From Dynamic Prices to Dispatchable Flexibility: Demonstrated OpenADR Implementation Pathways

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ABSTRACT

Utilities need cost effective and scalable pathways for converting dynamic electricity prices into dispatchable, measurable, and customer-compatible load flexibility. This paper examines that challenge in California's demand-flexibility context, where dynamic rates, standardized price access, and automation are developing as a connected solution framework. We leverage three studies to answer questions around operationalizing dynamic prices: the SCE-CalFlexHub EMS demonstration, PG&E's OpenADR 3.0 field test, and SCE-CalFlexHub multifunctional gateway prototype. Together, the studies compare how standardized price signals can be delivered, interpreted, acted upon, and verified across utility and customer pathways using OpenADR.

SCE-CalFlexHub's EMS demonstration evaluates cloud-based predictive control, showing how day-ahead hourly prices can enable comfort-preserving HVAC strategies in small and medium commercial buildings. PG&E's field test evaluates the utility pathway, validating OpenADR 3.0 price receipt through a VEN, tariff and site association, building automation system integration, and automated HVAC control in campuses. SCE-CalFlexHub's gateway project prototype evaluates device-edge interoperability, showing how a certified VEN and local gateway receive, modify, and redistribute price signals over low-bandwidth communications to lighting, plug loads, thermostats, and EV charging.

Cumulatively, the studies demonstrate that OpenADR-enabled dynamic pricing can support multiple pathways to interoperable demand flexibility, rather than a single preferred architecture. Their shared value is clarifying utility priorities: reliable price delivery, consistent signal interpretation, automated customer-side response, observable and secure telemetry, and reduced integration burden. By comparing EMS optimization, utility-to-building automation, and gateway-based device coordination, the paper shows how standards-based approaches support interoperability while allowing tailored implementation choices to customer segments and device portfolios.

Introduction

California's demand-flexibility policy agenda, reflected in its 7 GW statewide load-shift goal and Load Management Standards rulemaking, increasingly assumes that dynamic retail prices will help align customer loads with marginal system conditions, improve reliability, reduce renewable curtailment, and support broader electrification (CEC 2023). Yet the practical barrier has never been merely price design; it has been the absence of a scalable and secure technical pathway that allows diverse customer technologies to receive prices, optimize around them, and produce repeatable load response without requiring customers to manually monitor hourly tariffs or sacrifice comfort and service quality (CPUC 2022, 2025). The literature on dynamic pricing and feedback strongly suggests that price responsiveness improves when enabling technologies are present, while the impact of stand-alone feedback tools often declines over time because the intervention depends on continued user attention and engagement (Faruqui and Sergici 2010; Allcott and Rogers 2014).

The broader significance of this question is not limited to technical feasibility. It also involves market design and customer experience. Dynamic rates and highly dynamic prices can reduce system costs and emissions when customers can reliably shift or shed load in response to hourly price signals. However, dynamic pricing alone rarely produces predictable flexibility at scale because customers generally cannot (and will not) continually interpret complex hourly rates. Automation is therefore a necessary enabling layer that translates prices into device actions while preserving comfort and usability. Utilities and third-party providers also require repeatable methods to measure and verify (M&V) load impacts under dynamic rates. Without consistent telemetry and baselining practices, flexibility cannot be counted as a dependable resource. This paper, therefore, emphasizes not only the control performance, but also practical M&V requirements and integration patterns that lower the burden of deployment.

We present on three complementary automation pathways demonstrated by a Pacific Gas & Electric (PG&E) OpenADR Field Study and two Southern California Edison (SCE) cost-share projects with the California Load Flexibility Research and Deployment Hub (CalFlexHub). The first SCE's project is an energy management system-based (EMS) demonstration that converts hourly prices into predictive HVAC control strategies in small and medium commercial buildings. The second project, PG&E's OpenADR 3.0 field study, adds a utility-led pathway by demonstrating how day-ahead hourly prices can be delivered through standardized OpenADR signaling and translated into automated HVAC control across large, distributed commercial building systems. The third is a gateway-based approach that can receive and redistribute standardized prices to a heterogeneous set of devices, including in situations where broadband availability is limited (Lawrence Berkeley National Laboratory 2026; CEC 2021).

These projects are analytically useful because they represent distinct but interoperable layers of the same architecture. The EMS demonstrates how dynamic prices can be transformed into load-shaping logic at the building-systems level; the PG&E field test demonstrates how utility price signals can be operationalized through OpenADR 3.0 in building automation environments; and the gateway demonstrates how standardized communications and local translation can broaden device participation and reduce integration burden. Together, they illustrate a plausible utility-grade operating model for automated dynamic pricing in which prices are published, acted upon, and measured in consistent ways.

Policy & Market Context

Policy context for this work is vitally important as California's dynamic pricing and automation agendas are evolving together. In R.22-07-005, the CPUC sought to move beyond a legacy load-management framework and enable broader adoption of automated demand flexibility across bundled and unbundled customers (CPUC 2022). That rulemaking reflects a central "chicken-and-egg" problem: low-cost automation will not scale without a stable policy path for dynamic rates, but dynamic rates will not produce system benefits unless customers and vendors can rely on automation that is inexpensive, interoperable, and easy to implement (CPUC 2025).

