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Publication Date

2022-09-15

Peer reviewed

Building Technology & Urban Systems Division
Energy Technologies Area
Lawrence Berkeley National Laboratory

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Energy Technologies Area
September 2022

DOI #10.20357/B79S3T

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Office, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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ABSTRACT

As we transition from traditional to variable renewable electricity supply, and electrification increases, it is critical to enable building loads to be flexible in coordination with the grid. This paper describes the new California Load Flexibility Research and Deployment Hub, a four-year program to accelerate building load flexibility. CalFlexHub will achieve this by equipping customers with the technologies to provide that flexibility and increasing knowledge of customer needs through lab and field research. The technologies include HVAC, water heating, and other building end-use equipment, storage technologies, and electric vehicle (EV) systems.

CalFlexHub will support the California Energy Commission's Load Management Standards (LMS) that are developing requirements for utilities to publish dynamic electricity prices in a digital format, so devices can receive the signals and automatically respond. We will develop, demonstrate, and evaluate technology to actuate these loads using automation that is compatible with the LMS, which will be used to communicate the prices, other grid signals, and greenhouse gas (GHG) emission data.

This paper will describe the performance energy and GHG metrics for the technologies, usability, and the architecture of the price and GHG server. A key element of decarbonization is electrification of space and water heating. Electrification of these new loads will strain our electric systems unless they are capable of automatically responding to digital prices and other signals to create responsive flexible loads.

Introduction

There are numerous challenges in both managing today's evolving electric grid and in accelerating our pathways to decarbonization. One challenge is how to manage the dynamic balance between supply and demand on the electric grid as we replace conventional generation with variable renewable supply. A second challenge is the uncertainty of the nature of future loads that emerge with electrification of buildings and transportation systems. A key concept to enable better linking variable renewable supply systems with demand is to ensure that customers receive signals that incentivize flexible demand in the most expedient way.

This paper describes the California Load Flexibility Research and Development Hub (CalFlexHub)[1]. CalFlexHub is a 3.5-year program designed to enable scaled adoption of equitable, advanced, interoperable, and load flexible technologies that will drive and accelerate transformation of the California energy marketplace. The Hub will initiate this transformation by identifying, evaluating, developing, and demonstrating the most competitive pre-commercial technologies, implementation pathways, and strategies to advance flexible and grid-integrated energy efficiency and distributed energy resource (DER) technologies. Berkeley Lab's CalFlexHub has a multidisciplinary team of committed partners that will initiate a transformative research, development, demonstration, and deployment (RDD&D) program to transition buildings and electric vehicles from static to dynamic systems.

CalFlexHub has numerous directly funded partners and a number of additional partner sites. Our multi-disciplinary team includes researchers at four University of California campuses: Berkeley, Davis, San Diego, and Riverside, along with support from Humboldt State. Three organizations are providing technology for controls and communications: Olivine, Skycentrics, and e-Radio. Momentum is providing program management and outreach support. E3 and Guidehouse will assist in the flexible load valuation research. WattTime will provide real-time GHG signals. CalFlexHub has several partners involved in providing new hardware and software for load flexible (LF) technologies including Harvest Thermal and Extensible Energy. CalFlexHub is forming a disadvantaged community advisory group to be led by Rising Sun, which is a California-based non-profit providing career pathways for economic equity and climate resilience. Finally, we are also partnering with TeMix, which is a company with a platform for transactive tariffs (Cazalet et al., 2019).

This paper is organized as follows. The next section provides a description the barriers that CalFlexHub is designed to overcome. This is followed by a description of the California vision for load management and a summary of CalFlexHub's R&D structure. This is followed by a description of how CalFlexHub will address these barriers, which includes the research program, the technologies we are evaluating, and the process to compare the value of the different approaches.

Challenges to Automate Flexible Loads

There are many reasons that buildings are rarely involved in providing flexible load. CalFlexHub is organized to address the following seven key barriers.

