From the cloud to your basement: Can New Communication Protocols Solve the Interoperability Roadblocks in Residential Demand Flexibility?

Anand Krishnan Prakash, Brian Woo-Shem, Marco Pritoni, Lazlo Paul, Peter Grant, Weiping Huang, Jingjing Liu, Mary Ann Piette, Lawrence Berkeley National Lab
Bruce Nordman, Independent Consultant
Don Jackson, Clark Communications Corporation

ABSTRACT

Field studies show that demand flexibility in residential buildings can save up to 20% in energy costs, but requires secure, automated, and reliable coordination across multiple devices and stakeholders. Integration between platforms is typically done on a one-to-one basis, requiring device-specific and platform-specific programming and updates. This manual process is expensive, as developers must manage protocol translation and data exchange through proprietary or reverse-engineered APIs, often without a consistent or standardized data format. This fragmented approach hinders scalability and slows the adoption of demand flexibility technologies.

Recently, several communication protocols have emerged in the US to address these challenges by defining common data models and standard interfaces for device-to-grid and device-to-device interactions. Although many of these protocols intend to provide comprehensive interoperability, in practice, each addresses a specific segment of the ecosystem and serves a distinct set of stakeholders. Understanding their respective roles and limitations is essential for deploying flexible, interoperable energy systems at scale.

In this paper, we define a set of desirable features for achieving interoperability in residential demand flexibility and use them to evaluate emerging communication protocols, such as Open Automated Demand Response (OpenADR) 3, Institute of Electrical and Electronics Engineers (IEEE) 2030.5, Matter, Consumer Technology Association (CTA)-2045, Open Charge Point Protocol (OCPP) and Home Connectivity Alliance (HCA), and their underlying data models. We analyze their use cases, stakeholders and their areas of overlap. Finally, we outline our vision on how these protocols can work together to enable seamless utility-to-device communication, supporting scalable, interoperable demand flexibility and informing researchers, policymakers, and industry stakeholders.

Introduction

With the growing penetration of behind-the-meter energy resource and generation capabilities, while peak loads and overall load are expected to increase due to data centers, industry growth, and other factors, the electric grid in the United States is facing new challenges. In the residential sector, the increasing electrical demand from heating, ventilation and air conditioning (HVAC) systems and electric vehicles further constrains the aging distribution network. Traditional grid balancing mechanisms that maintain frequency and voltage through real-time generation dispatch become increasingly expensive and technically challenging as the DER capacity and the demand grows. Without corresponding flexibility on the demand side, grid operators must invest heavily in peaking generation, energy storage, or transmission and distribution upgrades to accommodate variability, which increases costs to grid operators and consumers (Specian and Aquino 2026).

Automated demand flexibility (DF) offers an alternative: the ability of building loads, including heating, cooling, water heating, EV charging, and controllable appliances, to shed or shift consumption in response to grid conditions or price signals. Data from conventional DF programs such as event-based demand response programs show that residential DF achieves peak demand reductions of 4-20% and energy cost savings of 10-20% for participating customers, depending on program type and customer enrollment rates (FERC 2023; IEA 2023). DF around continuously dynamic prices can have a payback period of 0 to 5 years for technologies including residential EV charging, connected thermostats, pool pumps, and water heaters (Grahovac et al. 2026). Benefits for the grid can be even greater. Load shift and shed, if adopted at the cost-effective economic potential, are projected to save over $4B in avoided grid costs annually in 2050 (Gerke et al. 2024). More importantly, distributed DF provides grid operators with a low-cost, scalable resource to balance supply and demand without requiring massive infrastructure upgrades. This is particularly valuable for distribution system operators (DSOs) managing feeder-level congestion, where targeted DF can defer or eliminate costly distribution system upgrades. The Federal Energy Regulatory Commission (FERC) and North American Electric Reliability Corporation (NERC) have recognized this potential. FERC Order 2222 (FERC 2020) mandates that organized markets create pathways for distributed energy resources, including demand response aggregations, to participate in wholesale markets on equal footing with conventional generators. These new drivers are accelerating utility and aggregator investment in residential DF technologies.

Current residential DF deployment in the United States reflects a patchwork of DF programs, approaches, platforms and communication protocols (IEA 2023; Toderean et al. 2025). Device control relies on manufacturer-specific APIs, smart home-specific protocols like Zigbee and Z-Wave (Toderean et al. 2025), virtual power plant (VPP) platforms with custom APIs or Institute of Electrical and Electronics Engineers (IEEE) 2030.5[1] or Open Automated Demand Response[2] (OpenADR) 2.0b integrations (Nordman et al. 2024), and manual behavioral interventions. Utilities and aggregators notify customers of DF opportunities through multiple channels, including utility apps, email, phone calls, SMS, aggregator platforms, and Home Energy Management Systems (HEMS) dashboards (SCE 2026), with communication approaches varying across providers and regions without standardization (SCE 2026; Mihalache et al. 2024).

A prominent example illustrates the custom integrations required: Consumer Technology Association (CTA)-2045[3] was mandated for utility-controlled water heaters in Washington, Oregon, and Colorado beginning in 2021-2022, with the expectation of broad adoption (Cox et al. 2024). However, CTA-2045 requires an aftermarket external communications module (Universal Communication Module or UCM) that customers must purchase and install separately (could be procured by the customer's utility as well), costing approximately $150-250 (Gabriel et al. 2024)[4]. The protocol between the UCM and demand response providers is not standardized. While this approach may be beneficial in some cases, such as when a cellular connection is needed to communicate with a device, it requires proprietary integrations by each aggregator. (Kehmeier 2026).

