Advancing Smart Home Optimization for Demand Flexibility: Are We There Yet?

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ABSTRACT

The emergence of advanced communicating household appliances and evolving connectivity standards represent a major leap forward for Smart Home energy management. Developed collaboratively by leading technology and utility stakeholders, several of these emerging protocols could enable seamless interoperability among consumer devices from multiple manufacturers, reducing fragmentation and simplifying customer adoption of utility demand flexibility programs and tariffs. California's Demand Response Emerging Technologies (DRET), a collaborative made up of California's three electric investor-owned utilities, is examining the potential for standardized communication protocols that could enhance mass-market end-use demand flexibility through improved device coordination, real-time energy data, customer education, and greater affordability.

This paper highlights existing Smart Home technologies, details current communications protocols, and presents two demonstrations that were conducted by the DRET. The first project utilizes Smart Speaker technology and a mobile app to motivate customers to respond to real time energy use, peak pricing, and power outages using technology they already own. The second explores enhanced interoperability, improved customer accessibility, low-cost options and optimized control of devices using OpenADR 3 through seamless integration with an automation hub that does not depend on broadband connectivity. These projects are part of a larger effort by the DRET to demonstrate the viability of demand flexibility using Smart Home technologies and explore potential solutions for new connectivity standards that would allow utilities and consumers to automate load shifting, manage distributed energy resources, and reduce peak electrical demand through a scalable framework that benefits all California rate payers.

Introduction

Within California, there are several regulatory agencies and policy makers that are increasingly prioritizing the need for research in Demand Flexibility (DF) over traditional Demand Response (DR). While DR has focused on temporary customer load reductions during electrical system emergencies or summer peak usage periods, DF emphasizes the continuous ability to shift, shape, and optimize electricity consumption in response to local grid conditions, renewable energy availability, customer preferences, and natural disruptions like extreme weather and wildfires. DR has a long history of performance and reliability through various programs, but as local grid needs and customer prosumer operations change in the future, DF will provide a more dynamic solution to meet those needs.

DF also supports California's broader goals of electrification, decarbonization, and grid modernization to match the adoption of new customer resources. As electric vehicles, heat pumps, batteries, smart panels, and other distributed energy resources become more common, electric service providers need to examine the opportunity to use these technologies as flexible grid assets rather than unmanaged loads. Through automation, smart controls, and open communication standards, DF can help customers manage energy use at the local level, improve grid reliability, integrate more renewable energy, and help mitigate costly infrastructure upgrades.

The consumer market for in-home technologies is also rapidly changing and many of these technologies are now enabled by new methods of device communication. The internet of things (IoT) is one such pathway and consists of a broad network of interconnected technologies that collect, exchange and act on data using the internet. IoT is used in a broad range of applications, including healthcare, agriculture, industrial automation, transportation, buildings and more.

Smart Homes are an example of how consumers can utilize a subset of IoT, focused specifically on single family homes. Smart Homes are equipped with connected devices and systems that enable automation and remote control of appliances, lighting, heating, cooling, security and other home functions. IoT in homes has accelerated consumers' ability to control and customize their lives, resulting in greater personal comfort and convenience, state-of-the-art home entertainment, increased security and over the last decade, home energy management.

To examine how these new enabling "smart" technologies can be enhanced for both consumer benefits and coordination with the smart grid, the DRET Collaborative facilitates research and demonstrations of innovative new demand response technologies, software, and system applications. DRET is funded by electricity ratepayers from California's three largest investor-owned utilities; Southern California Edison (SCE), San Diego Gas & Electric (SDG&E) and Pacific Gas and Electric Company (PG&E) and is authorized by the California Public Utilities Commission (CPUC) through 2027.[1]

The DRET Collaborative is dedicated to leading and sharing market assessments and demonstration project research designed to accelerate market adoption of emerging demand response enabling technologies across all customer sectors to support California's climate and electric reliability goals. With these goals in mind, the DRET conducted two demonstration studies that attempt to address some of the customer and grid value of Smart Home demand flexibility: 1) a behavioral approach using Smart Speaker technology led by SCE, PG&E and SDG&E respectively and 2) the Demand Flexibility Gateway Project, an advanced technology approach led by CalFlexHub[2], sponsored by the California Energy Commission (CEC) and developed in partnership with SCE, Lawrence Berkeley National Laboratory (LBNL) and technology developer Universal Devices, Inc.

