Enhancing Participation in Residential Demand Response: Insights from Case Studies Conducted in Alaska and California

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ABSTRACT

Residential demand flexibility (DF) has great potential as a demand-side management strategy that can enhance grid reliability and facilitate the integration of renewable energy. Technological and regulatory advancements are increasing opportunities for residential customers to participate in DF programs. However, the effectiveness and flexibility of residential DF resources continues to remain highly variable due to differences in energy use between households. A better understanding of differences can improve the dependability of residential DF resources. We present lessons learned from two thermostat-based DF field studies conducted in homes in rural Alaska and Central Valley California. We adopted a mixed-method approach combining qualitative and quantitative data to 1) gain insights on key factors that influence energy use difference between households, 2) collect comprehensive thermal comfort data during DF events and 3) understand how thermal comfort impacts of different DF strategies influence the persistent participation of households in residential DF events. Our study indicates that collecting household-specific energy use and thermal comfort data can help devise occupant-centric DF strategies that improve the participation reliability and efficacy of thermostat-based DF programs.

Introduction

In the United States, residential and commercial buildings collectively consume 40% of total energy produced (EIA 2023a). Despite gains achieved in lowering building energy use intensity, the U.S. Energy Information Administration's (EIA) 2023 Annual Energy Outlook predicts an increase in energy use of 14% to 22% from 2022 to 2050 (EIA 2023b). This predicted increase is attributed to the projected growth in electricity demand due to increased uptake of air conditioning and electric vehicle charging, and electrification of space and water heating -signaling an increased reliance of the building sector on the electric grid in the near-and medium-term future. On the other hand, the recent adoption of aggressive emission reduction targets (The White House 2021; California Energy Commission 2021) demands multi-sectoral solutions across the electric power, industrial, building and transportation sectors to improve energy efficiency and reduce energy use. In response to these policies, utilities and other actors across the nation have renewed efforts to increase the share of clean and renewable energy generation sources in the primary energy generation mix, undertake market transformation efforts to increase electrification of building space conditioning and transportation systems, and actively manage demand-side loads. Demand-side load management refers to the controlled utilization of resources on the consumer-side of the electric grid to achieve a balance between supply and demand through energy efficiency, load shedding, load shifting, load modulation or energy generation (Neukomm, Nubbe, and Fares 2019). Current estimates predict that demand-side management of U.S. building loads could save $100-$200 billion in electric power costs and decrease carbon emissions by 80 million tons (Satchwell et al. 2021).

Space heating and cooling are the largest energy end-uses in residential buildings. They are inherently controllable and flexible; hence they are a major focus of demand-side management programs. However, external management of residential space heating and cooling loads may cause occupant discontent. The EIA data on the potential vs actual utilization of DF[1] in residential sector for 2021 shows that the actual savings realized (3.8 TW) was less than 50% of potential estimated savings (8.7 TW) (EIA 2022). The difference between estimated vs actual savings is attributed to several reasons including variability in household participation in DF events. This variability stems from the socio-technical difference between households and the heterogeneity in the willingness to accept changes in indoor thermal environment during DF events. From a U.S. context, currently there is limited literature that addresses how these factors impact the participation of households in space conditioning-based DF events. However, this insight is critical as occupant-centric DF implementation strategies can lead to more reliable outcomes and encourage the persistent participation of residential households in recurring DF events.

This paper presents lessons learned from residential demand flexibility field studies conducted in homes in rural Alaska and Central Valley California. These studies aim to demonstrate the load-flexibility potential of DF-enabled space-conditioning technologies; and assess the occupant response to these systems in realistic residential settings. The study sites are in a rural and a disadvantaged community thereby offering an added perspective of the impact these technologies may have on traditionally difficult to reach demand-management program participants. This paper focuses on the occupant aspect of the study; energy load-flexibility results from these studies are discussed in other publications.