[1] https://standards.ieee.org/ieee/2030.5/11216/
[2] https://www.openadr.org/
[3] https://www.cta.tech/standards/ansicta-2045-b/
[4] https://store.skycentrics.com/ecoport - prices as of 2026

Such fragmentations creates several systemic problems: high integration costs as developers manage device-specific APIs and data parsing for each device-aggregator-utility combination; limited scalability for new actors who must develop integrations with every major utility and device platform; inconsistent reliability and latency due to lack of standardized performance requirements (Paresa et al. 2024); security and privacy risks from reverse-engineered APIs (Zhou et al. 2019) and undocumented integrations; and unclear architectural alignment across utilities and aggregators choosing different DF approaches (Outcault et al. 2024; Toderean et al. 2025).

Current Approaches

The literature identifies two main approaches to traditional DF. Explicit DF relies on flexibility events that are dispatched, while implicit DR relies on price signals to motivate device flexibility. More recently, other types of DF have emerged, including but not limited to network-aware, bidding/auction-based and hybrid, each with different communication requirements and grid coordination mechanisms. A detailed description of these approaches and their communication requirements is provided in the Background section.

At the same time, the previous decade has seen the rise of various communication protocols designed to facilitate smart home automation and residential demand flexibility (Bienert 2023). However, each one of them targets different market segments or end-uses. OpenADR is a mature protocol utilized primarily for signaling between grid operators and aggregators in North American and European markets, though the communication to consumer devices is generally handled by other protocols, such as Matter. In contrast, CTA-2045 provides a modular interface for direct grid-to-appliance management, though its practical application remains largely concentrated on water heaters with integrated control logic. While IEEE 2030.5 offers a robust framework for coordinating behind-the-meter resources, its deployment is predominantly focused on inverters rather than directly from the grid to consumer devices. Similarly, Open Charge Point Protocol (OCPP)[5] serves a narrow domain by facilitating communication within electric vehicle charging infrastructures. Matter[6] addresses local interoperability across diverse vendor ecosystems within the home; however, it currently lacks native mechanisms for coordinating directly with external utility or aggregator platforms.

Despite the emergence of these protocols, critical gaps prevent interoperability. First, there is no clear mapping between DF approaches and communication protocols; different approaches have fundamentally different communication requirements, yet no systematic analysis exists of which protocols best support which approaches. Second, protocol segmentation means each emerging protocol addresses a specific stakeholder segment with no standard translation between them. Third, there is no consensus framework defining what "interoperability" means in residential DF or specifying clear technical requirements tailored to residential use cases. Fourth, the fragmented regulatory landscape with different regions mandating different protocols (California Rule 21 mandates IEEE 2030.5; FERC Order 2222 does not prescribe protocols; Some state laws prescribed CTA-2045 for water heaters) creates uncertainty for manufacturers and aggregators.

In this paper, we address existing interoperability gaps by conducting an analysis of communication protocols for residential demand flexibility, establishing a clear mapping

[5] https://openchargealliance.org/protocols/open-charge-point-protocol/
[6] https://csa-iot.org/all-solutions/matter/

between these protocols, specific DF approaches, and their underlying technical requirements. We define a framework of desirable features to evaluate emerging and established protocols, examining their ability to represent grid signals, operational constraints, and telemetry data while assessing their stakeholder adoption and deployment maturity. Our evaluation produces protocol-to-approach mapping that identifies critical technical misalignments and functional overlaps across diverse scenarios. Finally, we propose pathways toward improved interoperability frameworks including gateway/middleware architectures, regulatory harmonization strategies, potential convergence on common data models, and implementation roadmaps for different stakeholders.

Background

Stakeholders in Residential Demand Flexibility

Residential DF involves multiple stakeholders operating at different levels of the electricity system. FERC Order 2222 defines the key market participants: regional transmission operators or independent system operators (RTOs/ISOs) that administer regional energy markets, distribution utilities (investor-owned and municipal) that operate retail demand response programs, and DR aggregators that enable residential customer participation in wholesale markets or utility DR programs (FERC 2020). In this paper, customers are residential building occupants (both single-family and multi-family). Modifying the operation of flexible residential assets requires communication through multiple intermediaries: device manufacturers' cloud platforms, local and cloud-based HEMS, aggregator platforms, and in some cases direct utility connections (Liu et al. 2024). Each communication pathway: utility-to-HEMS, aggregator-to-HEMS, manufacturer-cloud-to-device, and ISO-to-aggregator involves distinct stakeholders and requires distinct interoperability protocols, as detailed in the Communication Pathways section below.

Demand Flexibility Approaches

The demand flexibility approaches described in this section were derived from a review of demand response and demand-side flexibility literature, program documentation, and field-deployment reports. We build on the well-established distinction between implicit (price-responsive) and explicit (event-driven) demand flexibility (SEDC 2016; Carvallo et al. 2023; D'Ettorre et al. 2022), and extend it with additional categories that reflect coordination mechanisms increasingly observed in residential DF programs and the emerging literature. This section describes these commonly implemented DF approaches, which structure how DF information flows between grid operators, aggregators, and residential devices.

Price-Based (Implicit) Demand Flexibility

Price-based DF operates by publishing electricity prices such as Time-of-use (TOU) rates, Critical Peak Pricing (CPP) or dynamic/real-time pricing and allowing customers or automated systems to optimize consumption in response to those price signals without direct grid control (Carvallo et al. 2023). The utility does not explicitly control individual loads. Instead, economic incentives drive demand adjustments. TOU and CPP rates are the most widely deployed forms of implicit demand flexibility in residential settings (Carvallo et al. 2023; FERC

2023). Emerging dynamic pricing programs[7] extend this model by updating prices more frequently (hourly or sub-hourly) to reflect real-time wholesale market conditions, generation availability, or system constraints. Dynamic pricing creates stronger price signals for real-time load optimization but requires advanced metering and a communication and control infrastructure to implement effectively.