- **Deficiency of Capability** – Utilities and grid operators across the US have expressed the need for more flexible load, but current building technologies have limited flexibility and signal responsiveness. Expanded technological capabilities are necessary to facilitate innovative business models and increase utility engagement. Furthermore, current responsive load is often not predictable, reliable, and persistent. Utilities and grid operators do not trust the capability of load flexible technologies to provide deep, consistent response.

[1] CalFlexHub.org

- **Lack of Signals -** There is a lack of common digital price and environmental signals to customers to incentivize load flexibility. Also, not every customer has the ability to receive these signals over the internet, which is both an equity and a technology issue.

- **Insufficient Valuation Criteria-** There is a knowledge gap on how to evaluate which pathways are most promising for cost-effective mass adoption of flexible load. This gap is related to the lack of field performance and cost-benefit data of various technologies and strategies; barriers to customer adoption. This gap is also related to the need to understand how dynamic prices could incentivize the use of LF technology; value to ratepayers, load service entities, and grid operators; and lack of understanding of the environmental impacts of various technologies and research pathways.

- **Lack of Understanding and Usability -** While new technologies are developed to support LF, customers may not understand how to use them, and they may not be not be adopted due to low usability.

- **Severe Financial and Health Burdens -** Disadvantaged and low-income communities often suffer from financial hardships and energy burdens related to electricity cost, inability to respond to time-varying rates, lack of affordability of energy efficiency and LF technologies, and health issues related to poor air quality and extreme heat. Communities may lack internet connectivity needed for LF techs.

- **Paucity of Investment** - There has been minimal investment in LF technologies because of uncertainty in opportunities and the nature of the problems listed above.

- **Siloed Knowledge and Information Is Not Actionable -** While California has numerous research projects and demonstrations of LF technology, lessons learned on performance and customer feedback are not shared, resulting in inefficient knowledge transfer and lack of progress. Lessons from a broad set of activities throughout the US are not shared effectively, and raw data, field demo results, and research reports may not be in an actionable form.

To address these problems, CalFlexHub will identify, develop, evaluate, demonstrate and deploy cost-effective, scalable, building load-flexible (LF) technologies that are consistent with building energy efficiency, appliance, and load management standards. We will evaluate dozens of technologies and develop a CalFlexHub Solutions Center website and a clearinghouse to disseminate information, technology reports, and case studies to report on “what works”.

Supporting California's Load Management Standards

California has embarked on a unique approach developing *Load Management Standards* (LMS; CEC, 2021a) to increase efficiency and demand flexibility in California's electricity grid. These standards are designed to reduce rising electricity costs and improve grid reliability by improving the ability of buildings to provide dynamic load control. One element of this vision is to develop and support a system to use machine readable, or electronic tariffs to actuate dynamic load control. This concept is to develop the Market Informed Demand Automation Server (MIDAS) to be hosted by the California Energy Commission (CEC), which is a database of current and future time-varying rates, greenhouse gas (GHG) emissions associated with electrical generation, and California FlexAlert Signals. The concept of MIDAS is shown in Figure 1. MIDAS currently contains time of use tariffs from several IOUs, MUNIs, and consumer choice aggregation (CCA) utilities/retailers in California, and GHG signals from WattTime.