What Makes a Smart Home Smart

A Smart Home is defined as a residence that is equipped with a broad network of interconnected devices, systems, appliances and electrical components that enable local automation and remote control of lighting, heating, cooling, security and other home functions, as illustrated in Figure 1. While most Smart Home residences today contain many of these advanced features, not all are interconnected or enabled so that they can communicate with each other.

[1] https://www.dret-ca.com/
[2] California Load Flexibility Research and Development Hub, calflexhub.lbl.gov .

Configurations of these devices are often designed so that the devices and systems connect and communicate with each other through a Smart Home ecosystem that overcomes differences in communication methodologies and systems. Integration with multi-vendor, and multi-protocol devices often requires a central hub, platform or communication protocol that facilitates seamless communication, and coordination between devices and is the key component to a Smart Home ecosystem. Figure 2 illustrates this interaction.

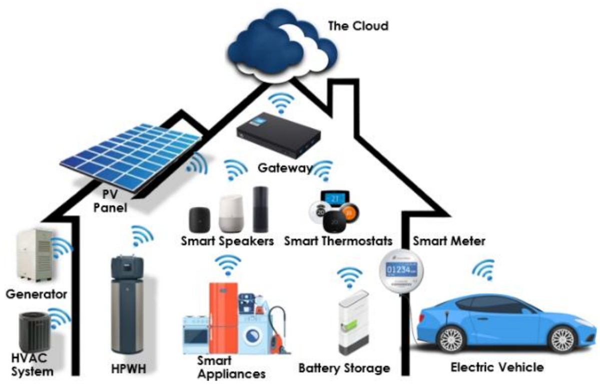

Figure 1. Smart Home

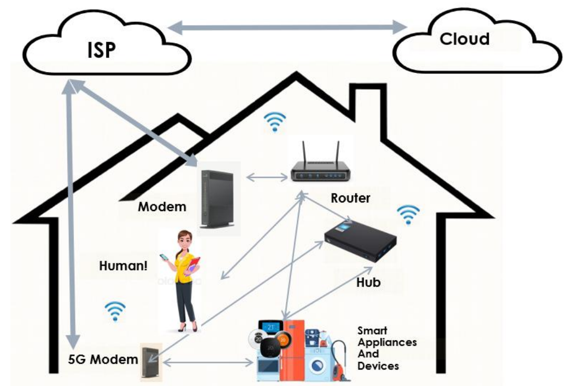

Figure 2. Smart Home Ecosystem

Communication protocols. A Smart Home communication protocol is a set of rules and standards that Smart Home devices use to communicate and exchange information with each other, along with gateways, hubs, controllers, and the internet. These protocols define how data are transmitted, received, and understood, ensuring compatibility and functionality within a Smart Home ecosystem. Communication protocols can be understood in two distinct layers:

1) **Application Layer**: Responsible for interpreting the data and determining what action should be taken. This is where devices often diverge: each manufacturer of a smart device often defines its own representation of rules, configurations, commands, properties, and state. These are commonly called communication protocols.
2) **Medium Layer (everything below the Application layer)**: Responsible for moving data from point A to point B. This is purely physical and at the transport-level: the wire, the radio signal, the network topology. The medium layer does not interpret the data; its sole function is delivery.

Each communication protocol exhibits specific capabilities across common features and considerations. They include:

- **Interoperability**: Allows devices from different manufacturers to work together. However, different protocols do not interoperate with each other. For example, Z-Wave and Zigbee are not interoperable.
- **Efficiency**: Optimizes data transmission to conserve bandwidth, energy, and processing power. For example, Bluetooth Low Energy (BLE) focused on conserving energy/battery vs. Wi-Fi.
- **Reliability**: Ensures stable communication between devices but this reliability is relative to the characteristics of the venue and the standard used. For example, Z-Wave mesh networking, vs. INSTEON brute-force repeating vs. Wi-Fi mesh networking.

- **Security**: Protects the protocol from unauthorized access or interference. For example, Z-Wave S2 vs. the multi-layer model promoted by Matter.

Table 2 lists the most widely used communications protocols in Smart Homes, their market share, and a short description of how they work.

Table 2. Communication protocols used in Smart Home ecosystems.