Event-Driven (Explicit) Demand Flexibility

Event-driven DF issues direct control signals often requiring advance declaration of flexibility capabilities (SEDC 2016). In this model, the utility explicitly signals grid conditions or control requests to devices or aggregators, which then adjust consumption according to predefined parameters or contractual arrangements. Common implementations include automated demand response events in which utilities send signals to thermostats, water heaters, or other controllable loads to reduce consumption during peak demand periods (FERC 2023). Participants may be notified of upcoming events with advance notice (e.g., day-ahead or several hours in advance), allowing them to prepare, or events may be initiated with minimal notice for emergency conditions.

Network-Aware Demand Flexibility

Network-aware DF communicates distribution system operating limits to devices or aggregators, within which they optimize consumption. This approach is implemented via real-time or day-ahead signals containing dynamic operating envelopes that specify available headroom on specific distribution feeders or transformers, thereby allowing devices and aggregators to shift flexible loads while respecting local grid constraints. This approach is emerging for residential-scale congestion management and hosting capacity optimization (Nasr et al. 2023). Rather than issuing explicit control commands, the DSO broadcasts constraint signals: "Feeder X has 2 MW of available headroom; optimize your load within this limit." Devices and aggregators then coordinate to maximize flexibility while staying within the announced envelope. This approach is particularly valuable for non-wire alternatives, deferring or avoiding costly distribution infrastructure upgrades by using distributed energy resources to manage local feeder constraints.

Bidding/Auction-Based Demand Flexibility

Bidding/auction-based DF allows customers or aggregators to submit flexibility bids into market mechanisms, enabling residential resources to participate in wholesale electricity markets, capacity markets, or ancillary service markets. Unlike price-based and event-driven approaches, which are primarily coordinated by utilities or DSOs, bidding-based DF leverages competitive market mechanisms to procure flexibility. This approach enables wholesale market participation by aggregated residential resources (Ottesen et al. 2018). Aggregators collect flexibility offers from customers and submit aggregated bids into day-ahead or real-time energy markets, capacity auctions, or frequency regulation markets. Residential loads can thus contribute to grid-level services traditionally provided by large power plants, such as frequency regulation or reserve capacity.

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

Hybrid Demand Flexibility

Hybrid DF combines multiple DF approaches at different timescales, creating a layered coordination strategy that leverages the strengths of each approach. For example, price-based signals can govern day-ahead scheduling decisions, event-driven automated dispatch can handle real-time load reduction in response to grid stress, and wholesale market bidding can enable capacity service participation. This approach is new but has shown promise in aggregator programs. A large smart thermostat aggregator's service, for instance, couples TOU rate optimization with automated thermostat dispatch across more than 5 million enrolled homes, while also developing wholesale capacity market participation for the aggregated residential resource (Blasnik et al. 2025). By layering multiple coordination mechanisms, hybrid approaches can extract greater value from residential flexibility while respecting the operational and commercial constraints of different market timescales. However, it is to be noted that hybrid approaches are still just emerging and there might be restrictions on participation in multiple DF programs simultaneously.

Other Approaches

In local/peer-to-peer DF and transactive energy architectures, customers and prosumers trade flexibility with each other, often mediated by blockchain or other distributed ledger technologies. These still remain largely experimental, with limited implementations at residential scale to date (Nizami et al. 2022). While these approaches offer promise for enabling decentralized, user-controlled flexibility markets, practical barriers related to regulation, market design, and technology standardization have limited their adoption in residential settings.

Review of Communication Protocols for Residential Demand Flexibility

Protocol Review Scope

As the scope of this paper is residential DF, we selected protocols for our evaluation based on following three criteria:

- Current or Emerging Residential DF Deployment: Protocols with active use in residential DF programs in the US are prioritized.
- Relevance to Residential Building Scale: Our focus is on communication protocols that interact with consumer (in home) devices. Protocols that do not conduct direct communication with typical residential devices are outside of our scope (such as International Electrotechnical Commission (IEC) 60870-5-104[8], Distributed Network Protocol 3[9], IEC 61850[10] GOOSE)
- Technical Feasibility for Modern Residential Devices: Protocols supported by residential devices manufactured after 2020 with embedded microcontrollers and external connectivity are prioritized.

[8] https://webstore.iec.ch/en/publication/3746
[9] https://standards.ieee.org/ieee/1815.2/7731/
[10] https://webstore.iec.ch/en/publication/6028

Protocols Selected for Detailed Review

Open Automated Demand Response (OpenADR)

OpenADR is a specification and a communication protocol for demand response communication maintained by the OpenADR Alliance. OpenADR defines two primary entities: Virtual Top Nodes (VTNs) representing grid operators or aggregators, and Virtual End Nodes (VENs) representing buildings, devices, or customers. It may be implemented through a variety of platforms including direct integration on a connected device. OpenADR 3, released in 2023 uses RESTful APIs and JSON instead of XML messaging over HTTP/HTTPS in OpenADR 2b. OpenADR is widely deployed in utility DR programs across North America and Europe and is mandated in California for some applications. OpenADR 3 reduces implementation complexity and costs, supports local communication, and improves security with OAuth2 and TLS 1.2 and was designed to support all residential DF approaches: price-based (price signal transmission), event-driven (event dispatch), and hybrid approaches.

Consumer Technology Association (CTA)-2045

CTA-2045 (formerly CEA-2045) is a standard electrical port and communication protocol for demand response on appliances (water heaters, HVAC, pool pumps). CTA-2045 defines a modular port on appliances and a basic set of DR events (shed, load-up, critical peak). It allows grid operators to manage power consumption in appliances like water heaters and HVAC systems to enhance grid stability and enable load shifting. CTA-2045 is mandated in Washington, Oregon, and Colorado for water heaters.