California's Load Management Standards, 7 GW statewide load-shift goal, and emerging dynamic-rate pilots provide the broader market context for this work. These efforts move demand response beyond static programs and event-based curtailment toward a more continuous model in which customer loads respond to time-varying energy and capacity conditions. The CPUC's CalFUSE framework reflects this same direction by emphasizing standardized price access, dynamic energy and capacity price elements, customer optimization options, and the systems needed for pricing, billing, and settlement. In this setting, OpenADR-based signaling and automated customer-side control are not simply technical add-ons; they are practical mechanisms for converting dynamic rates into repeatable building and device response.

These demonstration projects sit within this policy evolution by testing signal-responsive, interoperable, and customer-centered technologies that allow loads to function as flexible grid resources (CEC 2021). The projects examined here address complementary implementation problems: whether price-responsive building controls can generate measurable, comfort-preserving flexibility in ordinary commercial environments, and whether customers or devices lacking native dynamic-pricing capability can still participate through a low-cost, multi-protocol gateway model. Research on household energy burden demonstrates that affordability and access challenges are distributed unevenly, and any automation strategy that presumes always-on broadband, complex account linking, or repeated manual intervention risks reproducing those disparities (Drehobl, Ross, and Ayala 2020). The gateway project therefore tests not only technical interoperability, but whether standards-based demand flexibility can be made accessible to customers whose communications environments or device portfolios do not resemble those of early adopters.

Reference Control Stack & Architecture

To compare the EMS and gateway pathways, it is useful to define a common control stack consisting of the layers: price publication, standardized signaling, local or cloud optimization, device execution, and telemetry return. Hourly prices are published through CEC's Market Informed Demand Automation Server (MIDAS) or IOUs' price server and conveyed through a standards-based communications layer such as OpenADR 3. Then, an EMS or gateway interprets the price and determines device actions; devices execute resulting strategy; telemetry flows back to the utility, aggregator, or program administrator for M&V, and potentially settlement.

One critical design question is where demand flexibility optimization occurs. In Project 1's EMS architecture, optimization resides in a cloud platform with access to site-level device information, weather forecasts, and customer constraints. In the gateway project architecture, optimization can be hosted locally, allowing the gateway to translate received prices into device actions without relying on continuous cloud computation. This distinction affects latency, failure modes, customer data pathways, and even customer trust. For example, while cloud EMS and gateways may support richer cross-zone forecasting, a local gateway may offer simpler resilience and better fit for customers with limited communications infrastructure.

Southern California Edison-CalFlexHub EMS Demonstration

Objectives & Methodology

The SCE-CalFlexHub EMS demonstration evaluated whether day-ahead hourly prices could be translated into measurable, comfort-preserving HVAC flexibility in small to medium commercial buildings. The project tested a cloud-based energy management system that ingested hourly price signals and generated predictive HVAC control actions, primarily through precooling before high-price periods and setback during high-price periods. The central objective was not only to determine whether load could be reduced, but whether automated price response could operate within normal business conditions and customer-defined comfort limits.

The demonstration was conducted at two automotive dealerships with different operating schedules, building sizes, climate zones, HVAC configurations, and end-use characteristics. Site 1 was located in southern California, had approximately 26,300 square feet of floor area, included 13 heat pumps totaling roughly 60 kW of HVAC capacity, and also had 142 kW DC of onsite solar PV. Site 2, located in a different county, had approximately 50,000 square feet of floor area including 19 heat pumps totaling roughly 82 kW of HVAC capacity, and included three ChargePoint Level 2 EV chargers, two of which were accessible through API integration.

These sites were chosen because automotive dealerships represent operationally diverse small and medium commercial facilities with extended operating hours. Their loads are shaped by showroom conditioning, service-bay activity, occupancy variation, extended operating schedules, and customer-facing comfort expectations. Demonstrating price-responsive control in this setting therefore provides the testing criteria that automated demand flexibility can operate in ordinary commercial environments rather than only in controlled laboratory conditions. The next table summarizes the demonstration sites and their primary attributes.

Table 1. Summary of the demonstration sites

Attribute	Site #1	Site #2
Location	Orange County	Los Angeles County
Climate Zone	CZ6 (ZIP code 92675)	CZ9 (ZIP code 91711)
HVAC	13 heat pumps; 13 thermostats 2 – 6.3 kW (total ~60 kW)	19 heat pumps; 19 thermostats 1.5 – 5.8 kW (total ~82 kW)
Peak Demand	~80 kW	~175 kW
Utility Rate	ALDG-R	TOU-GS-3D
Floor Area	26,300	50,000
Business Hours	Mon–Sat: 9 AM – 8 PM Sun: 10 AM – 7 PM	Mon–Sat: 8:30 AM – 10 PM Sun: 9 AM – 9 PM
Rooftop Solar PV	142 kW DC	No
EV Chargers	ChargePoint Level 2 charger (inaccessible)	3 ChargePoint Level 2 chargers (2 API-integrated)

Evaluation Method

The evaluation protocol used a multi-week A/B testing framework in which baseline days and price-responsive control days alternated across the study period. Baseline days maintained relatively stable occupied-period setpoints, while treatment days implemented the EMS price-responsive control strategy. Spring testing occurred in May 2025 and summer testing occurred in August–September 2025, with data collected at five-minute intervals and reviewed for measurement and verification purposes. While not equivalent to a randomized controlled trial, the strength of this design lies in its ability to capture incremental effects under real operating conditions while limiting seasonal drift and other confounders, to generate field understanding required for applied utility innovation. The EMS integrated day-ahead hourly prices from the CEC MIDAS platform with weather data, thermostat and equipment signals, and customer operating constraints. After a "listen and learn" period, the EMS inferred site-specific thermal behavior and used that information to generate setpoint trajectories. For each test day, the EMS identified the largest hour-to-hour price differential within the relevant operating window, then executed a two-hour precooling period before the high-price window and a two-hour setback period during it. Comfort was managed within customer-defined temperature bands of approximately ±2.5°F around target temperatures, separate from thermostat deadband considerations.