Protocol	**Market Share**	**Description**
Wi-Fi	~ 45% - 55%	Wi-Fi (Wireless Fidelity) is a networking technology that enables devices to connect/ communicate without physical cables. It operates based on the IEEE 802.11 standards, allowing devices to exchange data over radio waves within a specific range. Wi-Fi devices use the home network to provide monitoring and access to the consumer through a local hub, app, or the Cloud. • Consideration: each manufacturer has its own proprietary protocol for application-level communications.
Zigbee	~ 15% - 25%	Zigbee is a wireless communication protocol designed for low-power, low-data-rate, and short-range applications. Commonly used in Smart Home and IoT devices. Zigbee 3.0 has gone through a name change evolution, becoming dot.dot, then CHIP, and the latest, still being tested, is now called Matter.
Z-Wave	~ 5% - 10%	Z-Wave is a wireless communication protocol designed for Smart Home automation, allowing devices like lights, thermostats, locks, sensors, and more to communicate and operate together seamlessly. Benefits include: • Reliability, low power consumption, and ease of integration across various manufacturers' devices. • Z-Wave LR (Long Rage) can be used up to one mile and does not require mesh for that extension.
BLE/ Mesh	~ 10% - 15%	Bluetooth Low Energy (BLE) is a wireless communication protocol designed to transmit data over short distances. It is optimized for low-power consumption and widely used in devices where energy efficiency is critical, such as wearables, IoT devices, and Smart Home systems. BLE Mesh extends the functionality of BLE by enabling a mesh network topology. This allows devices to communicate with each other over a broader area by relaying messages through intermediary nodes, making it suitable for Smart Homes, industrial IoT, and other large-scale deployments.

Protocol	Market Share	Description
LoRa	Industrial/ Agriculture N/A	LoRa (Long Range) is a low-power, long-range wireless communication technology designed for IoT applications. It is primarily used for transmitting small amounts of data over long distances, making it ideal for use in environments where devices need to operate on battery power for extended periods. Mostly used for industrial/agricultural IoT but also used for Smart Home irrigation and dry contact closures where long range and low bandwidth are requirements.
Matter	Residential N/A	Matter is the newest communication protocol for Smart Home devices. It is developed by the Connectivity Standards Alliance (CSA), formerly known as the Zigbee Alliance and is currently in demonstration with multiple utilities. Major backers are Apple, Google, Amazon, and Samsung. Matter tries to address key issues in the Smart Home ecosystem: • **Fragmentation**: Different ecosystems (Apple HomeKit, Google Home, Amazon Alexa) often lack cross-compatibility. • **Complexity**: Consumers face challenges integrating devices across multiple brands. • **Security**: Matter includes robust encryption to ensure user data privacy.

Integration and compatibility. Integration and compatibility Integration are central to realizing opportunities for DF across a Smart Home ecosystem: integration being whether a device can join a given hub or platform, and compatibility being whether it then operates correctly and as intended within that ecosystem. For example, a Zigbee bulb pairs successfully with a hub (integration) but only exposes basic on/off control, while its dimming and color features aren't recognized (not fully compatible) because the hub or app doesn't support that device's complete feature set. Many Smart devices rely on a central cloud-only or cloud-optional hub to manage communication and automation. Without the hub, these devices may not operate effectively or at all. Many Smart devices use different communication protocols (e.g., Bluetooth, Zigbee, Z-Wave) and not all platforms or hubs support all devices or protocols. Users may end up with incompatible devices that don’t work together, creating a fragmented experience where Smart devices can only be controlled via separate apps or interfaces. Dependence on the internet interferes with reliability as cloud only devices stop working if there’s no internet connectivity.

Then there is cost to consider. Many Smart Home ecosystems require higher upfront costs for hubs, compatible devices, and cloud only solutions are increasingly based on subscription fees. Integrating multiple devices from different manufacturers can be complex, especially if they rely on different platforms or apps. Security is also a concern as many Smart Home devices are connected to the internet, increasing the risk of hacking, data breaches, or unauthorized access. Lastly, as every new iteration of products, standards and protocols emerge, older devices become incompatible, further complicating reliability, affordability and the user experience.

Challenges of a Constantly Changing Consumer Market

Smart Home technologies continue to expand and evolve rapidly through consumer demand, manufacturer competition, legislation, and technological innovation. Strategic collaboration has been difficult in today's consumer markets where stakeholders have competing agendas, resulting in many products with powerful capabilities, and none of them to date providing a universal or interoperable solution. Another challenge is the consumer and their purchasing preferences (Aggarwal & Singh 2024), where comfort, cost and convenience are the main drivers for device adoption. Addressing and overcoming these types of challenges are the focus of DRET collaborative research objectives for improving customer adoption of Smart Home technologies.