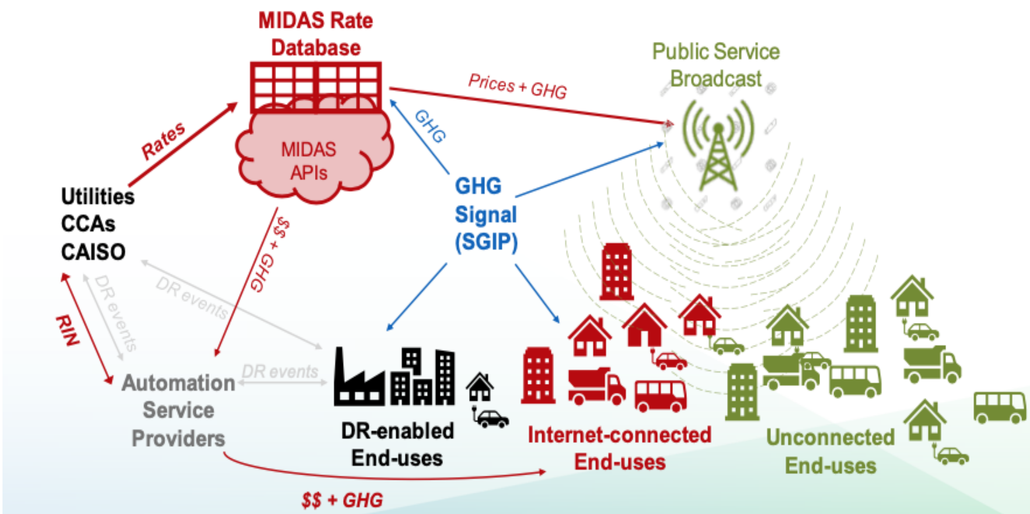

Figure 1. The CEC's Market Informed Demand Automation Server (MIDAS) will broadcast dynamic electricity prices to enable wide spread load flexibility (CEC, 2021a).

A second key element of CEC's strategy for enabling more flexible loads is the Flexible Demand Appliance (FDAS; CEC, 2021b) effort was authorized by Senate Bill 49[2] for the CEC to adopt standards for appliances to facilitate the deployment of flexible demand technologies. The goal is to reduce greenhouse gas emissions by enabling appliances to schedule, shift, or curtail operation in response to grid conditions. The LMS and the FDAS provide an exciting vision for deploying wide scale dynamic LF. An important benefit of this vision is that when retail electricity prices are used to incentive demand flexibility, there is no baseline or complex settlement needed because the electricity price alone is the vehicle for financial incentives for LF. Key R&D questions remain such as the following:

[2] Senate Bill 49 (Skinner, Chapter 697, Statues of 2019)

- What is required to enable devices, systems, and buildings to receive and respond to these signals?
- What is needed to build the communication platforms to stream these prices?
- What technology is needed to send and receive the prices?
- What business model innovation and customer adoption incentives might be required?
- How will this affect utility bills?

Another challenge is the lack of highly dynamic tariffs. We currently do not have electricity pricing that reflects dynamic system conditions. Policy and market innovation is also needed to require this shift to new rate designs, but this work is beyond the scope of CalFlexHub.

CalFlexHub's Research Structure

CalFlexHub has a set of tasks and activities designed to ensure that the team is conducting the most important and useful R&D to accelerate load flexibility in California relative to the LMS. These tasks are show in Figure 2. We identified 12 different technology R&D projects based on the program goals. We use the well-known Technology Readiness Level[3] scale to describe the technologies being evaluated. Six of the technologies are TRL 3-5 projects, with R&D taking place in labs and some in the field, are more early stage R&D. The other six are TRL 6-8, ready for field evaluation. This feature of CalFlexHub was required by the CEC in conceptualizing the R&D program. The five keys tasks in Figure 2 are as follows:

1. **Develop Valuation Methodology** - The research program begins with the development of a valuation methodology (further described below). CalFlexHub has a series of cycles of field work and a valuation process to modify the R&D portfolio to ensure we are working on the most important and promising technologies. The valuation process is developing Technology Characterization Metrics that will be generated for each of the 12 projects.
2. **Develop Price and GHG Signals** – CalFlexHub will test the use of tariffs available from MIDAS plus develop and test other dynamic price forms to evaluate how to accelerate the use of dynamic prices to achieve more load flexibility in California's buildings.
3. **Develop M&V and Workplans** – Each project has a unique M&V plan and the projects will be evaluated in both laboratory, and field installations.
4. **Evaluate Needs and Usability** – One challenge in developing and evaluating technology is ensuring we understand the user experience. CalFlexHub has a set of standard surveys and usability analysis to ensure that we are considering the experience of consumers, home owners, renters, tenants, and facility managers with the technologies we evaluate.

