CalFlexHub
Advancing Dynamic Energy Management

Load Flexibility: Keeping Users in the Loop with "Invisible" Technologies

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ABSTRACT

This paper focuses on user experience with emerging load flexible (LF) technologies, as demonstrated in residential and commercial building field sites in California. It draws from semi-structured interviews with people who interacted with LF technologies or who had energy services affected by these technologies during testing of their responsiveness to electricity price and greenhouse gas signals simulating those expected as California's grid evolves. Three aspects of the user experience are highlighted: (1) user orientation and setup in advance of technology testing; (2) user observations of LF test impacts, including perceived changes in energy services and unanticipated side effects; and (3) interactions with user interfaces, with a particular focus on topics related to user control (e.g., parameter settings, overrides, power shutoffs) and knowledge that can reduce uncertainty and aid in understanding the benefits of load flexibility. Although participants expressed generally positive sentiments about all three aspects of user experience, they also provided insights that could improve the design of market-ready technologies. Regarding aspect (1) of the user experience, an insight is that communication materials regarding LF need to improve if people are to understand it for purposes of enrollment and participation. Regarding aspect (2), insights include that user perceptions of impacts may differ from technology team expectations and may not necessarily match measured data on impacts. Regarding aspect (3), an insight is that tension exists between participants' expressed interest in more knowledge about upcoming tests and participation benefits, versus their demonstrated engagement with system interfaces.

Introduction

Decarbonization goals call for increasing the renewable energy generation integrated into the grid while simultaneously electrifying buildings and vehicles. Fulfilling these goals creates new challenges for grid reliability by increasing the dynamics and uncertainties of the electricity supply while increasing demand for that electricity.

For decades, an important tool in maintaining grid reliability has been demand response (DR). Traditional DR involves load-serving entities incentivizing customers to change their consumption patterns (i.e., shed load) as needed to support the grid. In emergency and event-based DR, consumption changes are requested, typically at times of critically high peak demand that occur infrequently and for a few hours at a time. In economic DR, consumption changes are more passively expected as rational responses to time-of-use rates set based on typical electricity load patterns. With decarbonization, however, there is a growing interest in more continuous adjustment of loads to balance supply and avoid capacity upgrades at both the levels of the bulk power system and the distribution system. This more continuous strategy, known as "load flexibility" (LF, or demand flexibility or energy flexibility), aims for more precise, round-theclock system and device adjustments than traditional DR. The aspiration is for sophisticated automation and communications technologies – many of which are currently non-commercial – to make a multitude of end-uses (e.g., electric vehicle service equipment, battery energy storage systems, space conditioning, water heating, pool pumps, etc.) flexible and responsive to grid signals, while the resulting energy service adjustments are "invisible" to consumers.

Although LF aims to take the human out of the loop of demand side management (DSM), behavioral considerations are still critical and complex aspects of the hoped-for adoption of LF-capable technologies and participation in related programs. Automated solutions in the energy space are often met with distrust and other hesitations, such as concerns about sacrifices of comfort and control. The International Energy Agency (IEA) Users Technology Collaboration Program (IEA UsersTCP) adapted the concept "social license to automate" (SLA) to understand the social dimensions that determine public support for automated DSM (Adams et al. 2021). The UsersTCP Social License to Automate Task outlined several themes underlying public resistance to or acceptance of automated DSM programs: (1) users' willingness and ability to modify energy consumption practices; (2) users' agency and sense of control; and (3) users' perception and experience of benefits. Acceptability of automated DSM is also highly dependent on contextual factors such as user characteristics, the actor initiating automated operations, and which appliances are automated (Michellod et al. 2022; Von Wirth, Gislason, and Seidl 2018; Winther and Sundet 2023).

This paper seeks to expand knowledge on the topic of LF user acceptance. It presents findings drawn from user assessments that are being conducted in conjunction with field demonstrations of load flexible technologies as part of the California Load Flexibility Research and Development Hub (CalFlexHub). CalFlexHub, which is managed by Lawrence Berkeley National Laboratory, brings together actors from across the load flexibility innovation ecosystem to identify, evaluate, develop, fund, and demonstrate cost-effective and reliable load-flexible and flexibility-enabling technologies. Figure 1 illustrates the wide range of (largely pre-commercial) load flexible technological systems which CalFlexHub is helping to develop across different building types and test for their responsiveness to electricity price and greenhouse gas signals simulating those expected as California's grid evolves. At last count, CalFlexHub involved 12 technologies/systems, 19 individual projects, and greater than 30 building/site locations (Piette 2023). The user assessments that inform this paper are part of one of CalFlexHub's tasks, which is to use social science methods to gain a better understanding of the broader context of these technologies.

