time-of-use optimization, and carbon intensity integration—were either minimally functional or dependent on third-party smart home platforms, underscoring that much of the claimed functionality remains under development.

Engagement with contractors, utility program managers, and building inspectors revealed that barriers to adoption extend beyond technical performance. Inspectors and officials reported limited familiarity with smart panel behavior, a lack of standardized training, and insufficient transparency into software-driven load management. Contractors highlighted high upfront costs, specialized certification requirements, and workforce shortages as limiting factors. Despite these challenges, stakeholders expressed broad support for the potential of smart panels to enable electrification without costly service upgrades, particularly as electrification pressures grow across the housing stock.

The results of this study confirm that smart electrical panels are technically capable of providing service upgrade avoidance while delivering accurate energy monitoring and basic scheduling.

Introduction

California's transition to widespread building electrification is accelerating, yet one of the largest infrastructure barriers remains: the limited electrical service capacity of existing housing stock. Many single-family homes were constructed with 100–125 A service panels, leaving insufficient headroom for the simultaneous operation of high-demand electric loads such as heat pump heating, ventilation, and air-conditioning (HVAC) systems, heat pump water heaters, electric vehicle (EV) chargers, and electric ranges. Conventional service upgrades are often expensive, time-consuming, and constrained by utility or site conditions. This reality creates an equity challenge for households unable to bear the costs of expanded service.

This report presents findings from the laboratory evaluation of residential smart panels. This study, carried out by the California Lighting Technology Center (CLTC) in collaboration with Vermont Energy Investment Corporation (VEIC), aims to assess the capabilities, integration opportunities, and market potential of commercially available smart panels.

VEIC conducted a market assessment in a previous effort, *Market Study of Household Electric Infrastructure Upgrade Alternatives for Electrification*, that provided the CLTC team with a foundational overview of products currently available in the market.

CLTC conducted an independent market assessment through web-based searches, direct communication with product distributors, and extensive engagement with manufacturers (Table 1). This effort identified multiple classes of smart panel technologies that provide similar core functionalities via distinct architectures:

- **Smart panels:** Full replacements for standard electrical panels, offering integrated monitoring and control.
- **Smart sub-panels:** Installed downstream from a traditional panel, these systems monitor and control circuits via integrated relays.
- **Smart breakers:** Retrofitted into existing panels, these replace conventional breakers and add metering and control capabilities.

Table 1: Summary of smart panel technologies evaluated.

System	Controllable Circuits	Supply Voltage	Max Current	Reaction Time
Smart panel	32 per panel	240V	200A	Variable
Smart sub-panel	12 per panel	240V	6*50A 6*20A	4 seconds
Smart breaker	Panel dependent	240V and 208V	60A 30A	N/A

Across all categories, one core feature of interest was the ability to meter total panel load and autonomously reduce circuit loads when preset limits are approached. This functionality requires compliance with the UL 3141 safety certification. The research team identified several products in each category, but most lacked UL 3141 certification—rendering them currently unsuitable for service upgrade avoidance applications. The research team ultimately selected one representative product from each subcategory that met UL requirements and included the necessary control and monitoring features.

To support testing, the research team prepared a dedicated laboratory space at CLTC with adequate electrical infrastructure to sufficiently load the panels being evaluated. This report presents the preliminary findings from tests performed on the first of three selected systems.

In parallel with laboratory testing, the project team conducted stakeholder engagement to assess market readiness, technical understanding, and adoption barriers for smart electrical panels. This included a content analysis of prior interviews with manufacturers, utility personnel, and contractors conducted for the 2023 *Market Study of Household Electric Infrastructure Upgrade Alternatives for Electrification*. Findings from these engagements highlight common knowledge gaps, particularly around smart panel software, access protocols, and training needs. Collectively, this engagement effort informs key challenges and opportunities for smart panel adoption across utility, installation, and inspection stakeholders, and supports the evaluation of their potential to enable safe, cost-effective electrification.

Objectives

The primary objectives of this study are to:

- Assess the ability of smart panel technology to enhance energy efficiency in residential single-family homes
- Evaluate the capability of smart panels to enable electrification while maintaining safety and reliability under overload conditions, thereby mitigating expensive service upgrades
- Identify market barriers to adoption and explore potential incentives or regulatory mechanisms to increase deployment
- Determine the potential statewide impact on energy usage and electrification

Methodology

Market Assessment

The research team conducted a market assessment to identify commercially available smart panel products, compare their technical specifications, and evaluate the current state of publicly available research and analysis on the technology. This assessment supports the selection of representative products for laboratory testing and highlights key product features relevant to service upgrade avoidance and load management.

The research team identified seven products through web-based searches and manufacturer communications. These include full panel replacements, downstream relay-based controllers, and smart breaker-based retrofits. While all provide some level of circuit-level monitoring or control, not all meet the definition of a "smart panel," which requires integrated control, monitoring, and automated load management functionality.

SP is a fully integrated smart panel system, replacing the existing service panel with a 100–200A NEMA 3R-rated unit capable of managing up to 32 controllable circuits. It includes compatibility with several battery systems and features comprehensive energy monitoring and remote circuit prioritization.

SSP is a downstream solution that adds relay-based control to up to 12 circuits on an existing panel, supporting circuits up to 60A. It is compatible with major battery systems and supports automated load shedding and scheduling without panel replacement.

SB uses relay modules installed in existing panels, offering selective control over specific circuits (e.g., 20A, 30A, or 60A) and real-time current monitoring via its Current Track Module. The system is designed for incremental retrofits rather than full-panel replacements.

Selected Technologies

The market assessment led to the selection of three technologies, each claiming to mitigate the need for residential service upgrades: all-in-one smart panel solutions, downstream smart sub panel solutions, and smart circuit breaker retrofits.

Smart Panel

All-in-one smart panel solutions replace standard residential panels with an integrated, relay-controlled panel (Figure 1). This equipment takes the place of the existing panel and consolidates both distribution and active load management. For this evaluation, the project team chose SP, which offers 32 controllable circuits and a 200 A maximum amperage rating.

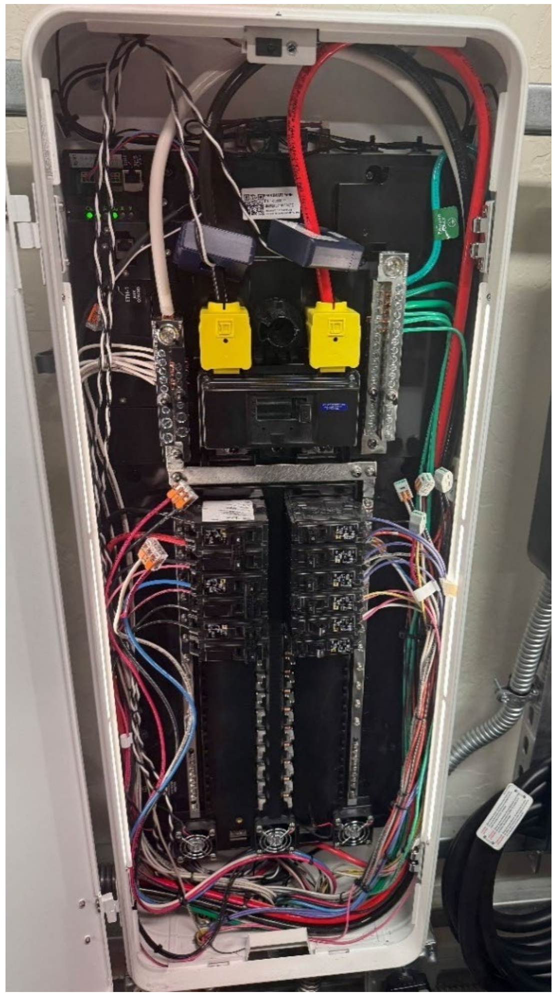

Figure 1: Image of SP with panel door open.

SP integrates traditional load center functionality with embedded electronics that enable real-time monitoring and control of individual circuits. Each circuit can be toggled on or off either manually through the SP mobile application or automatically based on user-defined priority rules.

One key feature is service upgrade avoidance enabled through load monitoring and automatic load shutoff. The panel continuously monitors total current draw from the grid to the panel and can temporarily disconnect lower-priority circuits when a preset threshold is exceeded. This allows for the addition of high-demand loads, such as EV chargers, without requiring an upgrade to the main electrical service. The panel also provides circuit-level energy monitoring through built-in metering that delivers accurate, real-time power usage data. Users can view historical consumption trends via the SP interface, identify energy-intensive loads, and optimize their usage patterns accordingly.

In systems with backup power sources such as batteries or generators, SP enables dynamic circuit prioritization during outages. Users can designate circuits as essential or non-essential, allowing the panel to manage load shedding in a way that maximizes the runtime of the backup system. Remote system management is facilitated through the SP app, available for iOS and Android. The app provides remote access to circuit control and monitoring functions and supports integration with select smart home platforms for voice commands, scheduling, and event-driven load management. The panel's internet connectivity also supports over-the-air software updates and continuous performance monitoring.

Smart Subpanel

In this study, the project team selected SSP as the representative smart subpanel device. It is installed downstream of the home's existing electrical panel and requires no modifications to the original load center (Figure 2). The system uses internal relays to automatically control power delivery to individual circuits, allowing for dynamic on/off switching based on predefined logic or external control. Current transformers (CTs) are integrated on each circuit to provide real-time monitoring of individual load power draw, and an additional CT set measures total panel power consumption for coordinated load management. SSP supports six circuits at 60 A and six circuits at 30 A. These values are derated to 50 A and 20 A, respectively, when ambient temperatures exceed 50°C.

Figure 2: Exposed SSP showing the internal relays.

SSP includes an automatic load management feature that can enable service upgrade avoidance by dynamically controlling circuit-level loads. It continuously monitors current draw on each circuit and the total panel load, using prioritization logic to shed lower-priority circuits when necessary. This ensures that total current remains within residential service limits during periods of high demand. Its retrofit-friendly design allows installation downstream of the existing service panel, with individual branch circuits routed through internal relays. This configuration supports both manual and automated switching of high-demand or critical loads via a mobile or web-based interface.

SSP also stores historical consumption data, allowing users to analyze usage patterns over time. This platform also supports advanced automation features. Users can define operating schedules and load-shedding behavior tailored to different scenarios, such as time-of-use pricing or backup power operation. SSP also integrates with many residential battery systems, dynamically controlling circuits based on the battery's state of charge or grid availability.

Smart Breakers

Smart breakers were selected as the third and final technology to be evaluated. The representative smart breaker, SB, integrates smart circuit breakers and a central controller directly into an existing electrical panel, avoiding the need for additional subpanels. The installation requires compatibility between the existing panel and SB's breaker form factor, but allows homeowners to selectively replace only the breakers controlling significant loads. SB offers 240 V/30 A modules, 240 V/60 A modules, and a dual-relay module that supports two independent 120 V/20 A circuits. SB continuously monitors total current draw at the panel and dynamically adjusts circuit states to prevent the total from exceeding the service rating.