Background

Demand Flexibility Potential of Residential Buildings

Demand flexibility refers to the capacity of demand-side loads to change their consumption patterns at different timescales in response to grid needs. It motivates lower electricity consumption when the generation cost is high or unreliable and demand is at its peak (Neukomm, Nubbe, and Fares 2019). Residential buildings are strong candidates for demand flexibility due to several reasons. Some residential buildings may have high thermal mass, which acts as a thermal storage device by delaying the rate of heat conduction through them. This phenomenon can be exploited to pre-heat or pre-cool the building for shifting energy use from peak to off-peak energy use periods (Masters 2013). Second, internet of-things (IoT) enabled space-conditioning equipment and smart appliances can be controlled externally through their application program interface (APIs). Commercially available DF-enabled technologies including smart thermostats, heat pumps and home-energy management systems support communication protocols (AHRI 2019; ANSI/CTA 2022) that enable communication of DF signals to devices. APIs that are interoperable with standardized communication protocols allow external agents to program temporary changes to the setpoints or duty cycles of thermostatically

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[1] a type of demand-management strategy where electric utility customers are requested to reduce their energy consumption for a few designated hours corresponding with typical peak demand.

controlled residential heat pumps and air conditioners during periods of grid stress. Third, the operational schedule of some residential appliances and devices may be flexible—hence occupants may be nudged to defer their use to off-peak periods through information campaigns and electricity pricing structures (Aloise-Young et al. 2021). Some households may be flexible in accepting slightly lower temperatures in the heating season and slightly higher temperatures in the cooling seasons. Finally, curtailable building loads respond faster, and are environmentally friendlier than back-up peaker plants in managing the electric grid's supply-demand balance (Masters 2013).

Challenges in Residential Demand Flexibility

In the U.S., buildings are estimated to have the capacity to impact 10.2 GW of peak demand load reduction (Satchwell et al. 2021), however actual savings from current load-management activities is 50% less than its estimated potential (EIA 2022). Researchers have reviewed barriers leading to under-utilization of building load flexibility potential (Weck, van Hooff, and van Sark 2017). For the residential sector, Weck et al. (2017) classified these barriers into technological, economic, and social. Technological barriers include low adoption of advanced-metering infrastructure; grid-interactive and DF-enabled devices and technologies like smart thermostats, home energy management systems and heat pumps; and challenges in appliance-to-grid communications. Examples of economic barriers include lack of enabling market policies and business models to support utility and third-party investments in advanced load-management infrastructure. Social barriers include customer inertia, fear of loss of privacy and autonomy, general distrust toward utility companies, lack of motivation, risk averseness and distrust toward digital technologies.

Beyond initial enrollment, the success of a DF program relies on the persistent participation of households in multiple DF events and through the entirety of a given multi-hour DF event. In the case of DF events involving temporary adjustment to space heating or cooling appliance operation, willingness of a household to persistently participate can be impacted by both direct and latent factors including household composition (Bird 2015), daily routines of energy consumption (Fell et al. 2014), thermal comfort preferences (Sweetnam et al. 2019; Martin-Vilaseca et al. 2022), level of interaction with thermostats or home energy management devices (Naghiyev et al. 2022), outdoor temperatures, DF event duration and impact of the demand curtailment on device service quality (Nyborg and Røpke 2013). A 2021 study that applied statistical models to analyze DF behaviors in large-scale residential trials found that warmer climates are more likely to participate than colder climates (Antonopoulos et al. 2021). Field studies conducted by Nyborg and Ropke (2013) found demand flexibility to be lower on days when outdoor weather was colder. They also found households without dependents or pets are more flexible, and events lasting up to one hour are preferable than two hour or longer events. Acceptable event duration is also dependent on outdoor weather conditions. The (Nilsson et al. 2018) field study found that flexibility reduces with increase in household size.