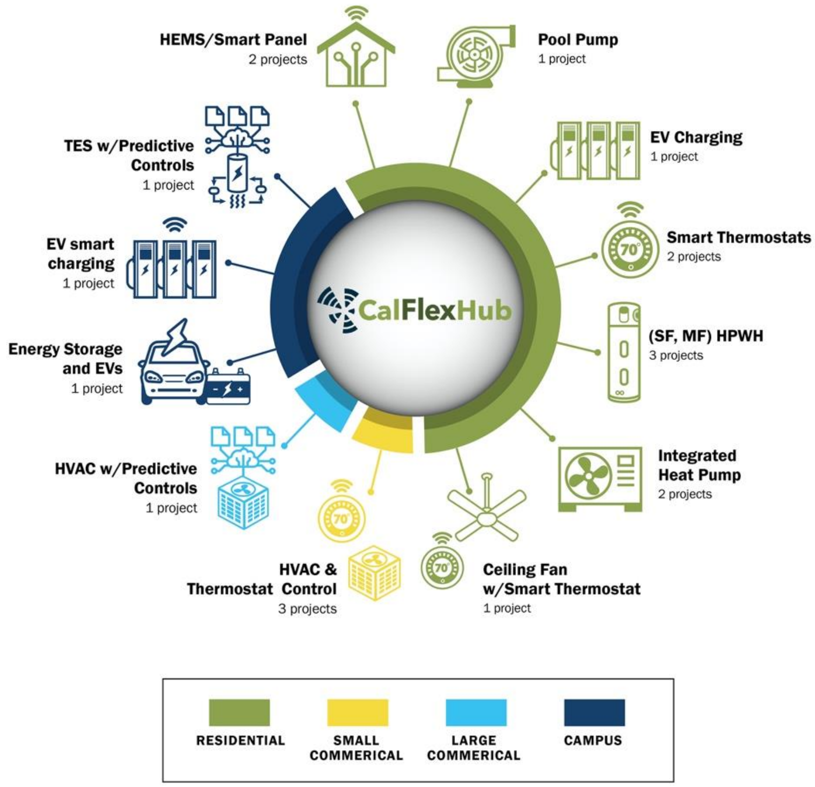

Figure 1: Portfolio of CalFlexHub projects (Piette, 2023)

Methodology

The approach to user assessment for CalFlexHub, ongoing through 2025, centers on semi-structured interviews with each type of identified user (e.g., energy manager, system operator, building occupant, householder) for each technology field demonstration. The user assessment team collaborates with the CalFlexHub lead/coordinator, Lawrence Berkeley National Lab, and each CalFlexHub partner technology team[1] to learn the details of the field demonstration procedures and timeline. Each technology team acts as liaison to the users, providing their email addresses to the user assessment team. The aim is to conduct interviews after the LF signals have been tested so that users have had a chance to experience any LF impacts and interact with related user interfaces. In practice, there have been long delays in some cases between LF testing and user interviews.

Interviews reported herein were all conducted via recorded Zoom calls that lasted between 30 and 60 minutes (45-60 minutes on average). Participation incentives were determined in collaboration with the technology teams and were typically a $50 or $100 Amazon e-gift card. One participant was a colleague of the research team and was not compensated; three others declined compensation, including two who were representing an institution and considered participation part of their job.

[1] Technology teams from various research institutions and industry partners are conducting the research and development on LF technologies.

A general interview protocol was created and adapted for each specific technology and field demonstration. The following topics were covered and are used to organize the results and discussion section for this paper.

- *User orientation and setup*: Experience with LF operations setup and information provided before the LF testing.
- *Impacts*: User perceptions of changes in energy services and any unanticipated side-effects during LF testing.
- *User interfaces*: User interactions with LF features via technology interfaces, including control (e.g., parameter settings, overrides) and feedback (e.g., notifications, real-time indicators).

User assessment has been completed for four technological systems, in keeping with the status of signal testing for field demonstrated technologies at the time this paper was written. Table 1 describes the technological systems, including the technology readiness level (TRL) reported by the technology teams, the field demonstration site(s), and participant information. A short summary of each technology demonstrated in the field, field research user interaction, and user assessment is provided next. While user assessments of each system could be reported as separate in-depth case studies, results are summarized across technologies in this paper. Reasons for this include protecting participant anonymity, given the very small sample sizes, as well as identifying patterns that may be generally applicable to LF technologies that are under development.