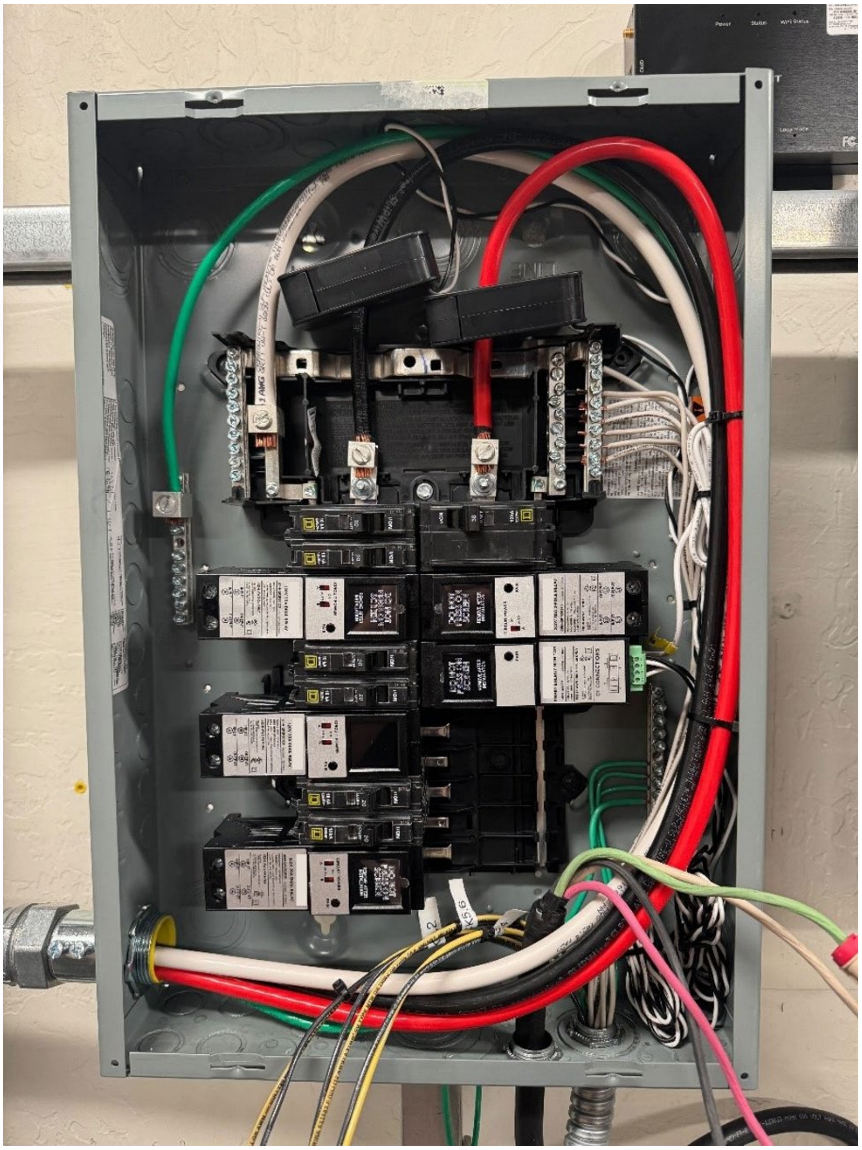

Figure 3: Exposed view on SB inside a generic panel.

SB's architecture supports a modular retrofit approach, enabling gradual upgrades on a per-circuit basis (Figure 3). Smart breakers, or breaker-mounted relay modules, are installed in standard breaker slots and are compatible with common breaker from major manufacturers. A dedicated central controller communicates wirelessly with each smart breaker, coordinating circuit-level monitoring and control. This controller manages automated load shedding and serves as the central interface for remote configuration.

SB includes a service upgrade avoidance feature, allowing users to define total service amperage limits and establish prioritization rules for circuit disconnection during peak demand. Automation can also be configured based on time-of-use rates or backup power scenarios. Real-time monitoring, historical usage data, and alerts are accessible through the SB mobile application. The platform also integrates with SB's broader smart home ecosystem, enabling advanced features such as scene-based control and voice-activated commands.

Lab Setup and Test Equipment

The project team collected electrical measurements using two Xitron XT2640-AH and one Xitron 2802 power analyzers (Figure 4). The two XT2640 units provided a total of eight channels. The project team assigned six channels to monitor individual 120 V branch circuits, while the remaining two channels measured current and voltage on each leg of the 240 V circuit supplying the electric dryer. The Xitron 2802 was used to meter input power from the simulated grid connection to the smart panel, capturing voltage and current on both service conductors. Data from the XT2640 units were logged to external USB drives, while the 2802 streamed data to a PC-based acquisition system.

Figure 4: Metering equipment- Xitron 2802 (top) and the two Xitron XT2640AH (bottom)

The lab infrastructure used to simulate a grid connection provided 208 V service, while the smart panel systems under test required 240 V (Figure 5). To accommodate this, the project team installed a 208 V to 240 V step-up transformer installed to simulate the appropriate grid source. The transformer's 240 V output supplied a distribution panel configured with dedicated 125A circuits for each smart panel system. Each system could be independently energized for controlled evaluation by turn on its corresponding breaker in the distribution panel.

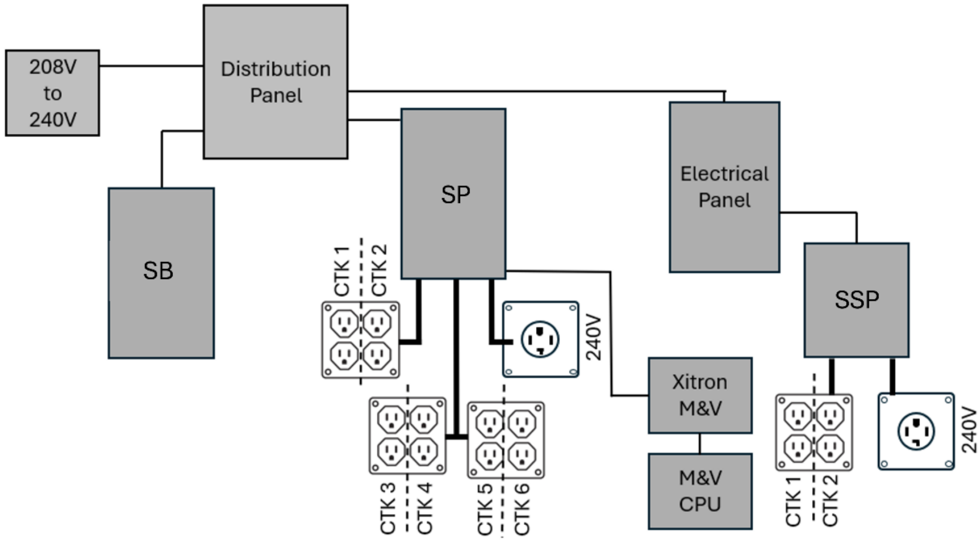

Figure 5: Illustrated diagram of electrical infrastructure supporting test procedures.

The project team used three types of loads to evaluate smart panel performance under varying current and power conditions. A Samsung electric dryer was connected to the 240 V circuit, drawing between 0.2 A and 30 A depending on operational state. Six resistive space heaters were distributed across the 120 V circuits, each drawing between 2 A and 12 A depending on thermostat state and internal cycling.

The team selected these loads to represent a realistic cross-section of residential demand profiles and enable detailed evaluation of circuit-level switching, prioritization logic, and system responsiveness under peak load conditions (Table 2).

Table 2: Summary table of smart panel loads.

Description	Min Current	Max Current	Input Voltage	Load Type
Dryer	0.2A	30A	240V	Resistive
Heater	2A	12A	120V	Resistive
Lighting	0A	10A	120V	Nonlinear, Capacitive

Service Upgrade Avoidance Feature Testing

The team developed a testing protocol to evaluate each system's performance under amperage overload conditions relative to the predefined current limit threshold (Figure 6). The protocol involves intentionally drawing current in excess of the system's max amperage threshold, with overload levels set at 5 percent, 10 percent, 15 percent, 20 percent, 22.5 percent, 25 percent and 100 percent above the max amperage limit. At each overload level, the system's response is monitored to determine whether circuits are shed and how quickly the system reacts. Key metrics include the activation of load-shedding mechanisms and the time required to execute corrective actions.

Figure 6: Smart panels lab setup, including test loads, measurement and verification system, and panel infrastructure.

The objective of these tests was to measure and quantify each system's response to overload conditions, specifically when total current draw exceeded the system's predefined maximum amperage threshold. To achieve this, the team energized loads sequentially, allowing sufficient time for each to stabilize before the next was added. The team determined stabilization times through preliminary testing, found to be less than one minute for all devices. Most loads exhibited steady-state behavior with minimal variation after being energized. The only exception was the electric dryer, which demonstrated a brief period of elevated power draw immediately following energization before settling to a stable operating level. The team designed each test to incrementally exceed the system's derated current limit by a specified percentage. Once the target overload level was reached, the team observed the system to assess its response. Key metrics included whether protective or load-shedding mechanisms were triggered and the time required for the system to take action.

In addition to overload initiation tests, the team evaluated reenergization behavior to determine how each panel decided when to restore previously shed loads. The team tested two scenarios:

- Passive wait test: After an overload event and subsequent load-shedding, the team made no changes to the active loads for up to one hour to see if the system would autonomously reenergize the disconnected circuit. If it did, the total load would again exceed the threshold.
- Step-down load test: After a load-shed event, the team reduced the total load in fixed increments to approach three conditions:
    - Still above threshold after reenergization
    - Exactly at threshold after reenergization
    - Below threshold after reenergization

These tests were designed to determine whether reenergization logic was time-based (e.g., a fixed delay before retry) or load-margin-based (e.g., waiting until enough headroom exists to restore the load without causing another overcurrent condition).

Results

User Interface and Setup Assessment

Upon delivery, the team installed each system at the CLTC and connected them to a facility sub-panel configured to emulate a typical residential electrical service in terms of capacity. The team followed manufacturer specifications for installation procedures. All three systems require two separate software interfaces: one for professional commissioning and another for end-user operation. Each offers distinct applications for installers and homeowners, enabling structured setup and ongoing control.

SP Installation and Applications

Installation of SP requires full replacement of the existing main breaker panel, typically a 200 A load center. During installation, all branch circuits are rerouted into the SP enclosure, and incoming service conductors are terminated at the integrated SP main breaker. The installation process is intended to be carried out by a SP-certified electrical installer. Certification requires registration with SP and completion of a web-based installation training course that covers hardware setup, configuration procedures, and safety requirements.