Institute of Electrical and Electronics Engineers (IEEE) 2030.5

IEEE 2030.5 is a REST/XML over HTTPS protocol designed for communication between utilities and distributed energy resources (DERs), including solar inverters, batteries, smart meters, and EV chargers. It is mandated in California for DER interconnection under Rule 21 (CPUC 2026). IEEE 2030.5 defines a comprehensive information model for DER devices, including capability reporting, control functions (active power setpoint, reactive power, etc.), and telemetry (power, energy, frequency).

Open Charge Point Protocol (OCPP)

OCPP is a protocol for communication between EV charging stations and charging networks. OCPP versions 1.5, 1.6, and 2.0.1 define increasing levels of functionality, with OCPP 2.0.1 including smart charging capabilities for demand response. OCPP supports price signals, charging schedules, and remotely initiated charging control. OCPP 2.0.1 enables vehicle-to-grid (V2G) and managed charging for demand response participation.

Matter

Matter is a smart home interoperable communication protocol developed by the Connectivity Standards Alliance (formerly the Zigbee Alliance) to enable cross-vendor device compatibility within a customer's home. Matter uses Thread (a mesh protocol over 802.15.4), Wi-Fi, or Bluetooth for communication between devices and a local hub/gateway. Matter includes clusters for device control, including emerging energy management clusters: Device Energy Management, Energy Measurement, Power Measurement, and device-specific clusters for thermostats, water heaters, and EV chargers. Matter communication does not directly support grid communication; integration with grid signals requires a separate protocol.

Home Connectivity Alliance (HCA)

HCA[11] is a manufacturer-led effort for cross-brand interoperability among long-life appliances, HVAC systems, and televisions, developed by an alliance of appliance makers. HCA defines a cloud-to-cloud (C2C) interface in which one manufacturer's cloud communicates with another's, enabling "any app to any device" control without requiring a local hub. The HCA Energy Management Specification (HCA 2026) extends this model to demand response and energy monitoring, defining APIs and data models for energy reporting, control, subscriptions, and notifications, and is designed to expose richer, appliance-specific controls. Adoption remains early, with the first integration of energy management specification happening in November 2025 (HCA 2025).

Proprietary Protocols

Device manufacturers often use proprietary communication protocols often with limited or no public documentation and manufacturer-specific cloud APIs subject to unilateral change. These create vendor lock-in, hinder interoperability, and raise barriers to market entry for new vendors and aggregators.

Other Protocols and Specifications

- **HTTP/REST over TCP/IP:** Many modern HEMS and appliances use HTTP/HTTPS with REST APIs for cloud communication. While flexible and developer-friendly, HTTP/REST lacks semantic interoperability for energy-specific data models, leading to proprietary implementations that do not solve interoperability.
- **Modbus[12]:** A simple industrial protocol widely used in building automation for communication between gateways, smart meters, HVAC controllers, and batteries. Modbus defines basic data types but lacks energy and demand response semantics, requiring custom register interpretation.
- **DLMS/COSEM[13]:** An international standard (IEC 62056) for smart meter communication, supporting price information and load control commands. While widely deployed for utility meters, DLMS is meter-focused and does not address building-level flexibility coordination or multi-device control.
- **Zigbee[14] and Z-Wave[15]:** Low-power wireless mesh protocols for home automation but both are being superseded by Matter, which offers improved interoperability semantics and manufacturer backing.
- **CEE Residential Integrated Home Specification**[16]: Provides energy efficiency, load response capabilities, consumption reporting, data sharing, security, consumer override, and communications requirements, but is not a communication protocol in itself, instead listing many of the other protocols listed in the above sections as options.

[11] https://homeconnectivityalliance.org/
[12] https://www.modbus.org/
[13] https://www.dlms.dev/dlms_cosem/
[14] https://csa-iot.org/all-solutions/zigbee/
[15] https://z-wavealliance.org/
[16] https://cee1.org/images/pdf/CEE_ResIntegratedHome_Specification_21Jul2021.pdf

Desirable Features for Communication Protocols to Achieve Scale in Residential Demand Flexibility

This section identifies a set of desirable features that help enable residential demand flexibility at scale. These features are drawn from existing literature with empirical evidence, surveys of customer experience with demand response, and studies identifying gaps in demand response programs. While not exhaustive, we believe these features are among the most impactful for enabling scalable DF in the residential sector.

- **Response guarantee:** For demand flexibility programs to be effective, devices should not only receive and interpret grid signals over a protocol but also reliably change their operation in response. A device may support a protocol, successfully receiving and interpreting a message without the resulting change in operation being tracked or guaranteed by the protocol (Paresa et al. 2024; Outcault et al. 2024).
- **Technical interoperability:** A device should be able to communicate with any aggregator or utility that uses the same protocol, regardless of where in the country it is installed (Toderean et al. 2025; Outcault et al. 2024).
- **Semantic interoperability:** Beyond exchanging messages, a device benefits when the meaning and interpretation of what is communicated remain consistent across different aggregators or utilities using the same protocol (Toderean et al. 2025).
- **Customer override and service priority:** Protocols that support customer override and opt-out mechanisms allow residential occupants to retain control over minimum comfort thresholds (e.g., heating setpoint floors, cooling ceilings) that aggregators or grid signals cannot violate. This feature addresses a key residential market barrier: surveys show consumers fear loss of comfort, and acceptance of demand flexibility programs depends heavily on demonstrated respect for occupant preferences (Mihalache et al. 2024; German Federal Network Agency 2021; Chitchyan et al. 2019).
- **Cyber-security and privacy:** Given customer concerns about exposure to security and privacy threats, protocols that implement state-of-the-art security practices (such as TLS 1.2+, mutual authentication, and certificate-based PKI rather than custom encryption) are better suited to residential DF at scale (Toderean et al. 2025; Onunkwo 2020; SunSpec Alliance 2018).
- **Transparent device-level flexibility reporting:** For applicable DF programs, devices that can report their flexibility capabilities to aggregators and grid operators, such as available capacity, ramp rates, minimum/maximum operating constraints, and customer priority overrides, over the communication protocol support more accurate dispatch and settlement (Zandi et al. 2017; SunSpec Alliance 2018; gridX 2026).
- **Breadth of asset coverage:** Residential flexibility is distributed across a heterogeneous mix of end uses and on-site resources such as HVAC, water heaters, batteries, EV chargers, pool pumps, and general appliances (Neukomm et al. 2019). A protocol that can address this range of asset types, rather than a single device class, might be better suited to enabling whole-home flexibility at scale (Neukomm et al. 2019; Toderean et al. 2025).