Table 1. Case Studies in User Experience of Load Flexibility

Technology	Field site(s)	TRL	Total interviews	Total participants
Residential connected thermostats	20 homes	8	6	4
Integrated heat pump with storage for water heating and space conditioning	1 home	5	2	1
Commercial district energy MPC	University central plant	6	4	4
Home heating and hot water thermal battery system	2 homes	7	2	2
		Totals:	14	11

Commercial District Energy MPC

- *Description of field demonstration*: A model predictive control (MPC) software solution to enable LF in district energy equipment was developed and tested on the cooling system of a large university campus. The system consists of chillers, cooling towers, pumps, chilled water (thermal energy storage, or TES) tank, and photovoltaics that provide space conditioning for the campus. When enabled and active, the MPC controlled which of the chillers were operating, their timing, and the water level and temperature.
- *User interaction in field research*: MPC users included the plant operators (stationary engineers) and plant administrative staff. The technology lead met weekly with plant

administrative staff during testing and regularly communicated via email with the plant operators. The technology lead sent advance notifications of testing to operators who would in turn notify the lead when they disabled MPC. The campus vendor for the plant's Building Management System (BMS) worked with the technology lead to incorporate MPC. A widget was added to the main BMS dashboard that the plant operators continuously monitor with an indicator for whether MPC was active or inactive and a control switch to enable and disable the LF control feature being tested. Another screen within the BMS provided historical data on system operations.

- *User assessment*: Multiple operators and administrative staff who were involved in the testing participated in user interviews. Interviews were conducted a year after testing due to rescoping of user assessment plans that did not originally include some lower TRL demonstration projects. It is important to note that from the operator perspective, differences between the LF testing and earlier functional tests were not discernable, so some experiences reported may reflect issues that were worked out during functional tests and resolved before LF testing.

Residential Connected Thermostats

- *Description of field demonstration*: The underlying technology is a commercially-available connected thermostat. This product does not have LF functionality (i.e., a price-based optimization algorithm) but it does have DR functionality to respond to emergency grid events and time-of-use (TOU) energy rates. The field demonstration leveraged these technology features to enable and test the CalFlexHub LF signals in 20 households with central air conditioning in the Pacific Gas & Electric (PG&E) service territory. About half of the households in the field demonstration were friends, family, or colleagues of the technology team (or referrals from friends, family, colleagues), and about half qualified as living in a disadvantaged community (DAC). The testing consisted of periods of pre-heating or pre-cooling followed by setbacks to delay heating or air conditioning, respectively, during several hours of peak energy use/pricing (based on the CalFlexHub hypothetical price signal but relatively aligned with PG&E TOU).
- *User interaction in field research*: The technology team emailed participants in the 20 participating households, providing written instructions to configure the "savings settings" feature (built to program response to TOU rates) for LF testing. Instructions included downloading the app and making sure the "savings" feature was enabled (this was the default setting) and set to level 3 or higher. Settings range from 1 (Minimum) to 5 (Maximum Savings). When LF operations were in effect, an indicator appeared on the app and thermostat device interfaces showing it was "on" and noting the heating and cooling setpoints in effect. Users could override the operations from either interface by changing the setpoint. One week in advance of each testing period, the technology team emailed participants notifications of LF testing. Communications before winter and spring testing periods included a general description of LF operations and a 5-minute educational YouTube video that was linked to the communication preceding summer testing. The video included a more in-depth description of the purpose of testing, the concept of load flexibility, and a walk-through of how to set up the "savings" feature.
- *User assessment*: The user assessment team was provided with contact information for seven participating households. Three households participated in interviews the week

following a 13-day springtime testing round and three (including two of the same) after a late summer 26-day testing round, for a total of five participating households. Only one user-assessed household was from a DAC.

Integrated Heat Pump with Storage for Water Heating and Space Conditioning (Heat Pump System 1)