DRET Case Studies: Demonstrating Potential for Smart Home Demand Flexibility in California

The DRET Collaborative has completed multiple demonstrations to determine the feasibility of Smart Home technology to support California's demand flexibility goals. This paper presents two case studies. Additional DRET projects and full reports for both projects can be found at https://www.dret-ca.com/.

The following DRET demonstration projects address two challenge areas: 1) customer education and motivation to participate in energy management using devices they already have and 2) an affordable, demand side load operation system that is accessible to rural and disadvantaged customers who don't have access to broadband internet.

Smart Speaker Pilots

The DRET Collaborative conducted parallel studies across SCE, PG&E and SDG&E to determine the effectiveness of Smart Speaker technology, such as Amazon Alexa and Google Home to encourage customers to reduce energy use during peak pricing periods. The studies also tested customer interest in energy management related to rate selection, Time of Use (TOU) pricing, demand reduction, and public safety power shut-off notifications using technology they already owned. Figure 3 illustrates the key components to this effort:

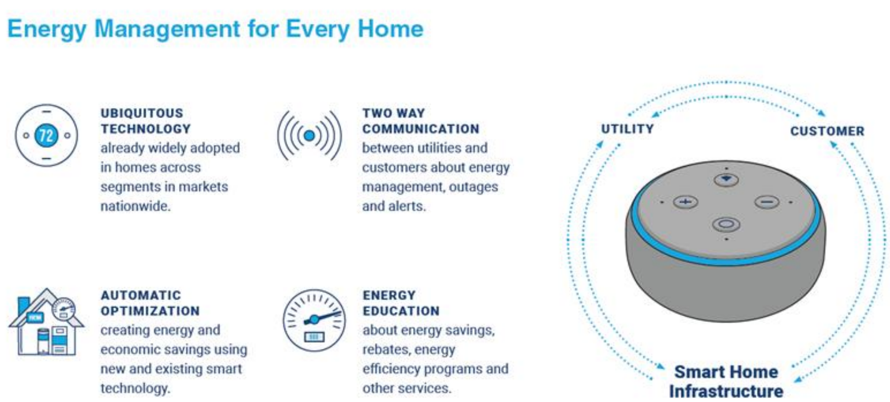

Figure 3. Smart Speaker Pilot Components

Each utility focused on a particular aspect of how Smart Speakers could be used to support behavior through educating customers on energy use, bill information, rates, pricing and marketing for existing programs. Table 4 provides an overview of the pilot by utility.

Table 4. Smart Speaker Pilot by Utility

SCE Smart Speaker Demonstration Project	**PG&E Voice Automation for Load Management**	**SDG&E Voice Activated Assistant for Energy Savings**
Demonstrated how Smart speaker voice commands can educate customers and automate connected thermostats and other common household devices to optimize energy usage. • 63 customers • Energy Expert Alexa Skill • Messaging on energy optimization and TOU • Smart switches, lights, ecobee thermostats • Connected to SCE Smart meter **Results** • TOU 5-8PM saved 10% or 0.22kW on Summer Weekdays. • TOU 4-9PM saved 9.7% or 0.23kW on Summer Weekends. • High participation rate of 69%.	Demonstrated how voice assistant technology could educate customers on energy usage, bill information, rates and TOU schedule and notification through voice and visual notifications. • 250 customers engaged • Energy Expert Alexa Skill • Education via speakers, display and mobile app • Messaging on energy optimization and TOU • Included Alexa color ring for notifications **Results** • High Price notification customers showed hourly TOU peak-period load reductions 3% to 5%. • Customers inquired about energy usage, on/off peak times and power outages. • 60% satisfaction rate.	Demonstrated how voice assistant technology could advance customer engagement, drive residential energy benefits and support marketing efforts for new and/or increase adoption of existing programs. • 7 customers (due to COVID) • Amazon Echo enabled with Alexa Skill • Ecobee Smart thermostats Notifications on TOU • Feedback on usage against baseline • Thermostat automation **Results** • Customers with Alexa enabled Smart Speakers stayed informed re: TOU. • Smart thermostats setpoints responded to customer preferences via the Alexa Skill commands. • Higher engagement led to improved performance.

Key takeaways. When interviewed, residential customers expressed that they are interested in managing their energy use through Smart Speaker technology and Smart Speakers are an effective way to educate and enable dynamic rate management. However, the study found that requiring customers to install additional hardware for automatic optimization was costly and inconvenient. As a result, a Smart Speaker + app configuration was developed for future use, providing a less costly and more effective way to engage customers in energy management using technology they interact with daily.