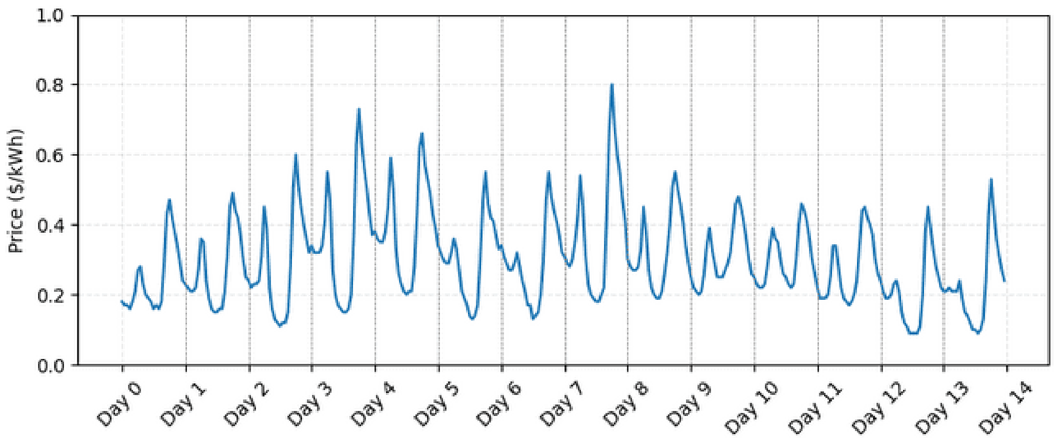

Figure 1. Two-week Profiles of WinterHDP MD Price Signal for spring testing.

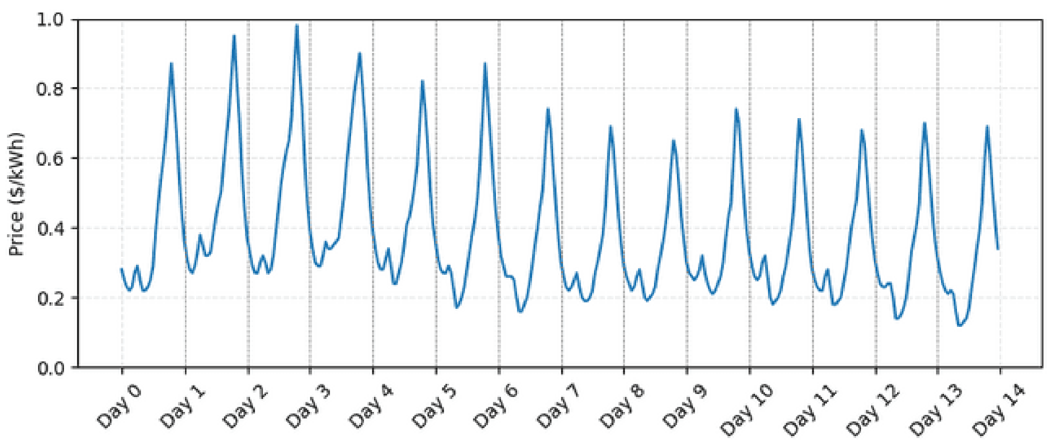

Figure 2. Two-week Profiles of SummerHDP_MD Price Signal.

Load Impacts

The spring and summer impact results are among the clearest empirical contributions of this paper. In spring testing, Site 1 achieved an HVAC load shed of 6.0 kW, equal to 59 percent of baseline HVAC demand during the 5–7 PM control window, while Site 2 achieved 20.9 kW, equal to 77 percent of baseline. In summer testing, Site 1 achieved 7.7 kW, or 68 percent of baseline, during 6–8 PM, and Site 2 achieved 29.6 kW, or 54 percent of baseline, during the same period. Normalized by area, the impacts ranged from approximately 0.23 W/ft² at the lower end to 0.59 W/ft² at the upper end. These normalized values are especially useful because they place the demonstrations in a form that can inform screening-level expectations for other small and medium commercial facilities.

The results also invite a more nuanced conclusion than simply that "automation works." Site 2 delivered materially larger absolute kW reductions, which is unsurprising given its larger size and peak demand, but the relative shed percentages and area-normalized impacts show that smaller sites can still produce meaningful and, in some cases, highly concentrated response. This supports the idea that small and medium commercial buildings (which are underrepresented in utility demand response portfolios) may be more relevant to dynamic pricing programs than their historical treatment would suggest, provided suitable control technologies are available**.**

Customer Cost Impacts

The cost results are modest in absolute daily terms, however, they are important in context. Over the active control windows, spring average savings were $6.0 for Site 1 and $24.1 for Site 2, while summer average savings were $9.3 and $36.4, respectively. Normalized by floor area, these values translate to roughly $0.22–$0.72 per day per 1,000 ft² (Lawrence Berkeley National Laboratory 2026). On their own, such savings may not justify the installation of new control systems for every site. However, they become more meaningful when interpreted alongside several other factors: the demonstrations were limited in duration; they did not monetize system capacity or other stacked value streams; and the controls were designed to preserve comfort rather than maximize savings at all costs. The more defensible interpretation is that the project validates operational feasibility and establishes an order of magnitude for direct bill effects, not that it fully captures the business case for automation. That distinction is important for how utilities and vendors discuss such technologies with customers.