- *Description of field demonstration*: The technology consists of a single outdoor heat pump for home water heating and space conditioning (heating and cooling) and integrated thermal storage via the water heater reservoir. The system can operate in five different modes, including a combined space cooling and water heating mode where heat transferred to the refrigerant at the evaporator during air conditioning is rejected to the water tank reservoir (condenser). This site, the home of a colleague of the technology team, had the first prototype of this heat pump hardware installed, as funded by another project. After the research team verified reliable baseline operation of the heat pump hardware, a LF controls system was developed and implemented on this first prototype. LF was achieved using a control algorithm to adjust the water heating and space conditioning setpoints in response to a dynamic price signal received daily from CalFlexHub. LF testing was initially conducted just with domestic hot water for a period of 2 months in the spring time, when the house did not have significant cooling or heating demand. Subsequently, LF testing with the integrated system controlling the water heating and space cooling was conducted for roughly one month in the summer. The control algorithms were in effect 24 hours per day during testing.
- *User interaction in field research*: The water heater had an aquastat that displays the water temperature and a web-based user interface. The space conditioning was controlled through the household thermostat. These interfaces allowed users to control setpoints and set schedules. The setpoints and setbacks provided by the LF algorithm are visible on both the aquastat and thermostat screens, and can also be accessed by their respective apps. During LF testing, both the aquastat and thermostat interfaces allowed for overrides of operations, after which the system would revert back to the automated set points. For the aquastat, the user can permanently opt out of LF testing by turning external control mode off. The override on the aquastat was for one hour, while the override on the thermostat could be set for 2 hours, 4 hours, or until canceled.
- *User assessment*: Two interviews were conducted with the householder, one on the heels of LF testing with water heating and one shortly after LF testing with space conditioning.

Home Heating and Hot Water Thermal Battery System (Heat Pump System 2)

- *Description of field demonstration*: This technology delivers home heating and water heating and is commercially available. The system consists of a smart controller managing a heat pump water heater, a hot water tank, and a hydronic air handler as a thermal battery system. It can respond to both event-based and price-based load modification signals. The CalFlexHub demonstration project aimed to demonstrate LF capacity and involved modification of thermal storage charging. The thermal energy storage has a capacity of 7 kWh capability is designed to shift load up to twice daily (mornings and evenings).

- *User interaction in field research*: There are currently no proprietary interfaces for the system, but the company is developing an app. The water heating setpoint is set at the time of installation and the company will change it upon customer request. Space heating is controlled through the customer's thermostat.
- *User assessment*: Testing was conducted at the homes of two existing customers and both were interviewed for the user assessment. Both homes are in the California Bay Area. They were selected because they still had heating loads in springtime when the testing was conducted.

Results

Before the Testing: User Orientation and Setup

Participants' descriptions of their experiences during orientation and setup were generally positive across all the field demonstrations. Heat Pump System 2 users understood from the communications they received what the LF testing involved, generally, and were satisfied with the communication format, timing, and source (i.e., the technology company contact with whom they already had a relationship). In the Residential Connected Thermostat study, all interviewees reported receiving the emails with information about LF testing and following the instructions for initial setup.

There appeared to be room for improvement in how well the provided materials supported participant understanding in the latter study, however. After testing, interviewees had little to no familiarity with the terms "load flexibility" and "demand response," with the exception of one interviewee who was formerly affiliated with the technology team. Interviewees did have some familiarity with the concepts of grid emergencies and/or time-of-use (TOU) energy rates through emails from their utility and local news, and some reported engaging in traditional demand response practices and in trying to modify electricity use based on their TOU rate. None watched the educational YouTube video provided by the technology team.[2] One participant expressed that a phone call would be a preferable communication channel to help them understand the study: "You know, you get all of this information in an email and I know they probably have a lot of participants. But [it would be helpful] for them to reach out or something to see if you know, you understood it correctly, or if you need any help."

Some interviews implied that there were additional benefits for project acceptance that could be gained with closer participant engagement and increased transparency during the orientation and setup stage of the field demonstrations. In the case of MPC for campus chillers, the local engineers were told by their administration that the MPC system was going to be implemented, but both they and their supervisor said that they were given little upfront information about the purpose of the system. Administrative staff described how engaging the operators more could build a sense of "teamwork" and get their "buy-in," which could lead to fewer operator MPC overrides: "I think if we really rolled it out well, and we gave the operators a voice, like you [interviews] are doing now, to share their concerns and then maybe address some of them... I think if we made it more of a team effort rather than a leadership idea--if we involved all the way down to the operator, it would be much more acceptable. And it would

[2] The technology team created an educational YouTube video after the first two testing rounds when they realized testing might be more successful if some users had a better understanding and more explicit instructions.

probably show a little more flexibility [for] the developers, to be able to actually test what the developer thinks could happen."

The case of the Heat Pump System 1 project provides a good example of how closer participant engagement could work. In this case, the participant was an energy professional who collaborated with the technology team. This individual even specified some conditions of the LF testing, including the indoor temperature range for space conditioning LF and the constraint of no water heating at night during water heating LF (as described in the previous section).