Martin-Vilaseca et al. (2022) emphasize the role of latent factors in residential DF participation. They found that people notice DF events through thermal sensation, surface temperature of various objects and equipment noises, and their responses to such latent triggers impact success of DF events. Finally, an analysis of open-source residential smart thermostat data (Sarran et al. 2021) and retrospective surveys conducted after field validation studies (NV Energy 2015; EPRI 2015) emphasizes the role of thermal comfort during DF events on willingness of residential households to persistently participate in DF programs.

These studies provide valuable insights about factors that impact DF participation and flexibility potential of households. However, information pertaining to relevant factors may not be readily available to program administrators or inferred easily from energy use data. Particularly, the impact of thermal comfort perceptions on DF participation can be challenging to infer as comfort preferences are heterogeneous and difficult to predict because thermal comfort models have low prediction power (Cheung et al. 2019). Moreover, comfort standards (ASHRAE 2023, 55; ISO 2005; CEN 2007) focus on conditions to maintain consistent indoor thermal conditions; as such they provide limited guidance for evaluating comfort in transient conditions. The limited guidance available in the standards are based on studies conducted in laboratory settings, primarily geared toward sedentary office workers; and hence fail to address real-life transient thermal conditions (Arens, Zhang, and Huizenga 2006) including those of DF events in residential settings.

To address these limitations, we adopted a mixed-methods approach in two case studies. The approach combines qualitative and quantitative research methods to develop a data collection and analysis framework focusing on collecting socio-demographic, household, thermal comfort, and energy use data; and analyzing this data to gain insight on how these factors impact persistent DF event participation.

Methodology

A mixed-method approach is applied to two DF field validation studies 1) Fan Integrated Thermostat Cooling (CoolFIT) summer demand flexibility study conducted in Stockton, California, to demonstrate the load flexibility potential and occupant response to fan integrated smart thermostat during DF events; and 2) Ductless heat pump (DHP) winter study conducted in Cordova, a rural fishing town in Alaska, to demonstrate the DF capabilities and assess occupant response to DF events implemented through cold weather heat-pump technology.

Study 1: CoolFIT Study, Stockton, California: The CoolFIT study tested the effectiveness and demand flexibility potential of ceiling fan integrated smart thermostats in hot summer climate conditions. In this study researchers from University of California, Berkeley demonstrated the technical feasibility of retrofitting existing ductless packaged terminal units with DF-enabled smart thermostats (Ecobee) and the benefits of adding supplemental cooling with low-power smart ceiling fans (Big Ass Fans). The study was conducted in five apartment units in a senior housing center in Stockton, California. Stockton experiences hot, arid summers with typical high temperatures ranging from 90 to 100°F (32 to 38°C). The CoolFIT study was conducted from late August 2023 to early October 2023. The outdoor temperature during this period ranged from 65 to 95°F (19 to 35°C). As part of the study, the team installed six ceiling fans and replaced the existing five rudimentary onboard controls of the packaged units with smart thermostats. A summary of the study details is provided in Table 1.

Study 2: DHP Field Study, Cordova, Alaska: The DHP study examines the potential of CTA-2045-enabled heat pumps as a grid resource for residential DF in the cold climate and rural region of Cordova, Alaska. Cordova is a small city of approximately 2600 residents that experiences subpolar oceanic climate with moderately cold, extremely snowy winters. The outdoor temperature in the winter months reach lows ranging from 3 to 30°F (-16 to -1°C).

The American National Standards Institute/Consumer Technology Association (ANSI/CTA)-2045 communication standard specifies a modular interface to facilitate communication with residential devices for energy management applications (EPRI 2014). The standard enables third parties to interact with residential systems such as water heaters, space conditioning heat pumps, variable-speed pool pumps, electric vehicle charging systems, and thermostats. As part of the study, three single family residential homes were retrofitted with ductless Mitsubishi heat pumps featuring CTA-2045-enabled universal communications modules provided by e-Radio. The heat-pumps replaced the participants original fuel oil-based primary heating source. The DHP winter study was conducted from November 2023 to March 2024 by researchers from the Pacific Northwest National Laboratory (PNNL) and the University of California, Berkeley. Table 1 provides a summary of this study.