Table 2. Summary average metrics for EMS by site and season.

Metric	Spring Site #1	Spring Site #2	Summer Site #1	Summer Site #2
Energy Cost Savings during Price Responsive Control Period	6.0	24.1	9.3	36.4
As a Percentage of Baseline 24-hr Energy Cost	12%	16%	9%	10%
Normalized Energy Cost Savings	0.22	0.48	0.35	0.72
24-hr energy cost with price responsive control divided by total energy consumption	0.27	0.30	0.353	0.345
As a percentage of the weighted average 24-hour energy price in the baseline case	86%	82%	92%	97%
Load Reduction (across 24hr)	6.0	20.9	7.7	29.6
As a percentage of baseline load	59%	77%	68%	54%
Load Reduction Intensity	0.23	0.42	0.29	0.59
Energy Cost Savings during Price Responsive Control Period	6.0	24.1	9.3	36.4
As a Percentage of Baseline 24-hr Energy Cost	12%	16%	9%	10%

Across both dealerships, control actions remained within customer-defined comfort bands, supporting low noticeability. Across repeated multi-week testing, there were minimal violations of the customer-defined bounds and no comfort complaints from site participants reported. Comfort preservation is assessed by comparing measured space temperatures to the EMS target bounds for each zone. The research team surveyed employee and customer inhabitants for any observed comfort effects, finding no complaints. The absence of reported comfort complaints suggests that predictive control under hourly pricing can operate within standard customer-service operations, rather than as an emergency curtailment intervention. That observation also reinforces the policy premise that automated rates can be compatible with ordinary customer experience if the technology layer is designed appropriately.

At Site 2, the project also tested limited EV charging modulation by reducing charging power to approximately 50 percent during the peak price window. The project did not quantify the resulting savings in detail, but it found the measure feasible and effectively invisible from a customer-experience standpoint. This small result points toward an important future direction: the value of dynamic pricing automation will likely increase as more sites combine HVAC, EV charging, and possibly storage or other flexible end uses. This component is included as a proof-of-capability for extending price response beyond HVAC; future work should quantify bill savings and explore customer acceptance across deeper curtailment levels & multi-day strategies.

Overall, Project 1 demonstrates that predictive EMS control can convert hourly prices into repeatable, comfort-preserving HVAC response in real small and medium commercial buildings. Its strongest contribution is not only the measured kW reduction, but the evidence that price-responsive automation can be implemented within normal operating constraints and evaluated using metrics relevant to utility program design.

Pacific Gas and Electric Company OpenADR 3.0 Field Test

Objectives & Methodology

Project 2 addressed the utility-side implementation pathway for automated dynamic pricing. The project's primary objective was to validate whether day-ahead hourly dynamic price signals could be delivered through an OpenADR 3.0 Virtual End Node and integrated with building control systems to support automated HVAC response in medium-to-large commercial facilities. Unlike the EMS demonstration, this project focused on the operational infrastructure needed to connect utility pricing systems to real building automation environments. This includes price-signal delivery, tariff/site mapping, customer authorization, building automation system integration, and round-trip control from utility price to HVAC operation. The project was deployed at two large secondary high school campuses in the San Francisco Bay Area. Both sites operated on the B19S tariff and used Alerton Compass building automation systems maintained by Syserco. Together, the campuses represented approximately 4.5 MW of HVAC nameplate capacity distributed across hundreds of individual pieces of equipment, making them useful test cases for evaluating how standardized price communication can support automated response in complex, multi-zone commercial buildings with limited operational staff.

Evaluation Method

The evaluation centered on whether the OpenADR 3.0 signal pathway could operate reliably in a live utility and building-control environment. Community Energy Labs implemented the OpenADR 3.0 VEN, integrated PG&E/GridX day-ahead hourly price signals into its optimization platform and mapped those signals to site-specific control logic for the two pilot campuses. The control pathway included price ingestion, normalization, storage, tariff association, optimization, and building-control execution through the existing BAS. The project therefore tested not only whether a price could be received, but whether it could be interpreted in the correct tariff and site context and translated into operational HVAC actions.

We used a staged validation process. Initial testing verified secure signal receipt, payload interpretation, tariff mapping, and internal data handling. A shadow-mode phase then allowed the platform to process prices and evaluate control decisions without active control. Supervised live deployment followed, with monitoring of daily pricing updates, hourly schedule coverage, control execution, latency, data completeness, and device or BAS constraints. A staged approach was important because the project was operating in real school facilities with existing schedules, comfort expectations, and building-system dependencies rather than in a laboratory environment.