CalFlexHub Demand Flexibility Gateway Project

The California Energy Commission (CEC) funded LBNL's California Load Flexibility and Deployment Hub (CalFlexHub) program through Electric Program Investment Charge (EPIC) solicitation GFO-19-309[3] to support California's vision of using dynamic electricity pricing to motivate demand side load flexibility.

SCE provided a cost share match to develop specific activities to amplify the synergies among SCE's Emerging Markets and Technology (EM&T) demand flexibility research program, SCE's Expanded Flexible Pricing Rate pilot (CPUC R.22-07-005) and the CalFlexHub research objectives. These synergistic efforts will help SCE implement its clean energy future vision with the ultimate goal of reducing ratepayer costs and improving grid reliability while also reducing emissions.

The SCE specific activities for investigation in the Technology Demonstration and Deployment (TDD) effort included six subprojects in the CalFlexHub program. At the time this paper was written, the Demand Flexibility Gateway TDD Project with technology partner Universal Devices, Inc. (UDI) has final results. Figure 4 illustrates the Demand Flexibility Gateway Concept vision.

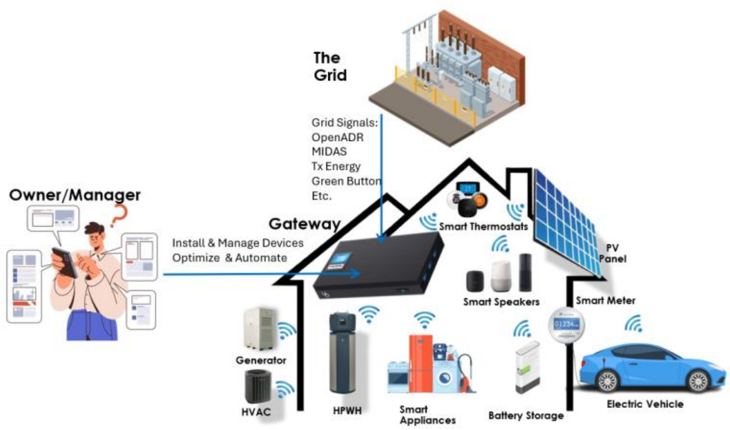

Figure 4. Demand Flexibility Gateway Concept

Objectives, research questions and audience. The key objectives of the Demand Flexibility Gateway Project were 1) to understand the barriers and associated costs of internet-based communication of utility hourly pricing signals for customers who lack a regular broadband connection and 2) to demonstrate a complete working system that securely communicates prices to a local gateway device, modifies those prices to facilitate demand flexibility, then rebroadcasts them locally - all over an OpenADR 3 secure protocol.

For the first objective (affordability of the gateway and cellular subscription costs) key questions included: What sorts of cellular services are available? Which are most appropriate? How much does the subscription cost? How can a cellular modem be integrated into the gateway?

For the second objective (functional working demonstration of OpenADR 3 operation) questions included: What steps are required to build a complete working system? Which Smart Home loads are best to integrate?

[3] https://calflexhub.lbl.gov/

SCE was interested in demonstrating a system architecture for price-based demand flexibility, and in particular how this system architecture could benefit electricity customers who lack ordinary broadband Internet access due to lack of funds, lack of availability or operational needs (e.g. the building does not provide broadband).

An on-site energy management gateway (as opposed to each device connected to a price server independent of each other), presents significant advantages in cost reduction and performance enhancement for flexible loads and devices, especially for customers who pay highly dynamic prices.[4] While this functionality could be incorporated into existing devices, certain scenarios—like non-broadband customers or situations requiring meter data—necessitate the deployment of new hardware. Add to this, the vast majority of California's current residential and commercial buildings cannot directly respond to dynamic pricing, making external price optimization crucial for millions of legacy devices.

The central technology developed for this project is a flexible, price-responsive gateway suitable for any residential (or small commercial) customer, with or without a broadband connection. Additional technologies required to develop the gateway include:

- **5G cellular radio**, cost-effectively integrated into the gateway for non-broadband customers,
- **Control of IoT devices** (including electricity loads) with communication, both within the gateway and (in the future) natively price-responsive devices and,
- **OpenADR 3** - implemented in the gateway itself, including contributions to the standard and to the OpenADR Alliance Reference Implementation.