Communication Pathways

The four primary communication pathways for residential demand flexibility are shown in Figure 1, illustrating the forward flow of grid signals and control commands from grid operators, utilities, and aggregators to customer devices. When both green and orange lines are shown, they indicate alternative implementations. While feedback from the devices to the grid may occur, it is not depicted in the figure.

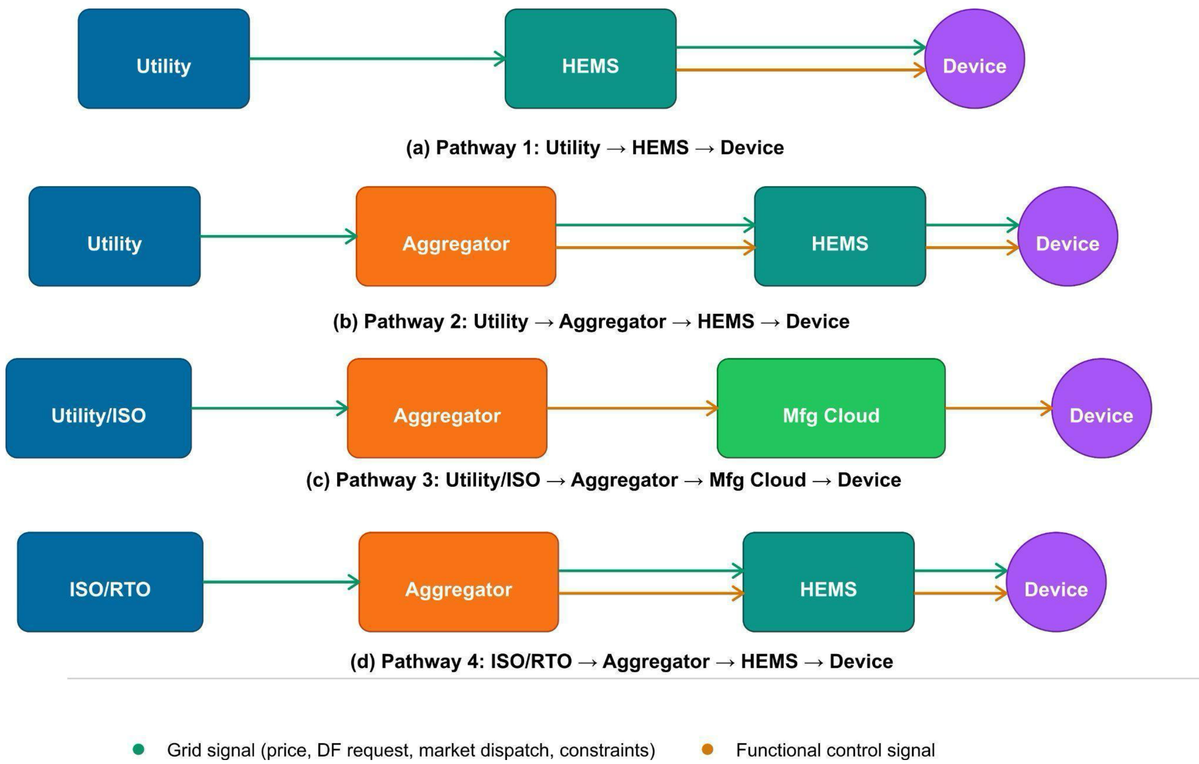

Figure 1. Grid & control communication pathways for residential demand flexibility

Pathway 1 enables direct utility-to-HEMS coordination: the utility sends grid signals (price, demand response events, or distribution constraints) to a customer's HEMS, which translates these signals into device-level control commands. **Pathway 2** introduces an aggregator as an intermediary, enabling virtual power plant (VPP) coordination and wholesale market participation: utilities send signals to aggregators managing customer portfolios, and aggregators dispatch commands through individual customer HEMS. **Pathway 3** leverages manufacturer platforms for device coordination: aggregators or utilities communicate directly with the manufacturer cloud, which then dispatches commands to individual appliances. **Pathway 4** enables wholesale market participation: independent system operators communicate market signals and dispatch requirements directly to aggregators, who then coordinate customer HEMS and devices for participation in capacity, energy, and ancillary service markets. Each pathway also involves implicit return communications, device acknowledgments (ACK/NAK), telemetry reporting (energy use, status), and flexibility capability declarations (not shown in Figure 1 for clarity).