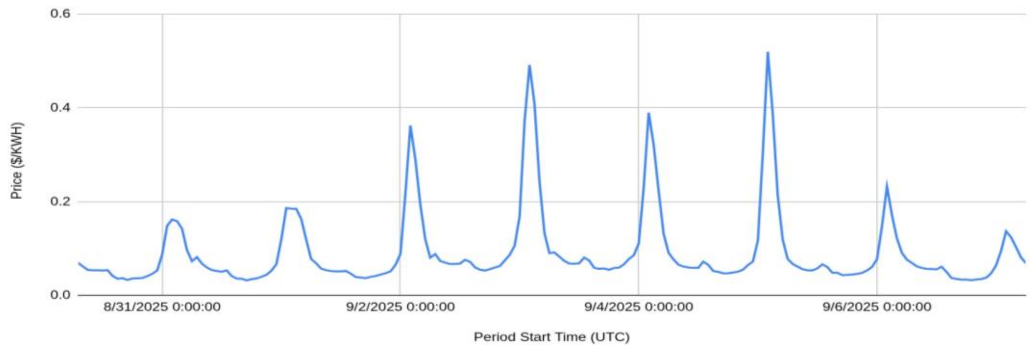

Figure 3: Week of data gathered by OpenADR 3.0 Hourly Flex Pricing API.

Results

During initial demonstration testing in October and November of 2025, CEL observed measurable responsiveness to dynamic pricing signals. In particular HVAC operation adjusted in response to hourly price variation. Because these tests were done in winter the load shifting behavior occurred during higher-cost morning peak periods (Figure 4). During the same period, the controls maintained occupant comfort within defined bounds even within the narrow constraints enforced by the system's "stuck" occupancy commands.

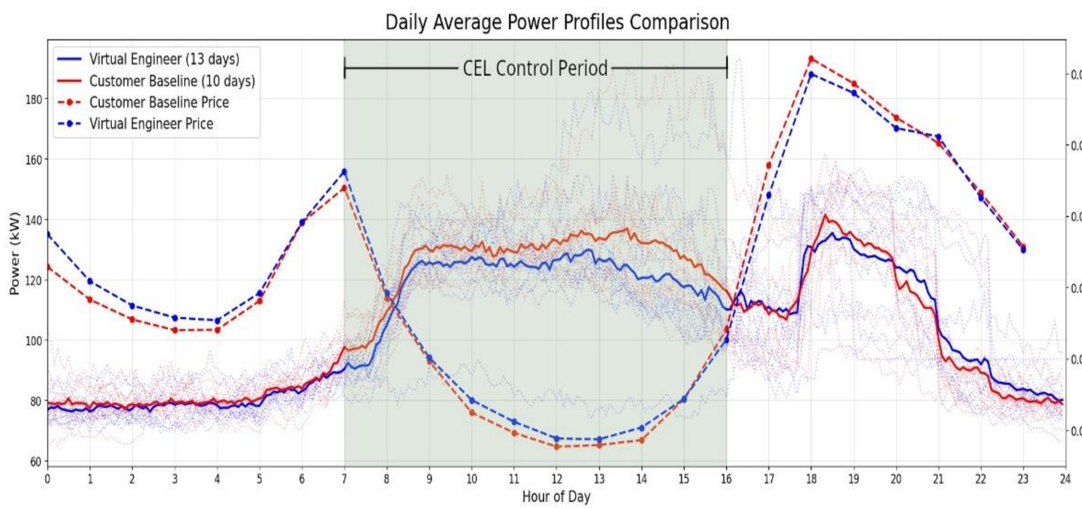

Figure 4. Price response analysis for the second high school: current results, testing continuing.

Load-impact findings should be interpreted in light of the study's operational constraints. During the formal study period, site-level control issues (including power outages, network reliability problems, and BAS state persistence) limited the project's ability to fully test dynamic price elasticity across all desired conditions. In particular, some of the control states became stuck after outages, constraining the range of available HVAC response and masking the full flexibility potential of the sites. Figure 5 shows whole-building power data following corrections.

Figure 5. Whole campus load (2nd HS). Improved performance post-programmatic safeguards.

Still, this project demonstrated reliable signal receipt, processing, and control execution, and later operational corrections supported sustained improvements in baseline efficiency and peak-load management. Even as outdoor temperatures rose and cooling load became more prevalent, the campus saw a reduction in baseline, non-peak load of approximately 20%, with reduced baseline cooling load serving as a significant contributor. Table 3 summarizes available PG&E metrics using a subset of the same performance categories as SCE's EMS demonstration.

Table 3. Summary post-correction metrics for PG&E OpenADR 3.0 field test

Metric	Site Result	Interpretation
Peak Demand Reduction	13.6%	Indicates improved peak-load management after site-level corrections/control safeguards
Total Energy Reduction	9.1%	Suggests that automated control affected not only peak timing but overall energy use.
Baseline Non-peak Load Reduction	~20%	Indicated improved baseline efficiency even against a more prevalent cooling load

Figure 6 further shows results from a panel with 4 HVAC units typical of this site and their energy consumption profile pre and post optimization. These improvements occurred despite increasing outdoor air temperatures.

Figure 6. Submeter with 4 representative HVAC units showing reduction in HVAC loads.

PG&E's field test successfully validated the core OpenADR 3.0 integration pathway. The system processed day-ahead hourly price signals, associated those prices with the appropriate site and tariff context, and translated them into automated HVAC control actions through the building automation system. In that respect, this project demonstrated end-to-end functionality from utility price signal to building operation. This is a distinct contribution from simply showing an EMS can reduce load; it shows standardized utility price communication can be operationalized in complex commercial facilities with distributed HVAC assets and existing BAS infrastructure.