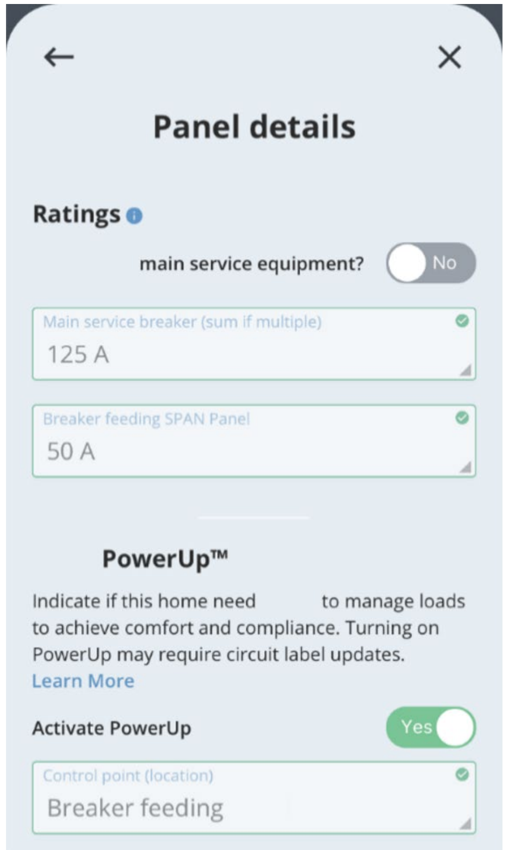

Figure 7: Screenshot from SP installer application, depicting amperage limit set screen.

The SP installer app is used exclusively by certified installers during commissioning. It provides tools to label circuits, verify electrical and network connectivity, and configure any integrated solar or battery systems. Critically, it also allows the installer to define the panel's maximum allowable current threshold—a parameter that governs overload protection behavior. This current limit setting is not accessible through the user-facing interface and is intended to be configured only during initial setup (Figure 7).

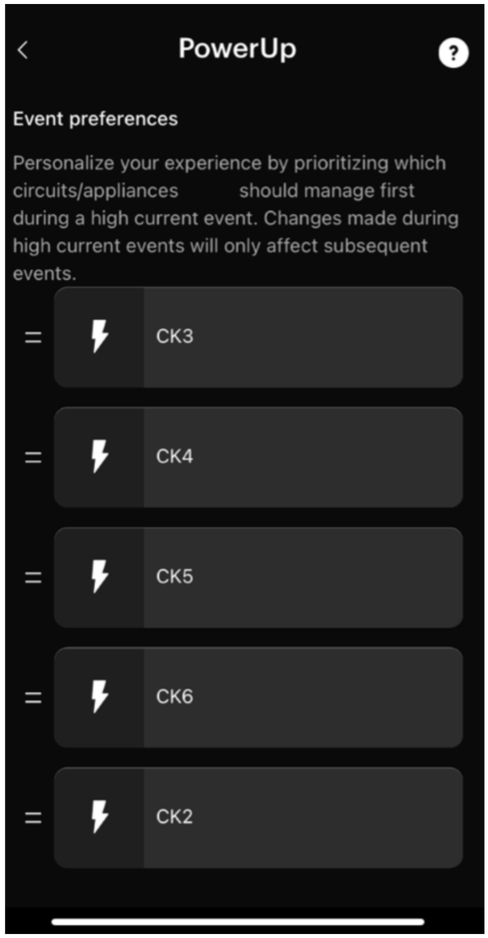

Figure 8: SP user application, depicting arrangement of circuit preferences in the event of service upgrade avoidance mediation.

Homeowners interact with the system via the SP app, a separate application designed specifically for end users. This app enables remote circuit control, real-time monitoring, scheduling, and load prioritization. Users can define which circuits should remain energized during an overload event, but they cannot modify the system's maximum current threshold (Figure 8). The separation of installer and user functionality ensures that key system protection parameters are controlled solely by qualified personnel, while still providing homeowners with full access to everyday control and energy management features.

SSP Installation and Applications

SSP preserves the home's existing main panel and introduces an in-line relay enclosure installed downstream. Selected branch circuits are physically routed through the SSP enclosure, which contains relay channels and integrated current sensors. This approach allows individual circuits to be remotely controlled and monitored without replacing the primary load center.

Installation must be performed by a SSP-certified installer. Certification requires registration with SSP and successful completion of an online training course covering hardware integration, electrical configuration, and system commissioning procedures. The installation process is carried out using a web-based or mobile installer interface, which allows the technician to assign relay channels to specific circuits, verify electrical operation, and configure system parameters including breaker associations and control logic.

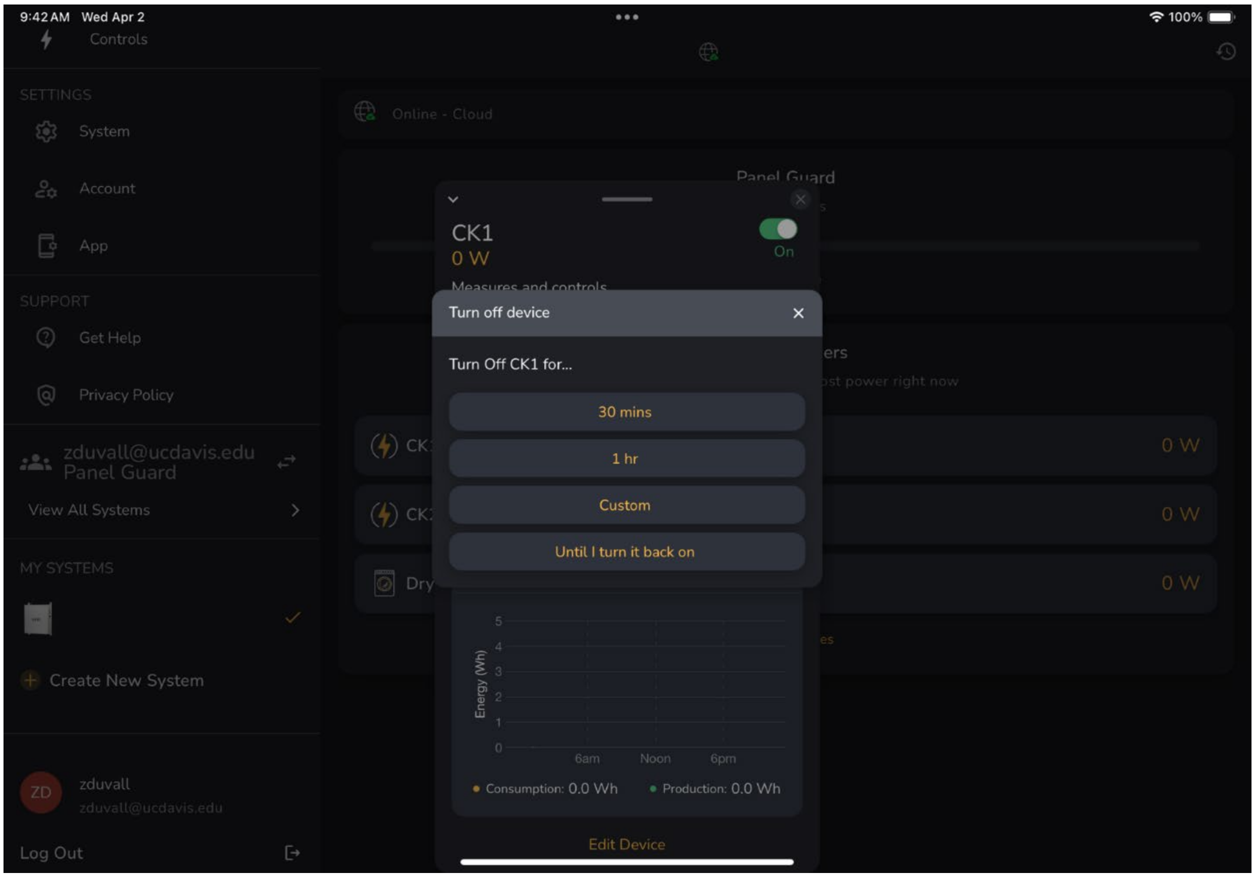

Figure 9: SSP application on iPad, showing remote circuit control and timing capabilities.

SSP provides two separate applications: one for certified installers and another for end users. The installer interface is used exclusively during setup and commissioning and grants access to protected configuration settings. The end-user application, available on iOS and Android platforms, enables homeowners to monitor real-time power usage, schedule circuit operation, toggle individual circuits, and apply load automation rules (Figure 9). Users can remotely disable circuits for predefined durations and view detailed circuit-level power data.

Importantly, system-level safety parameters—such as current thresholds or load management logic—are only configurable through the installer interface. These protections are locked out from the user-facing app to ensure that only qualified personnel can modify critical operating limits. This separation ensures proper system setup while still providing homeowners with robust control over routine operations and energy usage.

SB Installation and Applications

SB replaces standard breakers with smart breaker modules inside the existing panel. The core infrastructure remains unchanged, minimizing installation complexity. A central “Power Director” hub is mounted nearby and wirelessly connects to each smart breaker. The installer uses the SB commissioning interface to assign and configure breakers, while the homeowner accesses system functions through the SB app. This includes real-time power monitoring, event alerts, and integration with broader smart home automation features.

Service Upgrade Avoidance Feature Evaluation

The team targeted service upgrade avoidance (SUA) as a key feature for evaluation in this project. SUA allows an end user to connect a total load capacity greater than the panel’s rated electrical service, provided that active loads are managed to stay within the service limit. This capability can be implemented in multiple ways; among the three systems tested, the project team observed two distinct approaches: the SP and SSP systems employ an automatic load-shedding method to achieve SUA functionality while the SB system employ a scene-based SUA feature.

SP and SSP SUA – Automatic Load Shed

For evaluating the SUA feature in both the SP and SSP systems, the project team configured each panel’s software with a 50 A service limit, resulting in an active mitigation threshold of 40 A due to the panel’s internal 80 percent derating protocol. The team then overloaded the panels using the previously mentioned loads, beginning at the maximum achievable load and progressively reducing the overcurrent until no SUA behavior was observed. This approach allowed the identification of the lowest overload condition that triggered mitigation. For each system, three representative plots are presented: No Control—an overload condition that did not result in SUA action, Low Overload Control—the lowest overload condition that produced SUA action, and High Overload Control—the highest tested overload condition and the corresponding SUA response.

Because SUA control logic applies independently to each service conductor, the results are representative across both phases. Any imbalance manifests on the neutral, which is likewise constrained by the same service limit. Figures in this report alternate between Phase A and Phase B results for illustration only and should not be interpreted as indicating differences in behavior. The team tested overload conditions on both Phase A and Phase B independently, with results found to be identical between the two.

At each overload level, the project team monitored the system to assess whether and when load-shedding occurred. The team recorded and plotted power data from both the service lines and individual downstream circuits to characterize system response. The team observed no automatic load shed at any overload condition below 20 percent above the threshold (Figure 10).