Evaluation Results

Evaluating Protocols Against Desirable Features of Residential Demand Flexibility

Table 1 describes how each protocol supports the desirable features above; it is not a ranking, and supporting more features does not by itself indicate a better fit. No protocol strongly supports every feature, so practical deployments will likely pair protocols. OpenADR is a mature, asset-agnostic grid-signal protocol but offers weaker guarantees that a device acts on a signal. IEEE 2030.5 and OCPP support most features strongly, including semantic interoperability, but are domain-specific: covering distributed energy resources and EV charging, respectively. Matter is strong on local interoperability, override, and security but weaker on grid-facing reporting. CTA-2045 and HCA span many asset types but support other features only partially. Proprietary protocols may work within a single vendor's ecosystem but fail interoperability outright; despite this, residential DF today remains largely vendor-dependent and based on proprietary interfaces (Toderean et al. 2025; Outcault et al. 2024). Importantly, breadth of asset coverage should be weighed alongside per-feature support, since a protocol strong within one device class does not enable whole-home flexibility.

Table 1. Feature support across communication protocols for residential demand flexibility

Desirable feature	OpenADR	IEEE 2030.5	Matter	OCPP	CTA-2045	HCA	Proprietary Protocols
Response guarantee	P	Y	P	Y	P	P	P
Technical interoperability	Y	Y	Y	Y	P	P	—
Semantic interoperability	P	Y	Y	Y	—	P	—
Customer override and service priority	P	—	Y	P	P	P	Y
Cyber-security and privacy	Y	Y	Y	Y	P	P	P
Transparent device-level flexibility reporting	Y	Y	P	Y	P	P	Y
Breadth of asset coverage	Y	P	Y	—	Y	P	P

Legend: Y = Strongly supports, proven deployment; P = Weakly/partially supports or emerging; — = Not applicable

Evaluating Applicability of Protocols Against Different Communication Pathways and DF Approaches

Table 2 tabulates which protocols are applicable to which communication pathways and DF approaches and Table 3 summarizes a set of our recommendations. Pathways 1, 2, and 4 are strongly supported by OpenADR at grid-to-HEMS levels, paired with Matter or OCPP 2 for local device control. Pathway 3 (via manufacturer cloud) represents the largest interoperability gap as HCA is the only standardized protocol that exists for aggregator-to-manufacturer-cloud, but broader industry support is needed to replace the need for one-to-one integrations and promote customer choice avoiding locking customers into single manufacturers' ecosystems.

Table 2. Comprehensive Protocol Comparison Matrix for Residential Demand Flexibility

Applicable DF Approaches	Pathways	Information Exchanged	Open ADR	IEEE 2030.5	Matter	OCPP	CTA-2045	HCA
Event-driven, Price-based, Network-aware, Hybrid	Utility → HEMS	Grid signal (price, DR events, constraints)	Y	P	—	—	—	P
	HEMS → Device	Functional control command (mode, setpoint, flexibility)	Y	—	Y	Y (EV)	Y	P
Event-driven, Bidding/auction, Hybrid	Utility → Aggregator	Grid signal (price, DR events)	Y	Y	—	—	—	—
	Aggregator → HEMS	Grid signal & functional control (dispatch, flexibility)	—	—	—	—	—	Y
	HEMS → Device	Functional control command (mode, setpoint, flexibility)	Y	—	Y	Y (EV)	Y	P
Price-based, Event-driven	ISO → Aggregator	Grid signal (price, DR events, market price)	Y	P	—	—	—	—
	Aggregator → Mfg Cloud & Device	Functional control command (mode, setpoint)	—	—	—	P (EV)	—	Y
Bidding/auction-based, Hybrid	ISO → Aggregator	Grid signal (market dispatch, price)	Y	P	—	—	—	—
	Aggregator → HEMS	Grid signal & functional control (dispatch, flexibility)	—	—	—	—	—	P
	HEMS → Device	Functional control command (mode, setpoint, flexibility)	Y	—	Y	Y (EV)	Y	P

Legend: Y = Strongly supports, proven deployment; P = Weakly/partially supports or emerging; — = Not applicable

Table 3. Protocol Suitability Across Communication Pathways

Communication Pathway	Suitable Protocol (s)	Reason for choice
Pathway 1: Utility → HEMS	Grid signals: OpenADR	RESTful/JSON reduces latency and modernizes proven OpenADR 2.0b for <30 sec response
Pathway 1, 2, 4: HEMS → Device	Grid signals: OpenADR Functional control signal: Matter, OCPP (EV)	Matter provides local interop across thermostats, water heaters, batteries; OCPP 2.0.1 mandated for charging; supports local control and customer override
Pathway 2: Utility → Aggregator	Grid signals: OpenADR, IEEE 2030.5	OpenADR 2.0b proven in aggregator networks; 3 emerging with lower latency; IEEE 2030.5 better for DER-heavy portfolios

Communication Pathway	Suitable Protocol (s)	Reason for choice
Pathway 2, 4: Aggregator → HEMS	Grid signals: OpenADR Functional control signal: Matter, OCPP	Supports local hub deployment; RESTful enables aggregator control without cloud round-trips
Pathway 3: Utility/ISO → Aggregator	Grid signals: OpenADR, IEEE 2030.5	Wholesale market dispatch proven with OpenADR; it also enables aggregator-level optimization; 2030.5 for DER coordination; all support wholesale market participation
Pathway 3: Aggregator → Manufacturer Cloud	Proprietary APIs (current); HCA (emerging)	HCA is attempting to standardize cloud-to-cloud appliance coordination
Pathway 3: Manufacturer Cloud → Device	Proprietary (current); HCA, Matter (emerging replacements)	OEM cloud APIs lack standardization; each manufacturer has proprietary API. However, HCA or Matter adoption would enable interoperability
Pathway 4: ISO/RTO → Aggregator	Grid signals: OpenADR, IEEE 2030.5	Wholesale market dispatch proven with OpenADR 2.0b; 3 emerging for CAISO and PJM; 2030.5 for DER communication

Conclusions

This paper evaluated six standardized communication protocols against seven desirable features for residential demand flexibility (Table 1). The protocols examined were OpenADR, IEEE 2030.5, Matter, OCPP, CTA-2045, and HCA, along with proprietary approaches. We mapped these protocols to four communication pathways and the major DF approaches (Table 2), and summarized recommendations for each pathway (Table 3). No single protocol supports every feature, and protocols differ in which features they support and which pathways they serve. As a result, the most effective deployments pair a grid-facing protocol with a local device-control protocol. Across all three analyses, breadth of asset coverage emerges as an important consideration alongside per-feature support. Given that much of today's installed device base relies on proprietary interfaces, scaling residential DF in the near term will also require supporting proprietary protocols and gateway or middleware translation layers, rather than assuming a full, immediate transition to using an open protocol. Open, interoperable protocols, paired across pathways and bridged to existing devices, offer the most credible route to scaling residential demand flexibility while preserving customer choice.