Project 2 also showed why automation is necessary for this customer segment. Manual response to hourly prices would require operators to monitor changing prices daily, adjust schedules and setpoints across hundreds of HVAC units, stagger equipment operation to avoid coincident peaks, and maintain narrow comfort constraints during occupied school hours. The report identifies manual adjustment as costly and operationally infeasible for typical school maintenance teams, with one estimate of approximately $1,984 for a single day of programming support across the two schools. This finding strengthens a broader argument that dynamic pricing requires an automation layer if it is to produce persistent, customer-compatible flexibility.

The most important implication is that the limiting factor was not the OpenADR 3.0 communication pathway itself, but the surrounding operational context: enrollment readiness, data authorization, BAS reliability, site mapping, and customer-specific control constraints. The PG&E project therefore contributes a practical utility implementation lesson. For automated dynamic pricing to scale, programs must treat price communication, customer enrollment, data access, building-system readiness, and telemetry as parts of one operating model rather than as separate implementation tasks. In this sense, the PG&E field test complements the SCE-CalFlexHub demonstrations by showing how standardized price access can be connected to real utility program infrastructure and large-building control environments.

SCE-CalFlexHub Gateway Project

Objectives & Methodology

Project 3, the SCE-CalFlexHub low-cost gateway, addressed a different but equally consequential implementation problem: how to deliver dynamic prices to a wide variety of customer devices when native price response is not yet common and when broadband connectivity is uncertain. The project produced a low-cost prototype gateway with integrated or attachable communications options, including low-cost price data service, and incorporated an OpenADR 3.0 certified VEN client capable of receiving standardized price events and redistributing or acting on them locally.

The central objective was to validate a modular interoperability pathway for mixed device ecosystems. Many customer-side devices use different communication protocols, vendor platforms, and control interfaces, which creates a persistent barrier to scalable dynamic pricing implementation. The gateway project tested whether a single local coordination point could reduce that device-specific integration burden while preserving compatibility with standardized utility-side price communication. A relevant design question is how much intelligence should reside in the gateway versus the downstream device. In this demonstration, the gateway served as the primary coordination layer because the tested devices had different protocols, interfaces, and levels of native price-response capability. The gateway translated a common OpenADR price signal into simple device-specific actions, rather than assuming each device could interpret the price independently. This suggests that, in the near-term, gateway-level intelligence is most useful where devices are heterogeneous, broadband cannot be assumed, or cross-device coordination is needed. Device-level intelligence becomes more appropriate as end uses gain native price-response capability, reliable communications, and adequate awareness of local constraints. The decision point is therefore not gateway versus device, but which layer has sufficient information, connectivity, and control authority to act on prices with the least integration burden.

The project also explored whether price-responsive automation could be made more accessible in communications environments that do not presume conventional broadband. Prior field studies done in high-risk and vulnerable communities illuminated a need to find solutions for reliable communication technology beyond Wi-Fi and LTE (. In demonstrating connectivity through low-cost cellular hardware and service plans, the project examined whether price reception and basic control could be supported through low-bandwidth communications options. This is important because a scalable demand-flexibility architecture should not depend exclusively on fully connected, early-adopter homes or buildings.

Results

This project showed that cellular connectivity for price reception is technically feasible and economical for low-bandwidth, price-based automation. The project evaluated cellular service options suited to low-bandwidth IoT applications and demonstrated gateway connectivity over a low-cost cellular network model. The work also documented integration tradeoffs between module-on-chip (economical at scale) and USB dongles (simpler for existing products but higher per-unit cost), including driver development requirements for certain networks.

The research team tested several hardware/service approaches, including aforementioned USB dongles and module-based architectures, and reported viable data-cost scenarios on the order of only a few dollars per month or even a flat purchased data allotment for low-volume use cases. This is analytically significant because it reframes the "no broadband" problem. Customers lacking home broadband are often treated as structurally outside the addressable market for advanced automation, yet the gateway results suggest that price reception alone may require so little data that low-cost cellular alternatives are plausible. This does not eliminate all equity barriers, but it weakens a commonly cited one (Drehobl, Ross, and Ayala 2020).

Table 4. Example cellular data plan and hardware cost comparison for gateway connectivity.

Provider/ Option	Data Allowance	Cost/Unit	Hardware Interface	Recurring Cost
Verizon	15 GB/Month	$79.00	NOVATEL USB 730L	$20/Month
ChoiceIoT	300 MB/Month	$79.00	NOVATEL USB 730L	$4.99/Month
SimpleX	250 MB/Flat	$148.00	JACS USB TD191-TAA	$5/Flat

End-to-End Price Receipt, Modification, and Redistribution

The gateway prototype was more than a communications bridge; it was a standards-based signal processor. The project demonstrated retrieval of price data from a central server, delivery to a gateway through an OpenADR 3 VEN, optional price modification using an added greenhouse gas signal, and redistribution of the resulting values to local devices or control logic. One of the more consequential outcomes of this work was the identification of unnecessary redundancy of code and data fields in the initial OpenADR 3 price payload structure. The project team proposed a simplification in the encoding approach that was incorporated into OpenADR 3.1, illustrating that field implementation can materially improve standards by surfacing what developers and integrators actually need to make them efficient and more easily adoptable.

Standards should be understood not as fixed constraints, but as evolving infrastructure whose adoption depends on lightweight payloads, profiles, and certification pathways. This demonstration did more than comply with OpenADR 3; it contributed to OpenADR 3.1 simplification, making the next standard more viable for downstream adoption. As OpenADR 3.1 reaches device software and firmware, these improvements could enable on-demand firmware logic updates with benefits for customers, aggregators, and utilities.