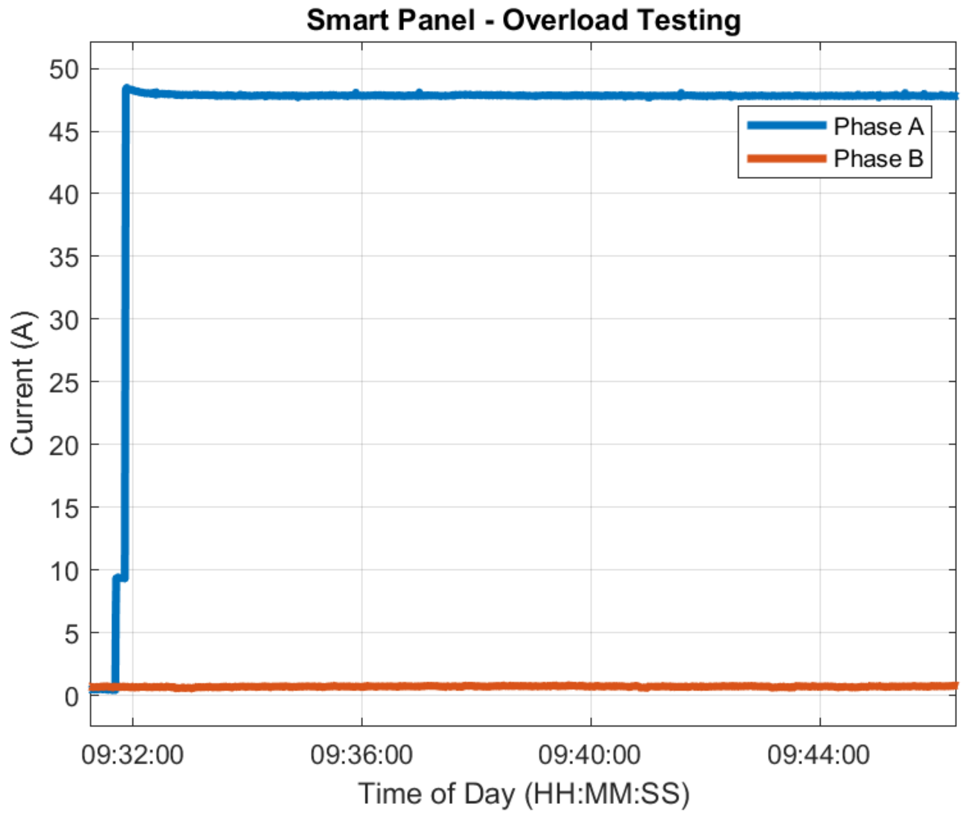

Figure 10: SP overload test resulting in no SUA shedding.

The team observed the first instance of load mitigation only when the total current exceeded 20 percent above the defined threshold. At this load, the system began shedding lower-priority circuits according to the user-defined configuration.

In this test, the project team energized the dryer first, followed by sequential activation of heaters until the total system load reached approximately 22.5 percent above the 40 A limit. Once this condition was met, SP began actively shedding loads by cycling lower-amperage circuits off within about 25 seconds (Figure 11).

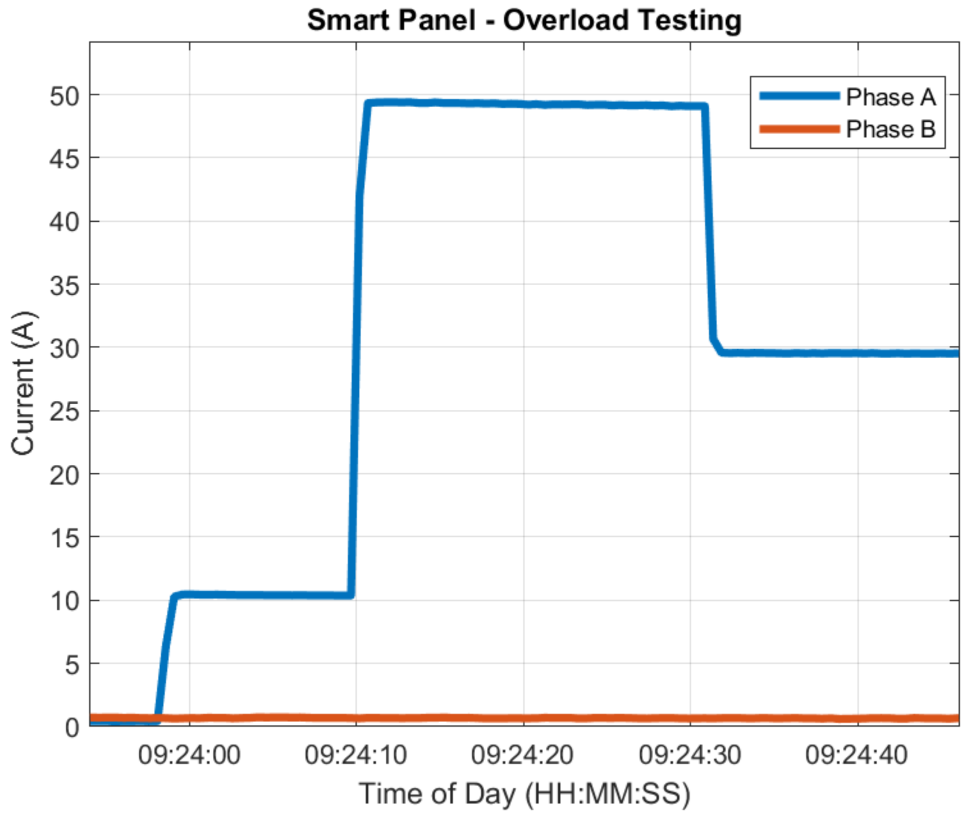

Figure 11: SP overload test resulting in SUA shedding – minimum overload

When SP was pushed to the highest tested load—approximately 80 A total, or 100 percent above its 40 A mitigation threshold, the system responded rapidly. At this highest load condition, the panel automatically disconnected the lowest priority circuits in the user-defined configuration, within only a few seconds of the overload being reached. This swift action contrasts with the noticeably longer response times observed at the lowest overload level that still triggered SUA, suggesting that SP's service upgrade avoidance logic may escalate its reaction speed as overload amperage increases. This behavior confirms the panel's ability to autonomously enforce its configured amperage limit under extreme sustained overload conditions (Figure 12).

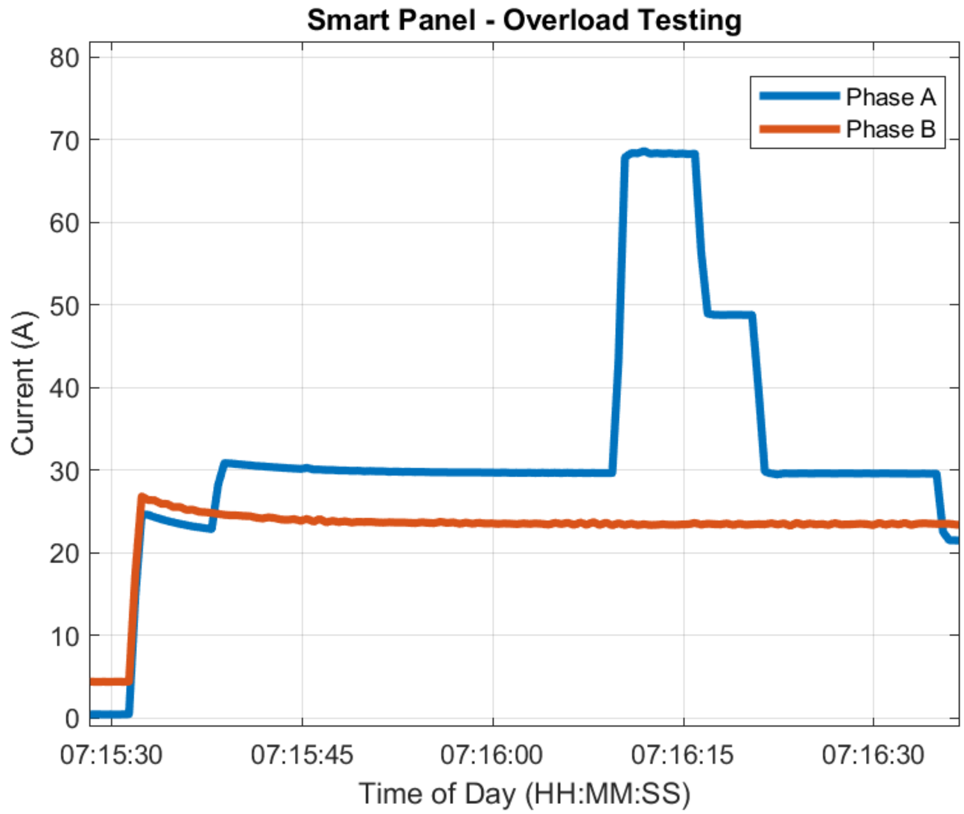

Figure 12: SP overload test resulting in SUA shedding – maximum available overload

The team conducted SSP testing in a similar manner, with its SUA max current setting configured to a 50 A limit, yielding the same 40 A active mitigation threshold. The team applied overloads, starting from the maximum achievable load with the lab's dummy loads and then progressively reduced until no SUA behavior was observed. As with the SP testing, three representative cases are presented to illustrate system performance: No Control—an overload condition that did not trigger SUA action, Low Overload Control—the lowest overload condition that produced a mitigation event, and High Overload Control—the highest tested overload condition and the system's corresponding response (Figure 13).