[3] Technology Readiness Levels (TRL) is a system to assess the maturity of a technology. TRL 1 is basic research, TRL 9 is technology that is ready for market deployment.

5. **Conduct Prioritization –** A unique element of CalFlexHub is the R&D cycles in which we conduct lab and field work, then develop a set of metrics to consider the priority of the various R&D topics.

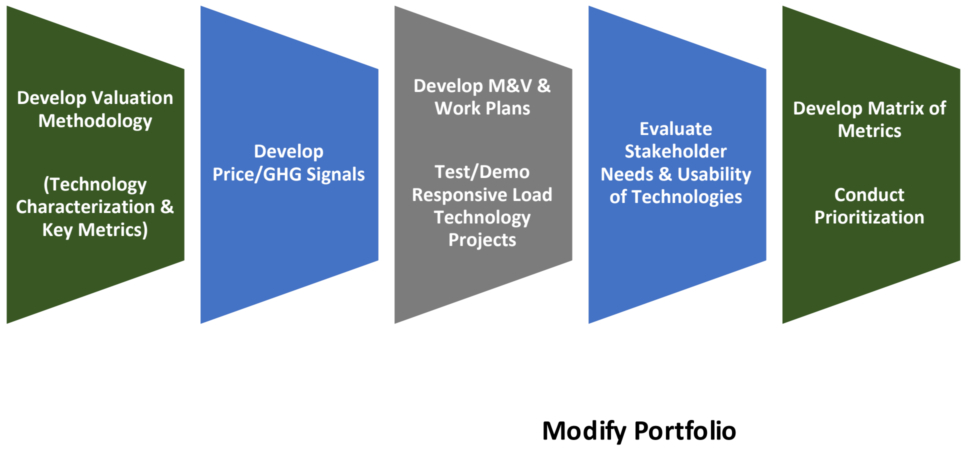

Figure 2. Tasks within CalFlexHub and the Technology R&D Prioritization Process.

Valuation Methods

CalFlexHub is developing a technology valuation method that builds on six years of research that LBNL has conducted to assist California policy makers. This research has produced supply curves of load shed and shift capability by end use and technology to assist in understanding the cost effectiveness and potential for demand response and demand flexibility in buildings (Alstone et al, 2016, 2017, Gerke et al, 2020). The California Public Utilities Commission defines a DER broadly to include distributed renewable generation, energy efficiency, energy storage, EVs, flexible load management, and demand response technologies (CPUC, 2021). These metrics are designed to capture the potential benefits of a given load flexibility technology to consumers, the power system, and the environment, relative to a non-flexible technology baseline, if it were to be successfully deployed on a wide scale across California. Figure 3 provides an overview of the analysis framework, which considers both the customer or building level perspective as well as the power, or utility system. To ensure we consider energy and environmental justice issues, we will have a disadvantaged community (DAC) perspective as part of the framework.

The annual prioritization process will consider the relative importance of each metric to determine a method for aggregating all metrics into an overall rating that allows direct comparison and prioritization of different technologies. For example, a set of metric weights may be developed to quantitatively aggregate results into a single score, or metrics may be sorted by order of importance. We may also include acceptability thresholds (e.g. the technology must have a given capability, or must not increase GHG emissions), and other ways of prioritizing. The prioritization task will result in a recommended for modifying and prioritizing of the technology research projects.