Acknowledgements
This work was conducted as part of the California Load Flexibility Research and Development Hub (CalFlexHub), the innovation hub supporting the scaled adoption of reliable load flexible technologies. This work was supported by the California Energy Commission under the Electric Program Investment Charge (EPIC) Program. The work is also supported by the Assistant Secretary for Critical Minerals and Energy Innovation, Building Technologies Office, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

AI-assisted tools used: Claude (Anthropic). Used for: drafting and summarizing textual content and language editing. Extent: drafting sections. Human review: The authors reviewed and verified all content, calculations, and citations.

References

Bienert, R. (2023). Standardizing Demand-Side Management: The OpenADR Standard and Complementary Protocols. In Energy Smart Appliances (eds A. Moreno-Munoz and N. Giacomini). https://doi.org/10.1002/9781119899457.ch5

Blasnik, M., Reid, D., and Lanzisera, S. Scaling Residential Demand Response by Prioritizing Comfort: Evidence from 25 Million Energy Shifts. Renew Home, November 2025. www.renewhome.com/resources/white-papers/scaling-residential-demand-response.

Carvallo, Juan Pablo, and Lisa C. Schwartz. 2023. "The Use of Price-Based Demand Response as a Resource in Electricity System Planning," November 2023. https://escholarship.org/uc/item/3mp147d8.

Chitchyan, Ruzanna, Palvi Shah, and Caroline Bird. 2019. "Eliciting Requirements for Demand Response Service Design to Households: A Pilot Study." In Proceedings of the 23rd International Conference on Evaluation and Assessment in Software Engineering (EASE '19), 299–304. New York: Association for Computing Machinery. https://doi.org/10.1145/3319008.3319355.

CPUC (California Public Utilities Commission). 2026. "Rule 21 Interconnection." Accessed June 21, 2026. https://www.cpuc.ca.gov/Rule21/.

Cox, V., Clasp Matt Malinowski, Rachel Margolis, and J. Mauer. 2024. "It's Flex Time: Using Flexible Demand Appliance Standards to Deliver Peak Load and CO 2 Reductions." www.aceee.org/sites/default/files/proceedings/ssb24/assets/attachments/20240722160820672_c1e16739-ef81-4705-b778-56941af9f35b.pdf.

Consumer Technology Association (CTA). 2021. *Modular Communications Interface for Energy Management.* ANSI/CTA-2045-B. shop.cta.tech/products/cta-2045

Daly, M., Langham, E., Tahir, F., Allen, S. and Briggs, C. Residential HEMS and controllers – Global Market Scan. Report prepared by the University of Technology Sydney for the 4ETechnology Collaboration Programme of the International Energy Agency. February 2025.

D'Ettorre, F., M. Banaei, R. Ebrahimy, S. Ali Pourmousavi, E. M. V. Blomgren, J. Kowalski, Z. Bohdanowicz, B. Łopaciuk-Gonczaryk, C. Biele, and H. Madsen. "Exploiting demand-side flexibility: State-of-the-art, open issues and social perspective." Renewable and Sustainable Energy Reviews 165 (2022): 112605.

ElaadNL. (2025). Residential flexibility: Protocols. Retrieved from https://elaad.nl/en/projects/residential-flexibility/core-aspects/protocols/.

FERC (Federal Energy Regulatory Commission). 2020. "Order No. 2222: Energy Storage, Renewable Energy, and Demand Response as Wholesale Power Market Resources." Federal Energy Regulatory Commission, September 2020.

FERC (Federal Energy Regulatory Commission). 2023. "2023 Assessment of Demand Response and Advanced Metering." www.ferc.gov/sites/default/files/2023-12/2023%20Assessment%20of%20Demand%20Response%20and%20Advanced%20Metering.pdf.

Gabriel, N., P. Grant, M. Egolf, W. Huang, A. Cortese, and A. Miller. 2024. *Development and Validation of Price and Load-Responsive Controls for 120-Volt Heat Pump Water Heaters.* Portland, OR: New Buildings Institute. calflexhub.lbl.gov/wp-content/uploads/sites/41/2025/01/Development-and-Validation-of-Price-and-Load-Responsive-Controls.pdf.

Gerke, B., S. J. Smith, S. Murthy, S. Baik, S. Agarwal, P. Alstone, A. Khandekar, C. Zhang, R. Brown, J. Liu, and M. A. Piette. 2024. *The California Demand Response Potential Study, Phase 4: Report on Shed and Shift Resources Through 2050*. Berkeley, CA: Lawrence Berkeley National Laboratory. escholarship.org/uc/item/0mc2593r.

German Federal Network Agency. (2021). §14a EnWG (Energy Industry Act).

Grahovac, M., S. Smith, S. Agarwal, V. Dementyeva, B. Woo-Shem, and M. A. Piette. 2026 "Are Flexible Load Technologies Affordable? A Population-Scale Cost-Benefit Analysis" *ACEEE Summer Study on Energy Efficiency in Buildings*. Manuscript in press.

gridX. (2026). *What is demand side response and why it is important*. Retrieved from gridx.ai/knowledge/what-is-demand-side-response-and-why-it-is-important. Access 13 March 2026.