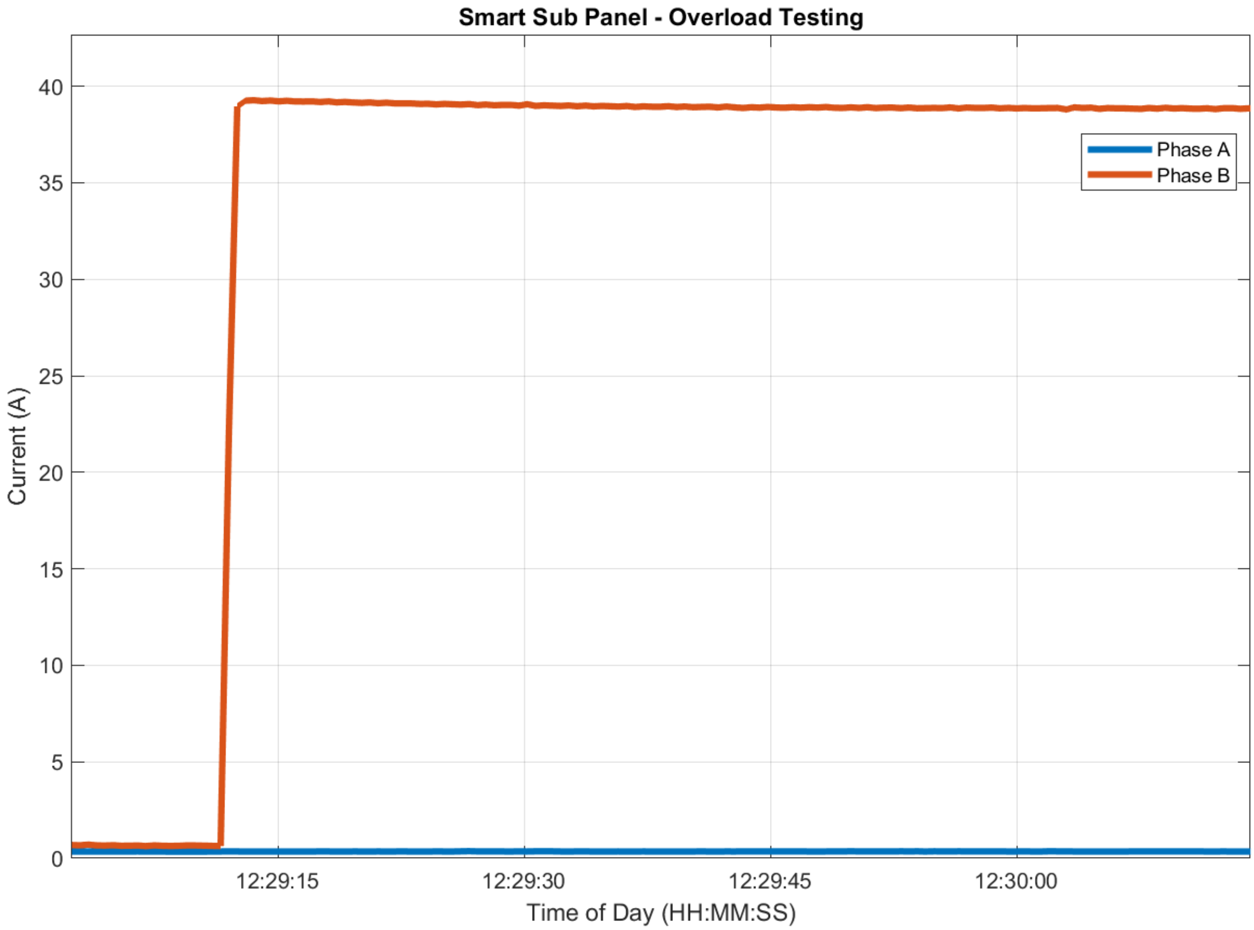

Figure 13: SSP overload test resulting in no SUA shedding.

In testing SSP, the project team observed that the system consistently responded as soon as the measured current exceeded the 40 A mitigation threshold. As a result, achieving a stable overload condition without triggering SUA action was not possible once the threshold was crossed. The *No Control* plot therefore represents the closest researchers could approach this limit, with the total load held just below 40 A. Under these conditions, no branch circuits were disconnected, and the system maintained normal operation throughout the test, illustrating the SSP's strict adherence to its configured amperage limit.

The team next loaded SSP to just above its 40 A mitigation threshold, representing the lowest overload condition that still triggered SUA action. Upon exceeding the limit, the system responded in approximately four seconds by disconnecting the lowest-priority branch circuit as defined in the user configuration (Figure 14).

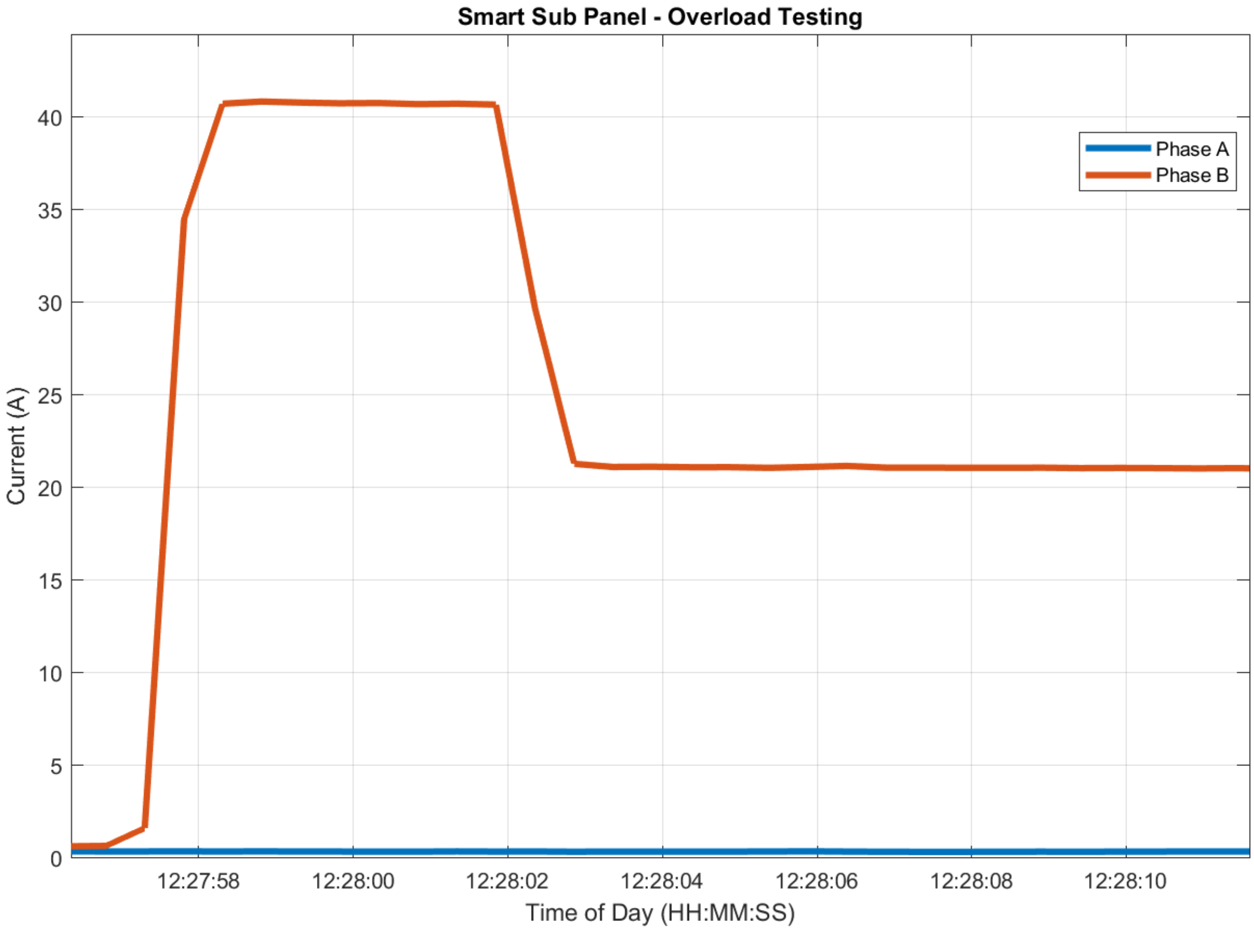

Figure 14: SSP overload test resulting in SUA shedding – minimum overload.

The load profile shows a brief period of stable overload followed by a sharp drop corresponding to the load-shedding event, demonstrating SSP's rapid enforcement of its configured limit even under minimal overload conditions. At the highest tested overload condition, the project team loaded SSP to the maximum achievable level using the lab's test loads, well above the 40 A mitigation threshold (Figure 15).

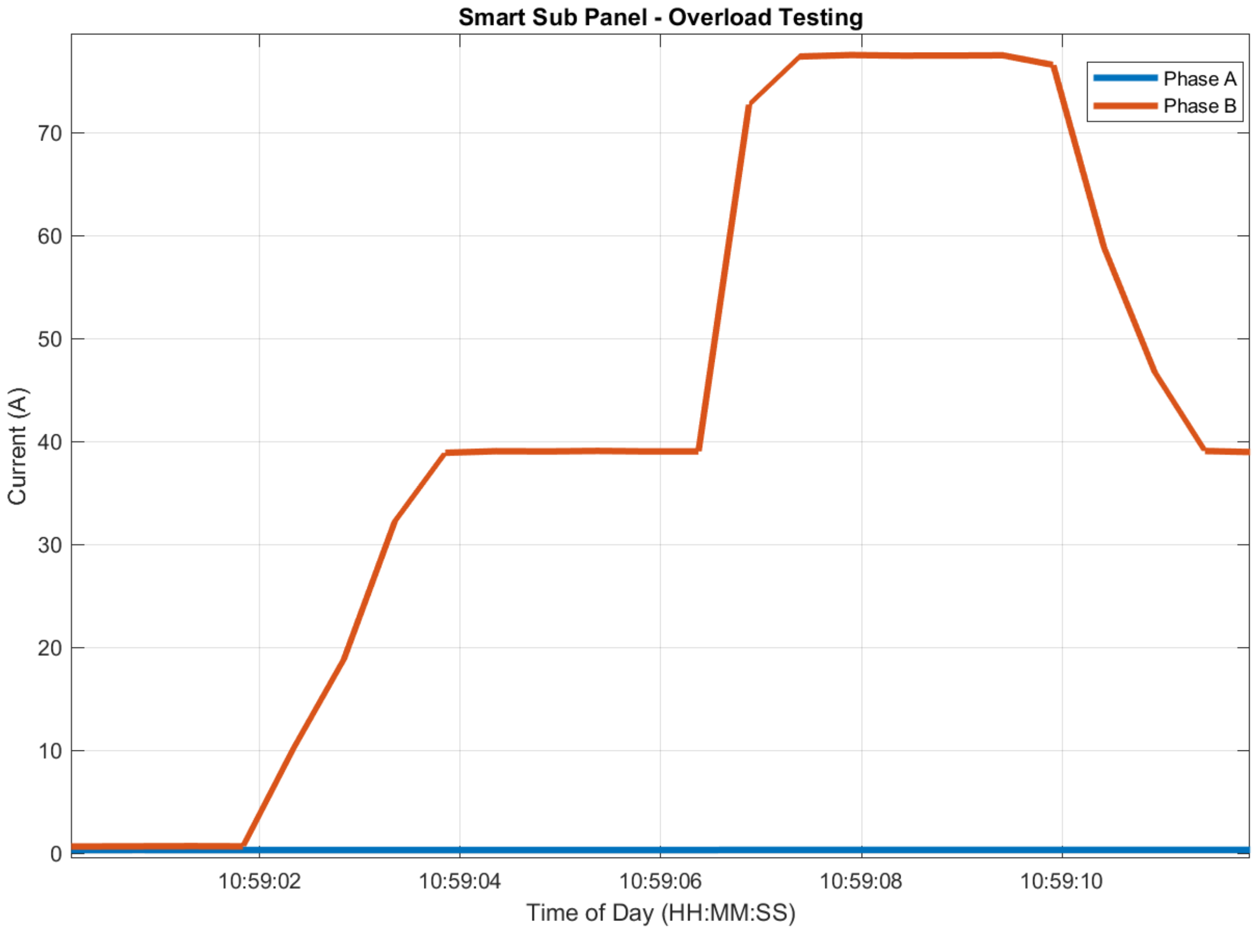

Figure 15: SSP overload test resulting in SUA shedding – maximum available overload.