Multi-Device Control Proof-of-Concept

The multi-device proof-of-concept showed that the gateway could translate dynamic prices into different device behaviors across protocols and end uses. Two Philips Hue bulbs adjusted brightness across six price levels, the Z-Wave smart plug duty-cycled or shut off above set thresholds, the Ecobee thermostat increased setpoints as prices rose, and the Tesla EV stopped charging above a designated price level. These intentionally simple rules isolated the communications and orchestration challenge from more complex optimization. The central finding is not that these rules are program-ready, but that a gateway can mediate among diverse devices, each requiring its own logic, protocol adapter, and telemetry pathway.

From a market perspective, the gateway project suggests that near-term interoperability will likely depend on hybrid control environments. Some devices will remain cloud-controlled, some locally addressable, and some will only be indirectly manageable through higher-level platforms. A gateway does not eliminate this heterogeneity, however it can organize it. This function becomes more valuable as buildings and homes add more distributed electric end uses.

Figure 7. Architecture of relationships between device components.

Discussion & Lessons Learned: A Procurement-Grade Flexibility Playbook

The three demonstrations provide different forms of evidence for utilities evaluating how dynamic prices can become operational demand flexibility. The cloud-based EMS project offers the clearest quantified load-response result: across two commercial dealership sites, predictive HVAC control produced peak-window reductions ranging from 6.0 kW to 29.6 kW, or 54–77% of baseline HVAC load, while maintaining customer-defined comfort limits. The PG&E

OpenADR 3.0 field test provides stronger evidence on utility-to-building implementation: it validated reliable price-signal receipt, tariff association, BAS integration, and automated control across large school campuses with approximately 4.5 MW of distributed HVAC capacity. The gateway project, in contrast, does not primarily demonstrate fleet-level load impact; its result is an enhanced architectural approach, showing that standardized price signals can be received through a certified VEN, modified or redistributed locally, and translated into device-specific actions across Zigbee, Z-Wave, thermostat, and EV interfaces. This comparison is useful because utilities should not expect all research studies to answer the same question: some validate load performance, some validate utility integration, and some validate market reach.

Project 1 results are instructive as a field test of what price-responsive control can deliver when the optimization layer is mature enough to preserve customer experience. The measured HVAC reductions were meaningful in both absolute and normalized terms, ranging from approximately 0.23 to 0.59 W/ft^2, during ordinary business operations, not just emergencies. Equally important, results showed minimal comfort-bound violations and no reported comfort complaints, suggesting that dynamic pricing can be made compatible with customer-facing commercial environments when control strategies are *predictive*, *bounded*, and *automated*. While bill savings were found as modest in daily dollar terms, the observation is a useful program-design finding: utilities cannot rely on short-term bill savings to justify adoption, especially when controls are intentionally comfort-preserving and if system value streams are not monetized.

The PG&E results establish how utility-specific implementation choices strongly shape whether a standards-based architecture becomes operationally useful. A particularly valuable field insight may be that the limiting factors were not primarily the OpenADR signal pathway, but the surrounding deployment conditions: enrollment readiness, customer authorization, data access, BAS reliability, power and network outages, and site-specific control-state persistence. This is a constructive finding for utilities because it identifies the non-algorithmic work required to scale dynamic pricing: customer enrollment, tariff mapping, telemetry access, BAS readiness, and operational fallback procedures must be treated as core program infrastructure, not administrative afterthoughts. Post-correction results suggest if site-level constraints are addressed, large campuses offer substantial flexible capacity under standardized price communication.

The gateway results should be interpreted less as a load-impact trial and more as evidence about access, interoperability, and device readiness. Unlike the EMS and PG&E projects focused on HVAC control in commercial buildings, the gateway demonstration tested whether a common OpenADR 3 price signal could be extended into a diverse customer-device environment. The gateway adjusted Philips Hue bulbs' brightness, duty-cycled a Z-Wave smart plug based on price thresholds, adjusted Ecobee thermostat setpoints, and curtailed high-priced charging of a Tesla. This laid a foundation for how a gateway can organize heterogeneous devices into a common price-responsive framework without requiring every device to natively implement OpenADR. Project 3 results also suggests price reception and basic control may be feasible over low-bandwidth, low-cost communications pathways, not requiring conventional home broadband. Broadband-dependent automation could exclude customers otherwise capable of providing flexible load.

A key comparative insight is that each project observes complexity in a different part of the same standards-based architecture. Project 1's complexity sits mainly in predictive control: the EMS must learn site behavior, integrate weather and price data, and select comfort-preserving setpoint strategies. Project 2's sits in utility implementation and building integration: price feeds, tariff mapping, authorization, BAS readiness, telemetry, and operational resilience determine whether the OpenADR signal can produce dependable response. Project 3's complexity sits at the customer-device edge: protocol translation, device-specific rules, communications options, and certification-compatible payloads determine whether standardized prices can reach mixed end uses. The contrast drives home how we cannot assume adopting a standard alone solves implementation. Standards create the common language, but field performance depends on where each utility and vendor places optimization, translation, authorization, and verification within the stack.

These demonstrations also suggest what kinds of thresholds may ultimately define procurement-grade flexibility. Resources should demonstrate repeatable peak-window response relative to a documented baseline over multiple test days rather than a single demonstration event. Next, comfort or service quality bounds must be formalized rather than treated informally. Lastly, telemetry completeness must be high enough to support independent verification. Though not yet formal California statewide standards, these are logical operational extensions of the state's move toward automation-enabled dynamic pricing.