HCA (Home Connectivity Alliance). 2025. "HCA EM Integration Press Release." Published Nov 2025. Accessed June 21, 2026. https://homeconnectivityalliance.org/wp-content/uploads/2025/11/HCA-EM-Integration-Press-Release_FINAL.pdf.

HCA (Home Connectivity Alliance). 2026. "Specifications & Guidelines." Accessed June 21, 2026. https://homeconnectivityalliance.org/technical-info/.

IEA (International Energy Agency). 2023. "Demand Response." www.iea.org/energy-system/energy-efficiency-and-demand/demand-response.

Kehmeier, E. 2026. "SmartShift Rewards Program: Customer Connectivity and Acquisition Lessons Learned" Presented at the 2026 ACEEE Hot Air & Hot Water Forums

Liu, J.; Piette, M.; Pritoni, M.; Nordman, B.; Grant, P.; Smith, S., et al. (2024). Assessing Customer Experience and Business Models around Price-to-Device Communication and Smart Control Pathways in CalFlexHub. Retrieved from https://escholarship.org/uc/item/3ng3x6b9

Mihalache, AE., Hampton, S. & Darby, S. Domesticating energy flexibility. 2024. Learning from great britain's 2022–2023 demand flexibility service. Energy Efficiency 17, 88 (2024). https://doi.org/10.1007/s12053-024-10268-z

Nasr, M. A., S. Chatzivasileiadis, and E. Yamashita. "Allocation of Dynamic Operating Envelopes in Distribution Networks: Technical and Equitable Perspectives." *IEEE Transactions on Smart Grid* 14, no. 5 (2023): 3530–3543. https://ieeexplore.ieee.org/document/10123018.

Neukomm, Monica, Valerie Nubbe, and Robert Fares. 2019. Grid-Interactive Efficient Buildings Technical Report Series: Overview of Research Challenges and Gaps. DOE/GO-102019-5227. U.S. Department of Energy, Building Technologies Office. https://www1.eere.energy.gov/buildings/pdfs/75470.pdf.

Nizami, S., Tushar, W., Hossain, M. J., Yuen, C., Saha, T., & Poor, H. V. 2022. Transactive energy for low voltage residential networks: A review. Applied Energy, 323, 119556.

Nordman, B., Pritoni, M., Piette, M. A., and Prakash, A. K. 2022. Communication Requirements for Price-Based Grid, ACEEE Summer Study on Energy Efficiency in Buildings, August 2022 https://escholarship.org/uc/item/4j30s17j.

Nordman, Bruce, Lauren Parker, Krishnan Prakash, and Mary Ann Piette. 2024. "Transforming Demand Response Using OpenADR 3.0." https://escholarship.org/uc/item/9hp6v9qq.

Outcault, Sarah, Eli Alston-Stepnitz, and Margaret Taylor. 2024. "Stakeholder Perspectives on the Role of Standards in Establishing a Load-Flexible Ecosystem." Lawrence Berkeley National Laboratory. August 2024.

Onunkwo, Ifeoma (2020). Recommendations for Data-in-Transit Requirements for Securing DER Communications. https://doi.org/10.2172/1813646.

Ottesen, S. Ø., Tomasgard, A., & Fleten, S. E. (2018). Multi market bidding strategies for demand side flexibility aggregators in electricity markets. Energy, 149, 120-134.

Paresa, D., M. Adham, G. Heiken, and Bass, R. B. (2024) ANSI/CTA-2045 Conformance Testing: Are Smart Appliances Ready for Large-scale Deployment?, IEEE Power & Energy Society General Meeting, DOI: 10.1109/PESGM51994.2024.10688693

SEDC (Smart Energy Demand Coalition). 2016. "Explicit and implicit demand-side flexibility." Smart Energy Demand Coalition: Brussels, Belgium (2016).

SCE (Southern California Edison). 2026. Demand Response Programs for Homes. www.sce.com/save-money/savings-programs/ways-to-save-at-home/what-is-demand-response (Accessed 13 March 2026)

Specian, M., and A. Aquino. 2026. *Faster and Cheaper: Demand-Side Solutions for Rapid Load Growth*. Washington, DC: ACEEE. aceee.org/research-report/u2601.

SunSpec Alliance. (2018). *CSIP implementation guide v2.1* (pp. 13.65). Retrieved from https://sunspec.org/wp-content/uploads/2019/08/CSIPImplementationGuidev2.103-15-2018.pdf

Toderean, L., Cioara, T., Anghel, I., Sarmas, E., Michalakopoulos, V., & Marinakis, V. 2025. Demand response optimization for smart grid integrated buildings: Review of technology enablers landscape and innovation challenges. Energy and Buildings, 326, 115067.

Woo-Shem, B. 2025. "Demonstrating Simple Price-Responsive Controls to Minimize Electricity Costs of Central HPWHs." Presented at the Advanced Water Heating Initiative Connectivity Working Group. May 9, 2025. www.youtube.com/watch?v=L2gxdU2RXdI.

Zandi, H., Kuruganti, T., Vineyard, E. A., & Fugate, D. (2017). Home energy management systems: an overview. https://www.osti.gov/servlets/purl/1423114.

Zhou, Wei, Yan Jia, Yao Yao, Lipeng Zhu, Le Guan, Yuhang Mao, Peng Liu, and Yuqing Zhang. (2019). "Discovering and understanding the security hazards in the interactions between {IoT} devices, mobile apps, and clouds on smart home platforms." In 28th USENIX security symposium (USENIX security 19), pp. 1133-1150. 2019.