Despite the substantially greater overload magnitude compared to the Low Overload Control case, the system-initiated SUA load shedding lasted approximately four seconds—virtually identical to the response time observed at minimal exceedance. The plot shows a stable high-load condition followed by a rapid drop as the lowest-priority branch circuit was disconnected. This similarity in response times suggests that SSP's mitigation logic does not dynamically adjust its reaction speed based on the severity of the overload, and instead applies a consistent delay before acting.

SMART BREAKER VS. TRADITIONAL BREAKER PERFORMANCE

Circuit breaker —time-current curves are plots that show how a breaker responds to overcurrent conditions. Breakers are classified by their amperage rating and by a performance type that indicates how quickly they trip under high-current events such as short circuits. Most breakers follow a thermal trip curve: current flowing through the breaker heats a bi-metallic strip until it bends enough to trip the mechanism (Figure 16). The SUA technologies evaluated in this project all operated within the overcurrent range associated with thermal tripping, rather than the faster magnetic tripping that occurs during short-circuit events.

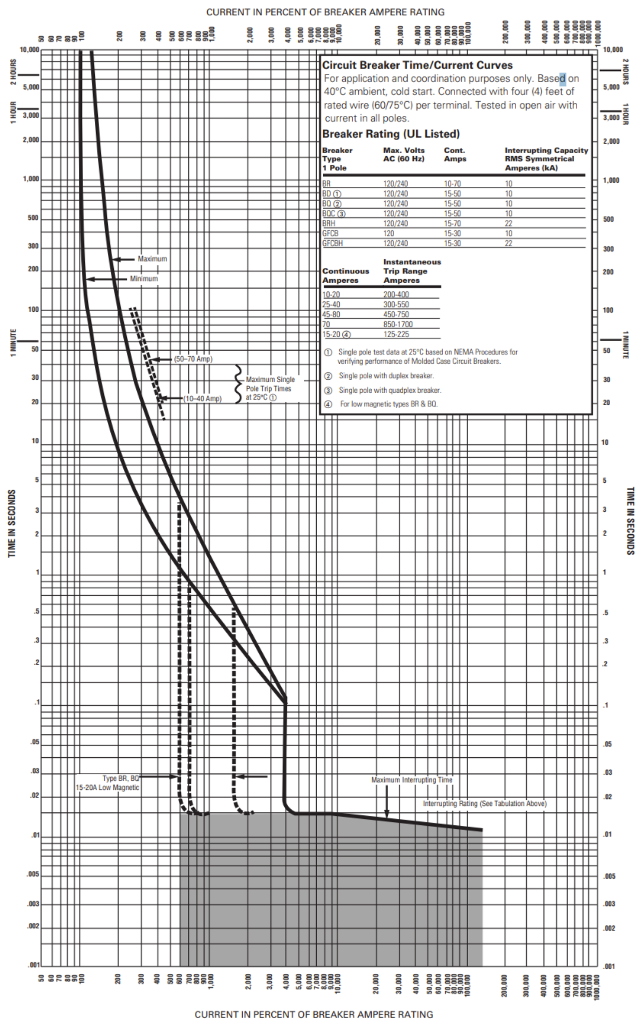

Figure 16: Typical breaker Time-Current curve.

The overload testing of SP and SSP produced two key data points for each tested condition: the percentage of overload relative to the configured 50 A mitigation threshold and the corresponding time to respond. All SUA events occurred within the sustained-overload range, activating before a main breaker's thermal trip would normally occur, and well below the threshold for magnetic tripping. By intervening within this range, SUA can reduce the likelihood of main breaker trips and limit prolonged stress on service equipment. The collected data therefore provides a clear basis for comparing how effectively each system detects and mitigates overloads before they escalate to a breaker trip (Figure 17).

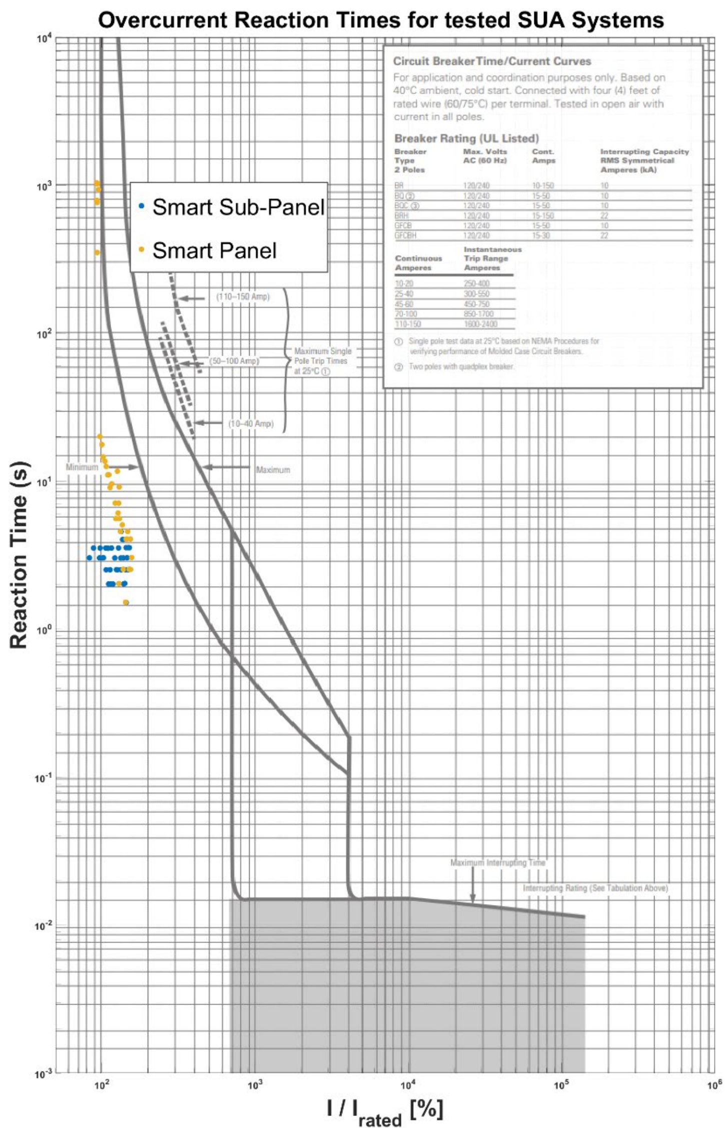

Figure 17: SP and SSP overload vs. response time data overlayed on a typical breaker curve.

Both systems execute load shedding faster than a thermal main breaker, which serves as the final layer of protection for electrical infrastructure. SP demonstrated an overload-dependent response time, closely mimicking the thermal behavior of a breaker but at a lower threshold, allowing lesser tolerance for brief inrush currents from appliance startups. SSP, by contrast, consistently initiated SUA at roughly four seconds after exceeding the threshold, regardless of overload magnitude. While still protective, this fixed-delay behavior may result in more frequent shedding during short, non-damaging surges and leaves open the possibility that, at extreme overcurrents—beyond the lab's testing capacity—a main breaker could trip before the SSP's SUA engages.

SP AND SSP LOAD REENERGIZING

After a load-shedding event, both SP and SSP were capable of re-enabling circuits, though their recovery logic differed. For SP, software behavior varied by circuit type: user-defined dedicated circuits such as a dryer was typically re-enabled about one minute after shutoff, whereas user-defined generic circuits remained deenergized for up to five minutes. SSP applied a uniform default one-minute wait period before relay reactivation. These differences in recovery timing and control strategies directly influence user experience and the risk of repeated SUA cycling, and they form the basis for the following analysis.

The project team conducted a test by loading the panel to 80 A using only generic circuits, with no dryer load included. The team chose this configuration because earlier incremental overload testing from 80 A to 50 A in 1 A steps had already revealed that SP applies different recovery times to dedicated loads—such as the dryer—compared to generic loads when re-enabling relays after a shed event. In the sustained test shown, the team applied 80 A of load for roughly one hour and left the panel to manage autonomously. Initially, two of the four generic circuits—each with a 20 A load—were shed almost immediately, followed by a third circuit approximately four minutes later. This staggered response suggests that SP's SUA algorithm incorporates recent overload history into its decision-making when determining shed thresholds. Over the course of the test, the system entered a repeating cycle in which, approximately every ten minutes, it attempted to re-enable a previously deenergized circuit (Figure 18). Each reenergization caused total current to exceed the 40 A limit, prompting the panel to subsequently shed another circuit in response.

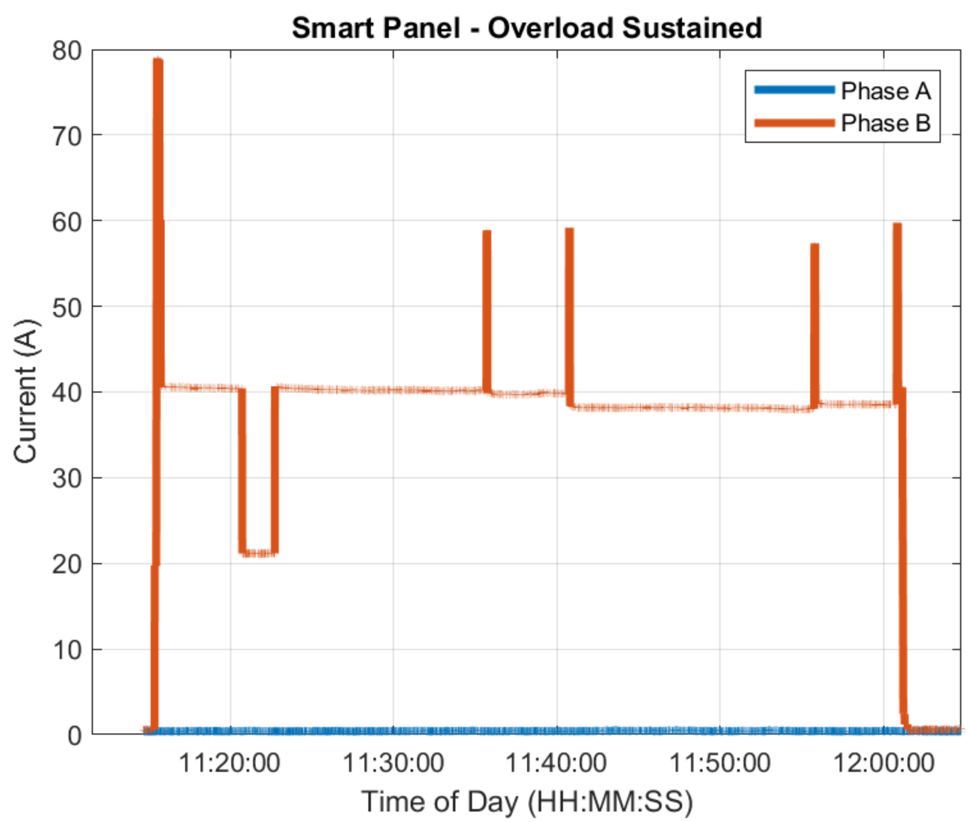

Figure 18: SP sustained 80A overload one-hour test, generic circuits only.