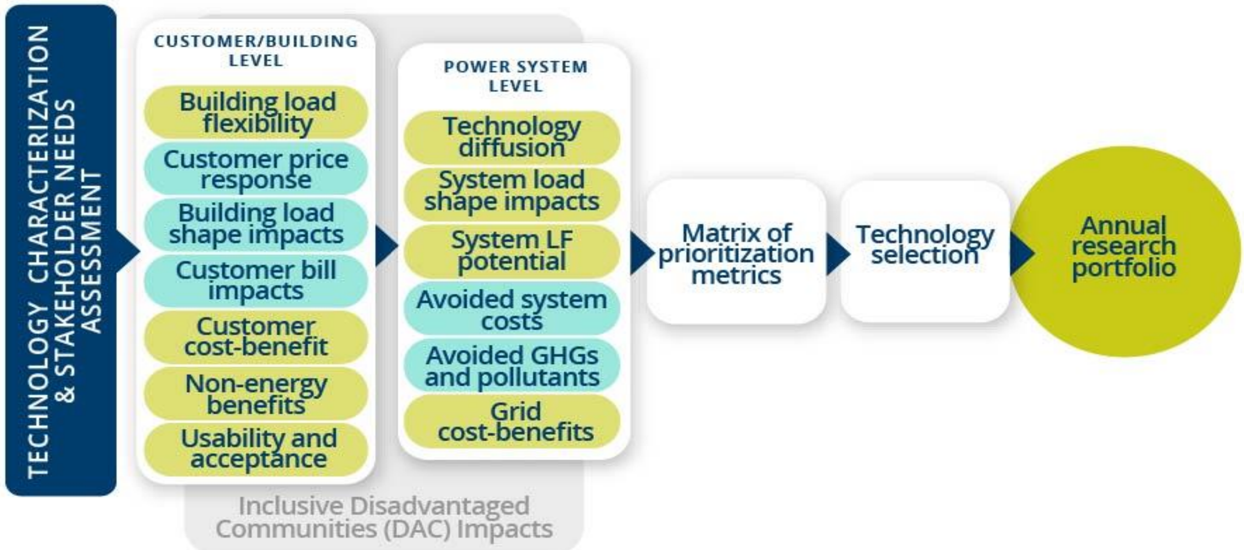

Figure 3. Description of CalFlexHub Technology Valuation Process

Price Communication Architecture

CalFlexHub is evaluating how to develop and evaluate technologies that enable buildings to change their energy consumption (or production) in coordination with the electric grid signals. Figure 4 shows the CalFlexHub price communication architecture and possible communication paths of information from the retailer to each distributed energy resource (DER). Any individual DER will likely use a single path from the price server to the DER. The orange lines in the figure show functional control commands sent after an entity other than the DER itself has combined the prices with functional operating considerations. Any of the four devices in the bottom half of the diagram can do the translation from price to functional control.

The core of price-based coordination is that the basic signal is one-way, sending prices from the utility to customers. Highly dynamic prices are likely to be initially hourly, and later 15-minute, or even 5-minute prices with a current price and a series of future prices for one day or more into the future. The figure also shows WattTime GHG emission signals which are part of the communications system. Consumers can choose to be more price oriented, or GHG oriented and we will explore ways to integration prices and GHG signals. There are three major ways to receive and respond to price. Each of these differ in where the intelligence is located for the control logic. They include:

- **Third party cloud control.** This is the most common way price automation will happen initially, with the intelligence in a vendor, or third party Distributed Energy Resource Management System (DERMS), or aggregator cloud.
- **Device level control**. The intelligence is in the DER itself, or a dedicated controller. FM broadcast of prices is most suited to this method.

- **Building gateway, multi-device control.** Shown as Building Central Entity on the graphic below.

The communication architecture is described in more detail in (Nordman et al., 2022).