Methodology and implementation. For the first objective of affordability, the approach was to survey at least three 5G cellular service providers for data plan subscription costs and then determine how to connect the hardware, which might be a wired connection, wireless, USB dongle, or integrated into the design of a new gateway device. This would help the team select the appropriate hardware and identify other costs for the connection. Understanding the network coverage and other relevant characteristics and capabilities would ensure the hardware and software could integrate into a single solution.

For the second objective of functionality, the approach was to outline the system architecture, integrate the CalFlexHub price server with the gateway and then choose appropriate loads to control for price response, creating integrations for each load.

The team investigated the technology, cost, and bandwidth implications of the three cellular (4G/5G) ISPs listed below. Considerable time was dedicated to developing drivers to enable communication with the hardware for both Verizon and Simplex, resulting in two solutions, not just the one required for the project. Table 5 shows the key data and cost parameters for the three providers.

Table 5. ISP Data Costs

	Data	**Cost**	**Comments**
Verizon	15 GB/Month	$20/Month	
ChoiceIoT	300 MB/Month	$4.99/Month	$0.04/MB Above 300 MB
SimpleX	250 MB/Flat	$5/Flat	Not monthly. $5 total for 250 MB

[4] https://www.pge.com/en/account/rate-plans/hourly-flex-pricing.html

SimpleX was determined to provide the least cost option if the monthly data use could be kept to 1 MB (considered realistic), enabling the initial 250 MB purchase to cover 20 years of operation. The data subscription cost could then be considered zero, with the $5 fee folded into the initial hardware cost.

The next step was to integrate the hardware into the gateway device. There are two primary methods for integrating hardware: 1) “module on chip” and 2) a USB dongle. The USB dongle was much easier to integrate with existing gateways or routers, but on a per unit basis was considerably more expensive. Table 6 lists the single unit cost for the dongle, and the unit cost if purchasing a million units. For SimpleX, the cost drops by almost two-thirds when scaling volume. Comparing ChoiceIoT to Simplex, at the high volume, the extra cost for Simplex is made up for at the end of three months with the lower data cost.

Table 5. USB Dongle Costs for Cellular Connectivity

	Hardware Interface	Cost / Unit	Cost @ 1M
Verizon	NOVATEL USB 730L	$79.00	$45.00
ChoiceIoT	NOVATEL USB 730L	$79.00	$45.00
SimpleX	JACS USB TD191-TAA	$148.00	$55.00

Integrating flexible loads with the gateway. There are three parts to integrating flexible loads with the gateway: 1) receiving the price from the CalFlexHub price server, 2) modifying that price, and 3) sending information over the Local Area Network (LAN) to flexible loads. Figure 5 illustrates the relationship between components.

Figure 5. Relationship Between Components

Reception. The existing CalFlexHub Event Server code and the current Virtual Top Node (VTN) Reference Implementation (RI) from the OpenADR Alliance were used as foundational baselines. Both systems are based on Python, so a Python virtual environment was created to efficiently manage and run the servers.

As the project progressed and the OpenADR specifications were finalized, the original code was abandoned in favor of a new code base for the Virtual End Node (VEN), which successfully passed the OpenADR 3 VEN Certification Test. This package is now available as an open-source implementation for a certified VEN, accessible for use by anyone through Universal Devices, Inc. github repository.

This process did have its challenges. The CalFlexHub code base was not aligned with the latest OpenADR 3 specifications, presenting significant challenges in implementation. The VEN worked but it was not authenticated properly due to an invalid authentication method used by OpenADR 3, and Reference Implementation had not followed the latest committed changes. These issues were rectified and the project was able to proceed.

In addition, during testing, OpenADR 3 payloads showed some inefficiencies which were raised with the OpenADR 3 Technical Working Group along with a proposed solution. Ultimately, the change was included in OpenADR 3.1. Uncovering and solving for these challenges shows the value of undergoing the type of test deployments completed in this project.

Modification. The gateway is capable of modifying the price before local publication. Meaning, the gateway could add a value that monetizes local greenhouse gas emissions (example: $100/ton) to convert it to a price component, then combine this with the retail price to create a local price. While this process in general is not difficult, price modification through the gateway only needs to be done in one place rather than in each flexible load, avoiding the need to add pricing to each separate device.

Communication with loads. There were two fundamental mechanisms tested to communicate with loads: 1) local broadcast of prices over OpenADR 3, and 2) optimization to the prices in the gateway. While optimization of the prices in the gateway worked effectively, broadcasting local prices over OpenADR 3 proved challenging at the time of this demonstration, as there is no known off the shelf commercially available product that included this capability. A second UDI gateway was used instead as a natively price-responsive device to test for functionality, and the full system was demonstrated to work as planned.