Next, the project team conducted a similar test, but using both generic and dedicated circuits. This histogram (Figure 19) shows the distribution of re-enable delays for a dedicated dryer circuit (yellow) and non-dedicated outlet circuits (red) with SP. Each bar represents the count of observed re-enable events. The x-axis is log-scaled to show both short and long delays, while vertical dashed lines mark 60-second intervals for reference.

Results show two distinct behaviors:

- **Dedicated circuit (dryer):** Most re-enable events clustered around 1–2 minutes (≈90–120 seconds).
- **Non-dedicated circuits (outlets):** Re-enable events clustered later, typically around 4–6 minutes (≈240–360 seconds).

These distributions confirm that the smart panel applies shorter timers to restore dedicated loads, such as the dryer, while applying longer timers to generic circuits to reduce the risk of nuisance cycling.

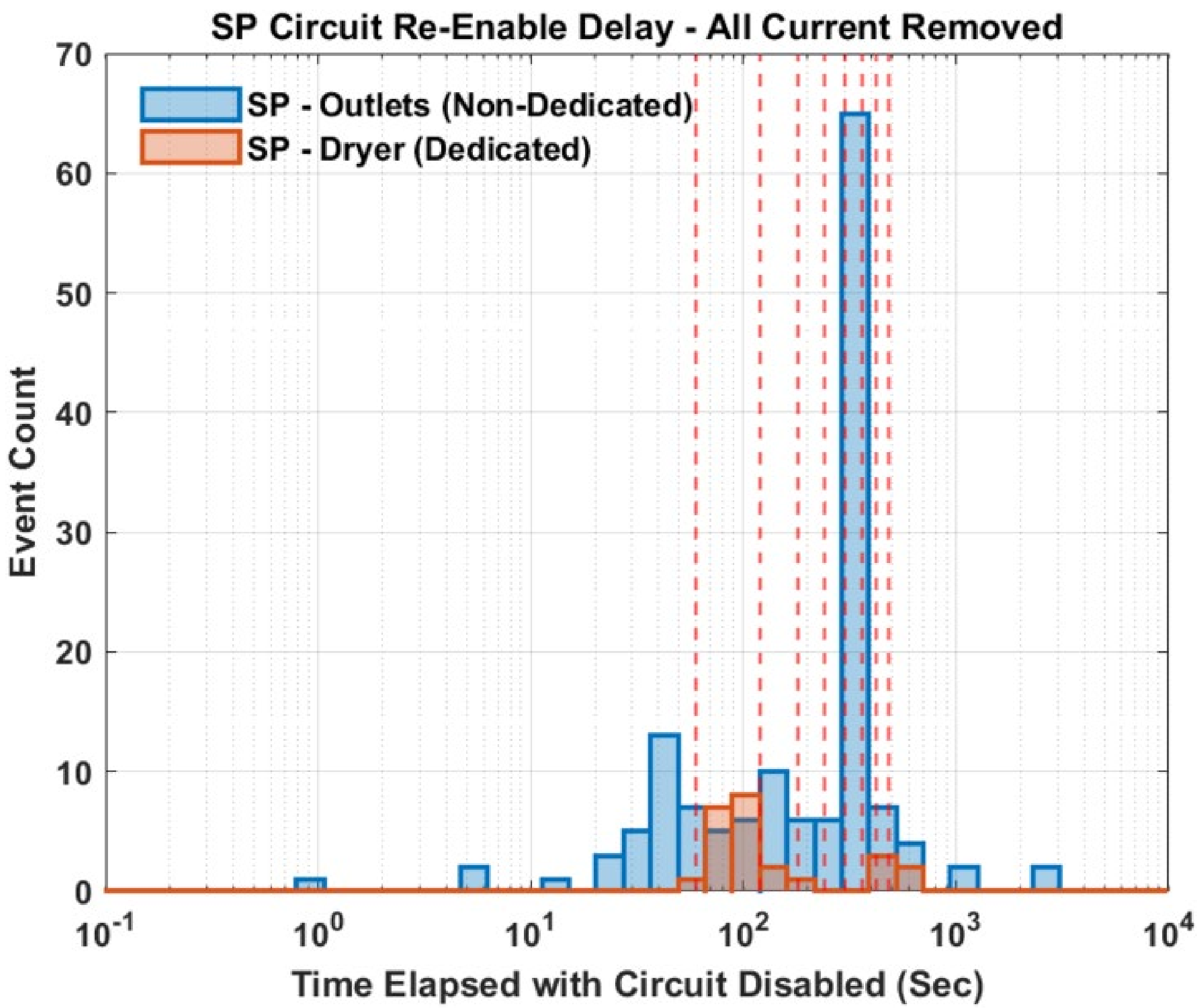

Figure 19: SP – dedicated vs. generic Circuit Reenable time delays.

The re-enable delay distributions indicate that the smart panel applies different recovery logic depending on circuit type. Dedicated loads, such as the dryer, were restored more quickly—typically within one to two minutes—while non-dedicated outlet circuits exhibited longer re-enable times, in the range of four to six minutes. The effect of this strategy is twofold: it minimizes disruption to high-demand dedicated appliances and reduces the likelihood of rapid on/off cycling of outlet circuits that could immediately retrigger overload conditions. Although effective in maintaining service stability, this approach may also result in non-dedicated circuits remaining de-energized longer than strictly necessary, highlighting a conservative rather than fully dynamic recovery method.

In contrast, the sustained 80 A test for SSP showed a fixed-interval reenergization pattern with no apparent adaptive logic based on load history. Once an SUA event occurred, each shed circuit was re-enabled on a one-minute cycle. Because the applied load was constant and immediately exceeded the 40 A threshold when a circuit was reenergized, the same circuit was promptly deenergized again, resulting in a repetitive on/off pattern throughout the test (Figure 20). Unlike SP's 80 A sustained test—where reenergization occurred on a roughly ten-minute interval and appeared to factor prior overload conditions into the timing—SSP's behavior suggests a simple timer-based reset with no modulation to avoid rapid cycling. While this approach ensures quicker restoration opportunities, it also increases the number of switching events on connected appliances. Over time, such frequent cycling could accelerate wear on motors, compressors, and other components sensitive to repeated power interruptions, particularly under high-load or startup conditions.

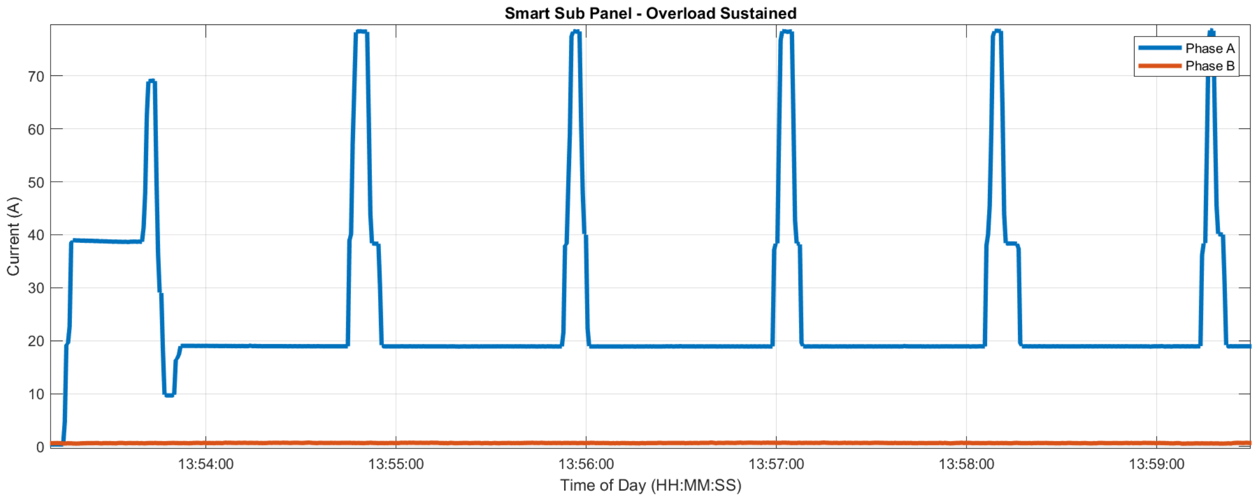

Figure 20: SSP sustained 80A overload one-hour test.

When subjected to sustained 80 A load, SP and SSP displayed distinctly different circuit reenergization strategies. SP used a longer reenergization interval—around ten minutes in this test—and appeared to factor prior overload events into its recovery logic, reducing the frequency of on/off cycling. In contrast, SSP employed a fixed one-minute re-enable timer with no observed load-history modulation, resulting in significantly more switching events. While SSP's approach offers faster opportunities to restore service, it increases the likelihood of frequent cycling on connected equipment, potentially shortening the service life of appliances sensitive to abrupt power interruptions. SP's algorithmically determined reenergization intervals may better balance protection with equipment longevity, particularly in scenarios where overload conditions are sustained for extended periods.

SB SUA – Scene Control

Unlike SP and SSP, SB does not perform continuous load monitoring or automated shedding in response to overcurrent conditions. Instead, its SUA strategy relies on user-defined "scenes"—preconfigured sets of panel circuits that can be energized simultaneously without exceeding the panel's main breaker rating.

Each circuit is designated as either controlled (smart breaker) or uncontrolled (standard breaker). For each circuit, the user enters the maximum expected load and the circuit's purpose. The system then allows the user to group circuits into scenes such that the sum of their declared maximum loads is less than the main breaker's rating. Only one scene can be active at a time, and the user must manually switch between scenes via the SB app to access different groups of circuits.

This approach enables the panel to support a total connected load greater than its main breaker capacity, provided no active scene exceeds the rating. However, the strategy is entirely dependent on accurate user input. If a circuit's maximum expected load is underestimated, a scene may appear compliant in software but actually exceed the breaker rating in operation.

In such a case, SB includes a fail-safe mode: if measured current approaches the main breaker trip point, the system will immediately deenergize all controlled breakers to prevent a main breaker trip. The manufacturer emphasizes that this is not intended as a load-shedding feature, but as an emergency protection measure. Once in fail-safe mode, each controlled breaker must be manually reset before normal operation can resume.