Impacts during Testing: How Users Experienced LF

In large part, LF operations during CalFlexHub demonstration projects did not result in sacrifices or disruptions in energy services provided to building occupants. Exceptions were with space conditioning LF, in which a few interviewees reported some thermal discomfort. Discomfort was mainly experienced during setback periods, as opposed to pre-heating or pre-cooling periods.

There were some cases in which participants suspected that they perceived LF operations and impacts, although they were not certain about this. During LF testing involving air conditioning setbacks and pre-cooling, one interviewee thought their household was more sensitive to the warmer indoor temperature during the air conditioning setback period because of the larger than typical temperature swing of having setbacks following pre-cooling. The Heat Pump System 1 participant thought the water supply was slightly hotter in the late mornings after the tank was charged during LF operations, although they noted that the setpoint was unchanged. The participant also thought the water supply was more ample in the evenings due to pre-heating; they reported adaptations to household showering behaviors to take advantage of this situation.

Some of the data suggested that users' perceptions did not always match actual events. For example, campus chiller plant operators recalled the thermal energy storage level dropping to lower levels during LF than was shown in the technology team's data. One Heat Pump System 2 user thought it might have taken longer to reach their heating setpoint in mornings when LF was operating, but this was not the case, according to the technology team.

Even when energy services were not impacted, LF was not necessarily imperceptible because in some cases users could hear the energy equipment operating at different times. At the campus chiller plant, sound served as a source of feedback notifying the engineers that MPC was active because they would hear mechanical noises associated with changes to equipment that they did not "manually" initiate from the BMS. The Heat Pump System 1 user asked the technology team not to run the water heater at night because the sound (and vibration of adjacent wall) it makes would be disruptive to their sleep. A Heat Pump System 2 user noted they heard a different pattern of system operation, but it was not disruptive as the noise level was low.

Campus chiller plant operators experienced a potentially serious negative unintended side-effect of the MPC project. At one point, engineers were in one of the cooling towers to perform maintenance when the chiller started up in response to the MPC. This could be dangerous, since large fans in the tower turn on when the chiller is on. The MPC was implemented and notifications had been received, but perhaps the intermittent nature of the "MPC active" indicator on testing days created conditions that led to a perception of low risk. It was this critical safety issue that led to the creation of an "MPC enable/disable" button to allow operators to manually turn off the MPC, a function that was not available at the time of the incident. Other administration suggestions to mitigate such risk include programing integrations through the BMS to automatically disable MPC when maintenance is being conducted or to trigger alarms when staff enter the cooling towers when MPC is enabled.

A more chronic issue was the increase in anxiety that operators experienced, despite feeling empowered by their administration and by the technology team to disable MPC as they saw fit. Their responsibility to maintain campus comfort while operating somewhat in the dark with regard to an experimental control system caused anxiety, as they felt they had to be more vigilant. As one described, "The personal liability—it was a lot more stressful than my normal day-to-day. None of us were excited about it; we accepted it. It's stressful when someone else is running your equipment from somewhere else. If it all breaks down, are we just going to tell everyone it was an algorithm's fault?"

Some participants in the residential projects experienced both LF participation co-benefits and problems by way of hosting field demonstrations of the enabling technologies. Residential Connected Thermostat participants were satisfied with their new connected thermostat and particularly appreciated the associated app. For one participant, the device replaced what may have been a faulty thermostat because they reported a dramatic decrease in energy bills. On the other hand, the Heat Pump System 1 household experienced time costs and additional stress tied to a variety of equipment failures with this innovative but low-TRL technology.

User Interfaces: Information and Control

Although participants' descriptions of their experience with user interfaces were generally positive, they did include some deficiencies. These can be grouped broadly by themes related to user interface control affordances and information features.

User control in the context of load flexibility can be considered along a spectrum ranging from (1) control of specific parameters of LF operations; to (2) control of a LF device for a short-term period through an override; to (3) the complete disengagement of a LF device through the user turning off the device.

(1) *User control of specific parameters of LF operations*: Heat pump participants reported their innovative systems lacked some basic controls for the core function of water heating, and one System 2 user wished for water heating setpoint control. Only the Connected Thermostat study had technology interface features allowing users to control parameters of LF operations, via the "savings" settings. Although all participants reported visiting these settings during the setup process, none reported changing the setting at all during the study and none recalled their current setting. Also, none had a basic, clear understanding of the relationship between savings settings and LF parameters (i.e., higher savings level = larger setbacks). Upon discussing this relationship, those who experienced discomfort during testing expressed that knowing this would have changed their behavior. One would have lowered their savings level so they might not have needed to override testing as often. The other actually wanted to increase their savings level, despite doing frequent overrides during testing; they did not seem to understand the connection between overrides and savings outcomes, or that the LF testing (with hypothetical price signals somewhat aligned with their utility TOU rate) was not guaranteed to result in

savings.[3] There were also cases in which participants may have changed their setpoint while unaware that LF testing was ongoing; this was suspected because no users recalled seeing the "savings" program active notification info on their thermostat device or app to indicate that testing was ongoing and some participants only vaguely recalled some kind of different notification pop-up to confirm they wanted to change the setpoint during testing.