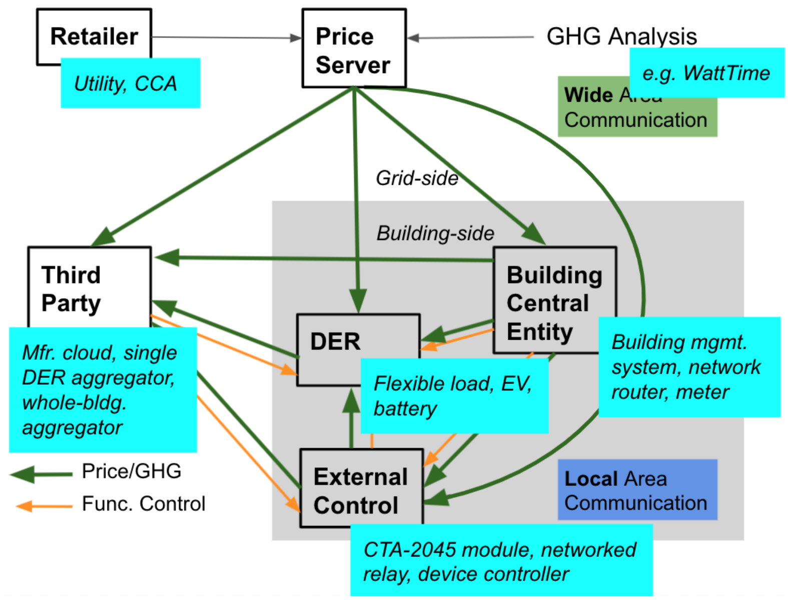

Figure 4. Architecture for price communication

Providing the infrastructure for the CalFlexHub lab and field tests is one important part of the communications research, but there are two others. One is to survey the "signal reception" of various technologies for wide-area communication of grid signals, e.g. broadband internet, cellular radio (including 5G), and FM radio. We will also study emerging technologies such as satellite Internet connections, LoRa, as well as utility AMI systems. In addition, the reach and reliability of local communication, particularly Wi-Fi, will be examined.

The second additional area of research is the technology infrastructure for a highly interoperable and robust system for price communication. CalFlexHub will evaluate the use of and need for open standards that can convey prices and how to build on existing communication standards such as OpenADR, IEEE 2030.5, and CTA 2045. Using prices to actuate dynamic loads will be most effective and least costly if it is standardized nationally, and globally. Many parts of this need attention including: harmonizing across relevant communication protocols, price server discovery (for local- and wide-area networks), emergency signals, retailer and tariff discovery, cybersecurity and privacy, physical and network layer innovations, differential buy/sell prices, GHG emission integration, locational pricing, and daylight-savings time management. CalFlexHub will contribute to the development of common price communication methods.

Technology R&D Projects

CalFlexHub will initiate 12 technology projects that consist of 6 low TRL early stage projects known as Applied R&D (ARD), and 6 later stage projects known as technology demonstration and deployment projects (TDD) projects. Table 1 provides a summary of the technology projects, sector, and specific end-use technologies being tested. All twelve of the CalFlexHub technology projects will include new control and communication technology required to receive and respond to dynamic prices.

Among the ARD projects, 5 of the 6 projects involve shifting HVAC and water heating loads with novel controls and thermal energy storage systems, and controls. One of the projects involves a smart panel for managing electric loads for low-cost electrification upgrades in homes. The technologies are designed for all types of buildings: single family and multi-family buildings, small, medium and large commercial, as well as campuses. Field work will take place on the campuses of UC Davis, UC Merced, and UC San Diego as living lab research sites.

The TDD projects include a set of technologies such as heat pump for HVAC and water heating projects that are currently on the market and ready for field tests. CalFlexHub also includes testing machine learning controls in small commercial buildings, evaluating bi-directional EV charging, and a large set of field tests of DERs that are current part of utility DR programs. These DERs include smart thermostats, pool pumps, and EVs that currently can receive event-based DR signals but will be tested to receive price signals for continuous load response.

While CalFlexHub has started with 12 technology projects, the long-term strategy is to grow collaboration with technology partners and integrators beyond these initial projects to serve as a hub for knowledge transfer. Also, and as mentioned, the modeling and assessment work done by the hub builds on the DR potential studies funded by the CPUC. Thus, the CalFlexHub technology evaluation work will foster knowledge transfer beyond the 12 projects that we are starting with in the hub. Similarly, Berkeley Lab continues to partner with the US DOE Building Technologies Office to evaluate how to support greater integration of dynamic building loads with renewable energy to support decarbonization. This research is coordinated with DOE's of Grid Interactive Efficient Buildings program that similarly supports research to enable more flexible load in the US buildings stock (Satchwell, 2021).

Table 1. CalFlexHub technology projects categorized by TRL by sector and technology.