Energy Reporting Accuracy

All three systems reported energy consumption at both the individual circuit level and for the panel as a whole. When compared to calibrated laboratory meters, reported values were within ±5 W of the reference measurements. This level of accuracy is adequate for providing end users with actionable insights into their energy use patterns—such as identifying high-consumption devices, deciding when to manually turn off loads to reduce costs or avoid peak periods, and estimating monthly electricity costs. However, it is not sufficient for revenue-grade applications, and none of the manufacturers claim such compliance.

Energy Efficiency Features

Although product literature and manufacturer claims referenced additional energy efficiency and load management capabilities—such as integration with pricing signals, carbon intensity signals, and advanced scheduling—testing showed that, at the time of evaluation, scheduling was the only feature available beyond the previously described SUA functions.

In practice, scheduling functionality was minimally implemented across all systems. For SSP, a scheduling option appears in the mobile app, but in testing it did not execute as configured, suggesting the feature is still under development. Other systems referenced scheduling capabilities when paired with third-party smart home devices (e.g., Amazon Alexa, Google Home); however, in those cases the scheduling logic resides within the smart home platform rather than being natively implemented in the panel's own software ecosystem. While this approach can achieve scheduled control indirectly, it does not constitute an integrated feature of the panel itself.

Despite current limitations, smart electrical panels are well-positioned to support both energy efficiency and load management in the future due to their central role in a home's electrical infrastructure. Many of these capabilities could be enabled through future firmware and software updates, allowing native integration of dynamic signals and advanced control logic.

Stakeholder Engagement

In addition to laboratory testing, the research team conducted a targeted stakeholder engagement effort to assess technical understanding, market readiness, and perceived barriers to adoption of smart electrical panels. This component included two parallel activities: 1) content analysis of prior stakeholder interviews with utility program managers and electrical contractors, and 2) new interviews with building department inspectors and officials.

Stakeholders (N=25) across all groups demonstrated general awareness of smart electrical panel technologies, but most lacked direct experience with their installation, configuration, or operation—particularly regarding software-driven functionality. Stakeholders identified key market barriers including low awareness, high upfront cost, insufficient workforce and inspector training, and limited transparency into software-controlled load management.

Content Analysis

The content analysis leveraged interview data from the 2023 *Market Study of Household Electric Infrastructure Upgrade Alternatives for Electrification*. The research team reanalyzed raw interview notes and summaries from a cross-section of stakeholders, including utility program managers (N=10, representing 4 investor-owned utilities) and electrical contractors (N=9, representing 5 contractor companies). This analysis revealed stakeholder familiarity and support for the technology, but also limited direct experience, technical misunderstandings, and potential barriers to smart panel deployment.

Among the utility program managers, all ten reported awareness of smart panels but lacked direct experience with their installation or operation. Out of the four smart panel technologies assessed in the 2023 Market Study, utility program managers were most aware of smart panels. Nine of the ten respondents lacked professional or technical experience with smart panels; only one respondent worked at a utility that offered a residential smart panel rebate. Utility program managers recognized the value of smart panels in deferring costly upgrades to a home's electric panel and potentially in avoiding a transformer replacement.

Among the electrical contractors, eight of the nine reported familiarity with smart panels but none had ever installed a smart panel. The contractor unfamiliar with the technology expressed excitement about installing smart panels in the future as a way to grow their business, increase residential electrification, and contribute to decarbonization.

Interviews with utility program managers and contractors contained persistent misconceptions, including an assumed need for continuous internet connectivity and end-user configurability, highlighting a lack of in-depth knowledge about smart panels.

These stakeholder groups identified the following potential market barriers related to the following:

SMART PANELS

Cost: Stakeholders expressed concern that smart panels incur high upfront costs—even if they are less expensive than an overall panel upgrade—and can have a long payback period. Cost may preclude low-income households from adopting this technology.

Longevity: A utility program manager experienced with smart panels shared that smart panels may lose functionality if the manufacturer no longer supports the product.

RESIDENTIAL CUSTOMERS

Housing type: A utility program manager experienced with smart panels reported that the product is not a good fit for multifamily homes, potentially limiting its residential market adoption.

Behavior: A stakeholder questioned whether customers would be willing to change their behavior by avoiding using appliances simultaneously and on demand.

ELECTRICAL CONTRACTORS

Experience: Contractors lack experience with smart panels, which may translate into a lower likelihood of recommending a smart panel to a residential customer.

Labor: Contractors cited a shortage of skilled electrical labor as a potentially limiting factor for widespread smart panel installations.

Preference: Contractors may prefer a particular standard electrical panel product, and therefore hesitate to adopt a new smart electrical panel product.

Certification: Contractors expressed concern that specialized knowledge and certification for smart panel installation could hinder contractor adoption.

Code Official and Building Inspector Interviews

To address a gap identified in the prior study, the research team initiated direct interviews with building department inspectors (N=4) and officials (N=2) to evaluate their awareness and perspectives regarding smart electrical panels. The six interviewees represented five unique jurisdictions: two in the Sacramento Valley, one on the Central Coast, and two in Southern California. This analysis demonstrated that increased electrification posed challenges for building departments, and staff were eager for solutions. While familiar with the technology, only one jurisdiction regularly inspected smart electrical panels, revealing challenges with training, documentation, and software transparency. These findings suggest that building departments support smart panel adoption despite the current low market penetration.

In the field, inspectors relied on code and listings to assess new technologies such as smart panels. All jurisdictions used the 2022 California Electrical Code (CEC), which is based on the 2022 National Electrical Code (NEC). A product listing was required to pass inspection, with UL as the most recognized body. Since code usually lags behind new technologies, inspectors relied on manufacturers' installation manuals during inspection. Manuals appear to be especially important for inspecting new electrical technologies, given that interviewees described electrical as the most nuanced code and often a weak spot among inspectors.

Though a potential weak spot, building department inspectors and officials framed residential electrification as an important topic and challenge. They witnessed electrification increases as residents electrified accessory dwelling units or installed solar panels, batteries, EV chargers, heat pump water heaters, and other appliances. Electrification also highlighted disparities in their jurisdictions, in which affluent residents were best positioned to afford a panel upgrade. Some described panel upgrades as expensive, time consuming, unnecessary, a strain on the grid, and potentially necessitating an expensive transformer upgrade. They were eager to identify alternative solutions.

Most building department inspectors and officials reported familiarity with smart panels. Only one inspector, however, possessed deeper knowledge derived from inspecting six to ten smart panels—predominantly SPAN—a year. Some inspectors were not aware of smart panels' load- shedding capabilities, and some shared misconceptions about smart panel functionality, such as end-user programming. Despite surface-level familiarity, building department inspectors and officials expressed excitement about smart panels' value and potential impacts, such as efficiently increasing electrification without upgrading a panel.

The jurisdiction with regular smart panel inspections provided in-depth insights into inspection processes and challenges. Most of the smart panel inspections were performed on SPAN products, installed to expand electrification, track electric usage from a newly installed secondary power source, or complement home repairs following fire damage. In the field, this inspector often relied on product labeling and manual web searches to verify compliance. The inspector emphasized the need for qualified personnel to access programming settings and highlighted potential risks if homeowners or contractors lack adequate oversight of system configurations. Additionally, the inspector underscored that current inspection workflows do not provide visibility into the software logic driving automated load-control decisions.

Overall, the building department interviews described low market penetration. Three of the five jurisdictions reported no smart panel inspections; only one jurisdiction had regular smart panel inspections, and a second had “few and far between” SPAN installations. A building department official cited issuing energy efficiency rebates for smart devices, subpanel installations, and panel upgrades, but never receiving a rebate request for a smart electric panel. Installations were more common in the Bay Area, according to one interviewee who described the region as a “unicorn” for its highly trained workforce, progressive politics, and informed jurisdiction staff. This finding suggests that smart panels are not currently a main electrification player in many Californian markets.

Interviews with inspectors and building officials identified additional market barriers to those reported in the above section:

SMART PANELS

Software: Inspectors lack visibility and access into smart electrical panel software, which can impede confidence and support from building departments.

BUILDING DEPARTMENTS

Experience: Building departments, including inspectors, lack direct experience with smart electrical panels. When combined with electrical code that lags behind newer technologies, a lack of experience may lead to building departments failing smart panel permits and/or inspections.

RESIDENTIAL CUSTOMERS

Awareness: Findings suggest that customers lack awareness about smart electrical panels as an alternative to service upgrades.

ELECTRICAL CONTRACTORS

Installation: Smart panel installation practices are likely new to contractors. They require load calculations and may necessitate coordination between multiple contractors, such as a plumber and an electrician. This added complexity may dissuade contractors from performing the work.

Discussion

The laboratory and stakeholder findings from this preliminary assessment highlight both the technical viability and the market-readiness challenges of smart electrical panel technologies for SUA. From a performance standpoint, all evaluated systems demonstrated the ability to intervene before a main breaker trip under sustained overloads, confirming their potential to defer or avoid costly service upgrades. However, differences in detection thresholds, response times, and recovery logic have implications for both user experience and equipment protection.

SP's variable reaction speed and adaptive reenergization strategy suggest a more nuanced load management approach, potentially reducing nuisance cycling while maintaining overload protection. By contrast, SSP's fixed-delay mitigation and recovery times ensure rapid intervention but may increase the risk of frequent cycling under sustained overloads or transient surges, with possible impacts on appliance longevity. SB's scene-based SUA, while simpler to implement, relies heavily on accurate user configuration and manual intervention—limiting its protective value in dynamic load conditions and raising potential reliability concerns if user inputs are inaccurate.

The ±5 W circuit- and panel-level metering accuracy across all systems is sufficient for homeowner decision-making but not revenue-grade, aligning with current manufacturer claims. Advanced features such as time-of-use scheduling, demand response, and carbon-intensity integration were either minimally implemented or dependent on external smart home platforms, indicating that much of the claimed functionality remains underdeveloped. This gap underscores the opportunity for firmware/software updates to expand capabilities without hardware changes.

Stakeholder engagement reinforced that market barriers are not solely technical. Low familiarity among inspectors, limited contractor experience, cost concerns, and lack of software transparency all impede adoption. Building department interviews suggest regulatory alignment and standardized inspection workflows will be critical—particularly regarding access to and verification of automated load control logic. Workforce development and installer certification pathways will also be key to scaling deployment without compromising safety.

Collectively, these findings indicate that while the core protective function of SUA is demonstrably achievable, the pathway to broad market adoption will require parallel advancements in three areas:

- Software maturity: refining detection/recovery logic, integrating native advanced control features, and improving transparency for inspectors and installers
- Workforce capacity: expanding installer familiarity, certification programs, and cross-trade coordination to streamline installation
- Market enablement: developing incentives, targeted outreach, and clear regulatory frameworks to build awareness and trust among homeowners, contractors, and authorities having jurisdiction.

Future testing under diverse load profiles, environmental conditions, and distributed energy resource integration scenarios will be essential for validating long-term reliability and informing policy and program design to support equitable electrification without the infrastructure burden of widespread service upgrades.

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