(2) *User control for a short-term period through an override*: Most users had a means for overriding LF operations, the only exception being Heat Pump System 2 users. The System 1 user wished for the further ability to turn off the water heater when leaving for vacation. In the Connected Thermostat study and Heat Pump System 1 space conditioning LF testing, several users frequently overrode the LF operations due to thermal discomfort, typically being too hot during setback periods. At the campus chiller plant, the MPC interface component on the BMS initially lacked the ability for operators to disable, as previously mentioned. All campus chiller plant operators interviewed reported disabling MPC occasionally, though at contrasting frequencies (ranging from about 2 to 12 times), typically when they believed the thermal energy storage level was too low or if they needed to do maintenance or repairs on equipment.

(3) *User control by turning off devices.* In the Connected Thermostat study, one participant reported operating the thermostat only manually, meaning they kept the system off entirely most of the time, turning it on and adjusting the setpoint when they wanted heating or cooling (mainly from the device), then turning it off again when they reached their desired setpoint. From the user's perspective, this was the most energy-conservative approach, to use conditioning only when needed. From the LF systems perspective, however, the thermostat could not engage in LF when the system was off.

Interest in user interface information features such as forecasts, advance notifications, and beneficial impacts of LF, spanned the commercial and residential building user contexts. Campus chiller plant administration suggested that MPC LF operations provide forecasts, such as a weekly schedule, which could be helpful for scheduling maintenance and putting the operators more at ease. They observed that a market-ready system could have the ability to program advance notifications, weekly schedules, and near-term forecasts. Similarly, a Connected Thermostat participant would have also appreciated advanced notifications, ideally directly prior to each time LF operations went into effect. With respect to beneficial impacts, campus chiller plant administration wanted to understand what the testing suggested the LF impacts would be on total grid demand and energy bills.[4] Similarly, a Connected Thermostat participant would have liked information about impacts, noting that this could provide a sense of accomplishment and reinforce his commitment to energy conservation: "If there was an obvious thing in the phone or the wall screen that said, 'You have saved this much today by being in this program'... that'd be interesting." A Heat Pump System 2 user also stated "If I could choose what features I can see through this app, I would like to see my usage when the system goes on and

[3] None had previously enabled the "savings" setting to respond to their TOU rate, which it is designed to do. The instructions in communications prior to LF testing were to turn this feature off during testing periods.

[4] Administration acknowledged receiving reports or presentations but implied the results were not directly or easily interpretable in terms of meaningful campus impacts.

goes off, how much energy is being used, being able to adjust the water temperature, obviously, or maybe even override my thermostat temperature remotely if necessary."

In many instances, however, users did not engage with all the information they were provided with via system interfaces. At the campus chiller plant, the engineers did not seem to realize they had access to more granular MPC operations data within the BMS, or at least did engage with it to try to observe patterns and create expectations about MPC operations, despite stating they felt "in the dark" about LF operations. The Heat Pump System 1 user did not visit the available web interface, although that individual already had an in-depth understanding of the technology as well as involvement in setup and frequent collaboration with the technology team to determine LF testing parameters. Participants in the residential studies often reported that there were adult household members (e.g., themselves or spouses) who never engaged with any of the technology interfaces, and sometimes were hesitant to engage because they did not want to interfere with the study. For example, one remarked, "I'm very cautious about what buttons I press." Another said, "I've always been so afraid to go in there [the app] and mess with something, because then I think I'm going to screw up, you know the whole setup that's on there [for testing]." Finally, one Heat Pump System 2 user did not even want an app: "No, you know I'm 84 years old, which means that I lived at least half of my life without computers, perfectly satisfactorily… I just have other things that concern me more than technological details, I guess is what I would say."