		Sector*	HP water heaters	Refrigeration	HVAC controls	Ductless HP	Pool and spa	EV charging	Plug load	Electric batteries	Thermal storage	HEMS
	Applied Research and Development (ARD) Projects											
A1	Residential Smart Fan with Integrated Thermostat	SF, SC, MF			X							
A2	Dynamic Heat Pump Design and Control for Residential Space Heat and DHW	SF, MF	X		X							
A3	Dynamic Heat Pump Design and Control for Small Commercial HVAC	SC			X	X						
A4	Integrated Heat Pump and Cold Storage for Small Commercial HVAC	LC			X						X	
A5	Model Predictive Control for Dynamic Large Commercial and District Energy Systems	LC, CC			X			X	X		X	
A6	Home Energy Management System to Maximize Electrical Panels with Electric Storage	SF										X
	Technology Demonstration and Deployment (TDD) Projects											
T7	Integrated Small Commercial Energy Management with DERs	SC			X					X		
T8	Integrated Heat Pump with Storage for DHW and Space Conditioning	SF	X		X	X						
T9	Residential HVAC and Hot Water Using Integrated Storage	SF	X		X	X					X	
T10	Household Flexible EV Charging	SF						X				
T11	Bi-Directional EV Charging	SF, LC						X				
T12	Control and Coordination of Distributed Flexible Loads	SF, SC, LC, MF	X	X	X		X	X		X	X	

*Sectors: SF - Single Family, MF - Multi-Family, SC - Small Commercial, LC - Large Commercial, CC- Connected Community. HEMS – Home Energy Management System. Red colored technologies include heating, blue – cooling, purple- heating and cooling.

Technology Transfer and Outreach

To support broad commercialization, CalFlexHub seeks to accelerate the commercial adoption of the technologies by communicating successes of the program to a broad stakeholder audience. Challenges and failures are also important to report to allow the load flexibility stakeholders to know what has not worked. CalFlexHub is committed to disseminating this information in an equitable and thoughtful manner. Core elements of the CalFlexHub program–embedded in the program's scope of work–that are designed to foster communications include:

- Equity Advisory Committee Meetings
- Stakeholder Needs Assessment
- Annual Market Assessment Report
- Communications Architecture Reports
- Annual Disadvantaged Community and Low-Income Research Memo
- Research Plan to Build Capacity in DAC and LI Communities
- Technology Transfer Best Practices Manual
- CalFlexHub Website
- Annual CalFlexHub Symposium
- CalFlexHub Clearinghouse
- CalFlexHub Solutions Center
- Coordination with Existing Programs

The Technology Transfer Plan will utilize these efforts, in addition to others, to engage stakeholders with targeted goals and objectives.

Summary and Future Direction

This paper has described CalFlexHub which is designed to identify and enable greater load flexibility in the buildings sector. The program provides a broad portfolio of activities both developing new technologies and conducting field tests to evaluate their performance. A key element of the program is supporting the use of dynamic prices to enable load flexibility. As describe above, CalFlexHub will explore what innovations in hardware and software are needed to use prices as the central mechanism for grid coordination for energy purposes. Price-based coordination is a continuous method, not confined to particular seasons, "event days" or times of the day.

Price formation — how to set retail prices, including local distribution system issues - is beyond the scope of CalFlexHub. For this research to be successful there needs to be strong market and policy commitment to evolving electricity rates toward more highly dynamic structures that reflect regional and local grid conditions. CalFlexHub will provide knew knowledge regarding the capabilities of building technologies to receive and respond to dynamic prices and help enable a grid with high levels of renewable energy. This capability is also related to the emerging business models for third party aggregators and DERMS. Many of the technologies we are testing can use multiple vendor and third-party cloud communication pathways. CalFlexHub will help explore the pros and cons of these different communication paths and evaluate the opportunity for long-term persistence load flexibility.

Acknowledgement

This work was supported by the California Energy Commission's Electric Program Investment Charge. We are grateful to the CEC's Matt Fung for his support of this program. The work is also supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Office of the U.S. Department of Energy under Contract No. DE- AC02-05CH11231.

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