In the end, four devices were selected and demonstrated: Phillips Hue light bulbs, a Smart plug, an ecobee thermostat and an EV charger.

Final Results. An affordable cellular data connection was successfully demonstrated via the SimpleX cellular network, through the USB dongle, to the UDI gateway device, and all four devices operated as intended to achieve the functionality objective.

- 2 x Philips Hue light bulbs via Zigbee locally dimmed as prices increased,
- 1 x On/Off plug using Z-Wave controlled outlet turned off when prices were high,
- ecobee thermostat over the internet increased AC setpoint at high prices,
- Tesla EV over the internet charged during low-price times.

The algorithms demonstrated are simplistic, as the purpose of this project was not to innovate on the algorithm, but to show that the complete chain of communication (and related activity) works in practice. Gateway devices are readily available in the Smart Home technology markets, as are many devices that include cellular technology.

The project clarified the affordability objectives by providing a cellular/gateway alternative for price communication with modest subscription costs along with one-time hardware costs. Compared to the potential benefits of system wide grid flexibility, the cost is not large - and only a small percentage of customers need a cellular connection.

The working hardware system provided proof of existence that optimizing loads to dynamic prices works and is readily implementable. This configuration allows future OpenADR VENs, supported by the gateway's protocols (Z-Wave, Zigbee, Matter, INSTEON, X10), to respond to price signals using either the native OpenADR 3 payload, a specifically transformed version for each protocol, or functional control signals over those protocols. Today Zigbee can carry prices, and Matter is currently in demonstrations with multiple utilities to prove its viability. However, significant work remains to ensure seamless end-to-end functionality across different protocols.

The Need for Standardization Efforts

Both DRET demonstration projects were successful in proving their stated objectives – consumers can be educated and motivated to participate in energy management using technology they already use and there is a path to an affordable home energy ecosystem that is not reliant on broadband. However, both projects highlight the very real need for a set of communication standards that would support evolution across manufactures and communication protocols and ultimately create a path to scale to meet California's larger demand flexibility goals.

Numerous efforts have been made to standardize communication between utilities and behind-the-meter devices: SEP 1.x, IEEE 2030.5, CSIP-AUS, CTA-2045 and others, yet none has achieved mass adoption. (NIST 2014; Han et al. 2020; SGCC 2015). Despite cataloguing dozens of competing protocols across multiple release cycles, NIST's own framework acknowledges that consensus across the Home Area Network domain remained unresolved years into the effort (NIST 2014). Research into Smart Home adoption confirms that technological fragmentation, the proliferation of incompatible protocols, remains one of the primary barriers to scaling (Han et al. 2020). The reason is structural: manufacturers depend on differentiation, and end-to-end standardization reduces them to commodities. They have also already invested heavily in their own customer-facing infrastructure, such as mobile apps, cloud backends, and proprietary APIs, which they have little incentive to abandon. Defining a superset standard that accommodates every manufacturer's capability and business model has proven intractable.

The one notable exception is OpenADR, precisely because it scopes the problem narrowly: it standardizes the signal from utility to venue and deliberately ignores what happens behind the meter. That constraint is what makes it adoptable. However, as the grid evolves toward highly dynamic or even subscription-based tariffs, even OpenADR's model may need to evolve. The more sophisticated our ability to optimize behind-the-meter devices becomes, the more dynamic and granular the utility signals need to be.

The result of a lack of standardization for demand flexibility communications is that customers are left managing a fragmented ecosystem, multiple apps, multiple platforms, multiple credential sets, one for each manufacturer that chooses differentiation over interoperability. For future consideration, any successful standardization effort must take a lesson from OpenADR's design philosophy: define the signal, not the implementation. Standards should be limited to conveying intent, such as a price signal, a demand event, an operating envelope, and nothing more. What sits behind the electric meter is a different problem entirely, and it requires a different kind of solution: not another standard, but a local intelligence layer capable of integrating a customer's existing (i.e.: Smart Speakers + app or local gateway hub) and future devices, understanding their preferences and constraints, and translating utility signals into optimal device behavior automatically. One that can evolve as tariffs change, as new devices are added, and as grid programs grow more sophisticated, without requiring a firmware update from every manufacturer or a hardware replacement from every customer.