Discussion and Conclusion

This paper focused on user experience with emerging load flexible (LF) technologies, as demonstrated in residential and commercial building field sites in California as part of the research and development efforts of CalFlexHub. Although the larger CalFlexHub project involves, at last count, 12 technologies/systems and 19 individual projects with multiple partners and technology teams, a smaller number of projects include field demonstrations and not all field demonstrations were completed at the time of this report. The testing of LF technologies in real-world settings is still so nascent, however, that the small number of people who have experienced LF technology responsiveness to CalFlexHub price and greenhouse gas signals represents a not insignificant portion of the U.S. population of people with such experience of any LF responsiveness to similar signals.[5] In this context, the sample of four technologies assessed with respect to the user experience of the LF technologies before and during testing, as elicited through the 14 interviews with 11 participants which we reported on in this paper, is meaningful. It also presents an opportunity to consider how future user assessment research could take part in a larger study, for example, by incorporating labeled magnitude scaling with respect to testing impacts as has been done in past research on non-energy impacts.

Although it is challenging to draw generalizable conclusions about user experience with LF given the context of this paper, certain patterns emerged from the interviews. First, participants expressed generally positive sentiments about the three assessed aspects of user experience, namely: (1) user orientation and setup in advance of technology testing; (2) user observations of LF test impacts; and (3) interactions with user interfaces. Second, participants provided insights that could improve the design of market-ready technologies and load LF programs.

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[5] Other significant populations include those involved in utility pilots as part of the California Public Utility Commission's (CPUC's) Demand Flexibility Rulemaking.

Regarding aspect (1) of the user experience, which occurs prior to testing, an insight is that communication materials regarding LF need to improve if people are to understand it for purposes of enrollment and participation. Although all technology teams leading field demonstrations communicated basic information about testing to users, not all of these communications were effective. Communication begins with shared language, but most users were not provided upfront with a succinct name and definition for the concept of LF. Researchers may be trying to avoid jargon but users, particularly early adopters, may appreciate having that shared language, and it would empower them to do independent research on the topic. On the other hand, the Connected Thermostat interviewees did not watch the educational YouTube video that the technology team created after the first two testing rounds when they realized testing might be more successful if some users had a better understanding and more explicit instructions. Note that similar disengagement was also seen with respect to user interfaces.

Communications in advance of LF operations should also help users set reasonable expectations, particularly with respect to the potential for bill savings. Communication designers should keep in mind that users may be quick to assume an energy-related program is promising energy bill savings because that is what most energy related programs do. One of the interviewed respondents, for example, presents a case in which a connected thermostat user emphatically described significant bill savings as a result of program participation, likely due to replacing a faulty thermostat. The high reported satisfaction of that user suggests that framing the relatively small savings potential associated with LF as part of a package that also includes other potential short- or long-term co-benefits features (e.g., additional savings) of an LF-enabling technology could encourage adoption. In general, future research on effective ways to communicate about LF with potential participants, including messaging and framing strategies, would be valuable, and should draw on best practices in the communications literature.

Regarding aspect (2) of the user experience, which involves user impacts of LF operations, we see that today's emerging LF technologies are far from "invisible" and can affect users in several ways. One related insight is that user perceptions of impacts may differ from technology team expectations. This was the case with the sounds of LF operating technologies, which fell outside of the usual aural patterns of normal technology use and had the potential to impact sleep. This was also the case in the potentially dangerous situation in which campus chiller plant operators were performing cooling tower maintenance when the chiller started up in response to the MPC. It seems likely that technology developers will not be able to anticipate all such cases; this argues for strategies such as designing systems with more override options, as in the chiller case.

It also provides a good reason for technology teams to work together with users in a collaborative innovation approach. In the context of field demonstration projects, technology testing teams should consider actively and regularly soliciting questions and feedback from users through personal and integrated iterative communications; this may both protect users from negative impacts and facilitate more meaningful testing. This is particularly important when testing LF technologies with low technology readiness levels, which may mean equipment and software have bugs to work out while user interfaces are still under development. The study of Heat Pump System 1 was unique in that the user was a professional engineer and colleague of the research team who not only understood LF, but also had considerable input on the LF testing parameters. In contrast, there was a missed opportunity in the other projects to benefit both the testing and the users by engaging them more. There might have been fewer intentional and accidental overrides of the testing if users were more in the loop.