Onboarding and Interoperability Lessons

The demonstrations reinforce a broader market conclusion: the most significant obstacles are often not the algorithms themselves but the friction surrounding integration, onboarding, and signal access. The first project depended on price integration, thermostat visibility, and sufficient site data to support predictive control. The second depended on hardware compatibility, cellular integration, device adapters, and certification-compatible OpenADR implementations. These align with the policy argument that a common statewide technical foundation, encompassed by standardized price access, common signal conventions, and more predictable device-control pathways, would lower market costs and accelerate adoption (CPUC 2022). In programmatic terms, it belies implication that incentives ought to reward verified performance & persistence over simple counting of installed devices or gateways.

Customer Experience and Equity

Customer experience is not a peripheral consideration in automated dynamic pricing; it is central to persistence, reputational acceptance, and ultimately, scale. Literature on dynamic pricing and feedback strongly suggests that price responsiveness improves when enabling technologies are present, while feedback-based behavioral interventions often require repeated engagement and can exhibit cycles of customer action and backsliding over time (Allcott and Rogers 2014). The EMS project supports that conclusion by demonstrating a form of flexibility that is largely invisible to occupants when control strategies are bound by agreed comfort constraints. This imperceptibility is not trivial and suggests that rate-responsive control can be normalized within ordinary building operations – not experienced as repeated disruption.

The equity implications are equally significant. High household energy burdens and unequal access to enabling infrastructure mean that a demand-flexibility market built only around fully connected, already-optimized homes and buildings will miss precisely the customers and communities for whom affordability benefits and system participation could matter most (Drehobl, Ross, and Ayala 2020). The gateway architecture is valuable here because it lowers one important barrier: it provides a plausible path for receiving dynamic prices without requiring home broadband and can coordinate multiple devices through a single control point. While this does not solve all equity issues, it supports a more inclusive design philosophy than assuming native broadband-connected devices at each site.

Limitations & Recommendations

Several limitations should shape the interpretation of these results. EMS results were drawn from two commercial sites, both in cooling-dominant use cases, and therefore cannot by themselves establish performance across other sectors or in heating-dominant conditions. The gateway results are more proof-of-concept demonstrations, not yet a statistically representative deployment, so their primary contribution is architectural validation rather than quantified load impact across a fleet. We reconcile that the customer value proposition is modest in this report, but system value may be larger when flexible loads can both reduce demand during constrained periods and load up when low-cost or low-carbon energy is available. New analysis should therefore model the broader utility value of this flexibility, including avoided power purchases, reduced reliance on alternative generation, and improved use of available energy.

Future utility field work should treat these communication and control pathways as complementary but not interchangeable. A cloud EMS is well suited where the goal is optimized HVAC flexibility with measurable load impacts. A utility-led OpenADR-to-BAS pathway is ideal where the goal is to validate price delivery, enrollment, telemetry, and operational integration for large commercial customers. A gateway is suitable where goals are to expand participation across fragmented devices, limited broadband environments, or customers not yet served by native price-responsive equipment. This comparison can guide targeted program design by identifying the key bottleneck (control performance, utility integration, or device reach) and selecting the architecture and metrics best suited to that need. Future work should expand seasonal and sectoral validation of predictive control; deepen multi-end-use optimization, especially HVAC plus EV charging; & accelerate native OpenADR 3 adoption so gateways can evolve from translators to coordinators; so integration burden does not remain a dominant market costs.

Conclusion

This paper began with a practical question: how can California's emerging dynamic pricing framework be converted into dispatchable, measurable, and customer-compatible device response? Across the three projects, the answer is not a single device, vendor platform, or program design, but a modular standards-based operating model that connects price publication, interoperable signaling, local or cloud control, and telemetry-based verification. The inclusion of PG&E's OpenADR 3.0 field study strengthens the paper's comparative value because it adds a utility-led implementation pathway, showing how standardized hourly prices can be integrated into automated HVAC control in large, distributed commercial campuses.

Together, the projects reveal complementary layers of a price-to-device ecosystem. The EMS demonstration shows that small-medium commercial buildings can produce measurable, comfort-preserving HVAC flexibility under hourly prices through predictive control. PG&E's project shows OpenADR 3.0 can connect utility price signals to large-building automation systems, while also surfacing the practical conditions that shape scalability: enrollment readiness, tariff mapping, customer authorization, data access, and site-specific control constraints. The gateway project shows standardized prices can reach mixed device ecosystems through a local bridge, including customers lacking broadband or native price-response capability.

The resulting conclusion is therefore stronger than "price-responsive automation is feasible." These demonstrations show that automated dynamic pricing with Open ADR possesses the traits required of a utility-grade resource: standardized signal delivery, repeatable control pathways, observable telemetry, comfort-compatible operation, and a credible path toward broader interoperability. They also show that scale depends as much on implementation details as on technology performance. Customer enrollment, data authorization, device compatibility, building-system readiness, and measurement practices must be treated as integral parts of the operating model if demand flexibility with dynamic prices is to become a dependable, procurement-grade resource for California's future needs.

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Disclosure
AI-assisted tools used: Grammarly, Copilot.
Used for: Rephrasing of some sentences and sourcing related works for citation & references.
Extent: light editing / citation research.
Human review: The authors reviewed and verified all content and citations.