Critically, this methodology does not ask manufacturers to abandon their existing investments. They can retain their current infrastructure, their communication protocols (proprietary or otherwise), and their customer-facing platforms. What changes is not how they talk to their devices, but how those devices participate in a broader Smart Home energy ecosystem. Manufacturers integrate once, on their own terms, and their customers gain the ability to respond intelligently to both personal preferences and grid requirements, without friction, and without compromise.

The role of AI in the Smart Home. Communication standards and protocols that integrate software with artificial intelligence have a meaningful role to play in optimizing the relationship between utilities and behind-the-meter devices. At a high level, there are two complementary types of AI relevant to this problem: Discriminative AI analyzes and classifies existing data, learning the boundary between categories rather than creating anything new. Examples would be image classifiers, spam filters, anomaly detection, and sentiment analysis. Discriminative AI is, in essence, a critic: it judges what something is (Feuerriegel et al. 2024).

Generative AI learns the underlying distribution of data and produces new content such as text, plans, configurations, and code. Large Language Models (LLMs), image generators, and voice synthesis are all examples. Generative AI is the artist: it creates something new (Feuerriegel et al. 2024). Applied to Smart Homes, the distinction maps cleanly to function: Discriminative AI handles classification and intent resolution, determining that "what's my range" refers to the vehicle, that "is it paired" refers to the speaker, or that "check for intrusion" means scan the event log for anomalous access patterns.

Generative AI then acts on those classifications, producing executable plans. An example would be: If range exceeds 100 miles or price is below 50 cents, set charge target to 100% and begin charging, set all cooling setpoints to 72°F; otherwise suspend charging, set charge target to 80%, turn off pool equipment, and set cooling to 75°F; apply this only on Mondays and Thursdays from five minutes after sunset to sunrise (Giudici et al. 2024).

Applied to standards, the implications are more profound: Discriminative AI is poised to reduce dependence on rigid application-layer standards: rather than requiring every developer to know that 0x26 means charge state, a device can describe its own capabilities in plain language, (Srivastava et al. 2024; De Vito et al. 2025):

- The commands it accepts with their parameters and units of measure,
- The events it emits,
- The settings available for configuration.

Generative AI takes this further, enabling new device integrations to be derived directly from publicly available APIs or documentation, without a human developer writing a driver (Srivastava et al. 2024). Together, these two AI types shift the burden of interoperability away from standards committees and onto the device itself, enabling semantic-level integration that no specification body could anticipate or mandate. This capability is well-suited to deployment at the gateway level, where local inference on edge hardware makes it practical without cloud dependency.

Conclusion

The title of this paper asks the question: Advancing Smart Home Optimization for Demand Flexibility - Are we there yet? Spoiler alert - we are not. But "we" and the Smart Home markets with the latest advances in both innovative technology and intelligent software are closer than ever before, and the path forward is more encouraging than it has ever been.

The case studies presented here demonstrate that the behavioral and technical foundations for the development of new forms of demand flexibility are in place. The Smart Speaker demonstrations illustrate that consumers can be educated and motivated to participate in real time energy management using technology they already own. The Demand Flexibility Gateway Project establishes that the end-to-end chain works: price signal to gateway to multi-protocol device control, all at an affordable price without the need for broadband. What remains is the harder problem: implementing at scale, across hundreds of millions of legacy devices already installed in homes, without requiring consumers to replace equipment or developers to write a new driver for every product on the market.

This is where artificial intelligence is positioned to change the equation. As described in the preceding section, discriminative AI can resolve user intent and device identity without rigid protocol schemas, and generative AI can derive new device integrations directly from manufacturer documentation, without a human developer in the loop. Together they shift the burden of interoperability away from standards committees and onto the intelligence layer of the gateway itself. A gateway that understands devices semantically and does not need to wait for the next version of a specification. It adapts.

Open source, vendor neutral, and plug and play are not aspirational labels, they describe how consumers already expect technology to work. WordPress powers nearly half the web. Android and iOS created ecosystems that neither mandated nor anticipated every application built on top of them. A Smart Home demand flexibility platform has the potential to follow the same trajectory: an app-based, plugin model that gives consumers high functionality and personal choice, gives developers an open and stable foundation to build on, and gives utilities a reliable, scalable path to the behind-the-meter resources they need.

We are not there (at scale) yet. But the gateway is built, the customers have shown interest, the platform model is proven, and recent research demonstrates the technical feasibility of AI-enabled semantic integration at the gateway level. The question is no longer whether it is possible. The question is how quickly the industry chooses to move.

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