A second important insight is that the impacts that users perceive during LF may not necessarily match measured data on LF impacts. This occurred with user-perceived negative impacts. For example, data did not match the observations of a Heat Pump System 2 user who thought it might have taken longer to reach their heating setpoint in mornings when LF was operating, nor did it match or the recollections of chiller plant operators regarding the thermal energy storage level dropping to lower levels during LF. It also occurred with user-perceived positive impacts. This happened in the case of the thermostat user who reported experiencing an overly-large decrease in energy bills which they falsely attributed to the tested device's load flexibility (the savings were probably based on the device's substitution for a faulty thermostat). Implications of the distinction between perceived and observed impacts include both (1) a potential need to question approaches to measuring user impacts; and (2) a need for LF technology developers to take into consideration psychological phenomena in which perceptions of reality can be quite powerful, even if they do not match objective reality (see, e.g., the "placebo" effect). This latter consideration implies the need for user-oriented LF product design which empathizes with users who may experience additional stress with perceived loss of control. This is a well-studied topic in the literature on risk perception and communications which might be leverageable to good effect in LF technology design, particularly with respect to user interfaces. A useful example is how introducing visualization of flight paths into commercial air passenger displays helped relieve some passengers' fear of flying because it helped them feel a greater sense of control.

The interviews provided several insights into aspect (3) of the user experience, in which people interact with technology interfaces during LF operations.[6] First, all three of the control options available to users in the CalFlexHub testing were exercised by at least one participant, and two of those options were enabled by interfaces. These control options are (1) control of specific parameters of LF operations; (2) control of a LF device for a short-term period through an override; and (3) the complete disengagement of a LF device through the user turning off the device. Of these three control options, the second one (overrides) was the one most consistently supported across the user interfaces of the tested technologies, with only one technology interface (Heat Pump System 2) completely lacking the means for users to override LF operations. By contrast, the first control option, in which users control parameters of LF operations, was supported by the interface of only one tested technology – connected thermostats (user control took place via the "savings" settings). Regarding the third user control option, turning off the device, one respondent reported doing this regularly as a particularly strong energy conservation measure. As this fully disables the LF capability of the device, the behavior seems to reflect either a lack of participant understanding of the nature of the technology tests or a prioritization by the user of conserving resources over supporting the grid. These findings regarding user control options suggest that LF technology interfaces should enable key user interactions, such as being able to enable or disable LF operations as desired and to set parameters of LF as appropriate. They should also provide sufficient information to support those interactions, so users understand when they may or may not want to allow LF and what their options are for setting the parameters, ideally outside of turning the device off.

[6] User interfaces for tested technologies were generally underdeveloped, particularly with regard to offering feedback and control over LF operations.

A second insight regarding the interface aspect (3) of the user experience is that participants would appreciate it if interfaces included more transparency regarding LF operations (e.g., advance notifications, weekly schedules, and near-term forecasts, features which reduce uncertainty and feelings of loss of control) as well as information confirming the value proposition (e.g., cumulative bill savings or community/grid impact of LF participation).[7] Such features can reinforce user motivations for participation and sustain engagement. These findings are consistent with Diamond, Mirnig, and Fröhlich (2023), which identified the following key interface features to promote trust in automated DSM strategies: control options and communication about control; automation transparency; benefit information; and feedback.

This relates, however, to a third insight about interfaces, which is that they need to be designed and introduced to users so people engage with and understand the information the interfaces provide. In the case of any given LF technology, there will virtually always be a user that requires some affordances for control as a condition of technology acceptance. When users have control, however, they must also have an understanding of LF that informs their interactions with the technology so that flexibility can be maximized as a grid resource. Building this understanding requires effective communication for user engagement. In the CalFlexHub tests, however, there were many examples of people not engaging with communication and interface materials (e.g., not watching the YouTube video on LF, not accessing granular MPC operations data within the campus chiller plant BMS, not visiting heat pump web interfaces or thermostat interfaces, etc.). For the most successful roll-out of LF to support decarbonization, researchers and other proponents of LF should focus on establishing best practices for user communication strategies and user interface design in tandem with developing the core functionalities of LF enabling technologies and best practices for LF signals and device control algorithms. Future LF demonstrations should prioritize the advancement of user communications strategies and interface development with an eye to shaping future utility LF programs.

Some final recommendations for technology developers and program designers include consideration of occupancy schedules and user activity patterns (Cass and Shove 2018) when designing LF parameters and rate structures. They should also understand users' baseline control strategies for the LF enabling technology or system it is replacing, and consider whether and how they should encourage users to program equipment in ways more synergistic with LF operations (e.g., set thermostat back instead of turning it off, or use programming features). A potentially useful strategy for promoting adoption and positive user experience is to leverage or create (and communicate) co-benefits for users (e.g., hotter water than usual at certain times of day allowing for a more luxurious shower).

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[7] In the case of demonstrations, interfaces could present hypothetical impacts.

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