Table 1: CoolFIT and DHP Study Summary

	CoolFIT Summer DF Study	**DHP Winter DF Study**
Location	Stockton, California	Cordova, Alaska
Load flexible technology used	Smart fan integrated smart thermostat	CTA-2045 enabled ductless heat pump
Study period	8/2023 – 10/2023	11/2023 – 4/2024
Building type	Multi-family housing	Single-family detached
DF dispatch	Via ecobee API	Via e-Radio API
Number of planned DF experiments	20 per home	65 per home
DF event time	Between 3:00 pm and 7:00 pm	Between 5:00 pm and 9:00 pm
DF event duration	1 hour to 3 hours	1 hour to 3 hours
DF event temperature offset	1°F to 5°F relative to typical cooling setpoint	1°F to 6°F relative to pre-event heating setpoint
Pre-conditioning strategies	Pre-cooling, ramped setpoint offset	Pre-heating immediately and one hour prior to DF event start

Research Design

Both studies followed a three-phase research design – pre-study phase, study phase and post-study phase. The following sections present overview of the methodology and key findings from each phase. The pre-study phase focuses on preliminary data collected about the building's physical characteristics, participant socio-demographics, households' energy use behaviors and comfort experiences with the pre-intervention space-conditioning systems. The study phase focuses on the DF events and key findings from energy and comfort data collected from each participating site. DENT power loggers are used in the DHP study and Hobo CTs in the CoolFIT study to collect energy data. Additionally, e-Radio API for DHP Study and ecobee API for the CoolFIT study are used to collect minute-level thermostat setpoint data. Hobo sensors continuously monitored the indoors and outdoors temperature and humidity levels in the study houses throughout the study duration. Additionally, a bespoke version of the right-now surveys (Duarte Roa, Schiavon, and Parkinson 2020) administered through the Qualtrics platform and disseminated through text messages helped collect real-time information on occupant's subjective response to thermal comfort conditions during the study period. Finally, the post-study phase focuses on key findings from participant interviews summarizing retrospective reflections of occupants with the DF-enabling technology and DF events.

Data Collection and Key Findings

Pre-study phase: During this phase of the study, we conducted physical inspections of each study site and one-on-one semi-structured guided interviews of adult study participants. The DF-enabling technology interventions were completed either immediately prior to or concurrently with the site inspections and guided interviews. The researchers also took the opportunity to educate the participants about study objectives, demonstrate the operation of the newly installed technology, inform participants of the potential impact the DF events may have on their thermal comfort, ways to override or opt-out of the DF events and answer any questions or concerns the participants had. Data collected from the site inspection and interviews include 1) physical characteristics of the study site including house type, year of construction or major renovation, area, general space layout, envelope type, window/skylight type and layout, primary and back-up HVAC system types, number of floors and other notable physical features; 2) household characteristics including participant ages, gender, ethnicity, number of dependents and pets, time of house move-in, and occupation of participants; 3) household routines and energy use patterns including typical occupancy schedule, typical months when space heating/cooling is used, typical hours when space heating/cooling is used, typical rooms and times where household spends their time, and typical patterns for primary or secondary space heating/cooling system use 4) thermal comfort related questions including preferred thermostat setting and thermostat use behaviors, general satisfaction with thermal comfort in the house, areas of home that are more prone to discomfort and potential causes, typical thermal discomfort adaptation habits and general agreeability among household members on temperature setpoints, and general satisfaction with thermal comfort in different parts of their home, time of day, and seasons.

Key Findings: The data collected from this phase was analyzed qualitatively by using content and thematic analysis approaches (Clark et al. 2021). Table 2 provides a summary of the key findings from the thematic analysis. Noteworthy themes include age, presence of dependents and pets, typical HVAC use, typical interaction with thermostat, comfort preferences and attitudes toward energy use, environment, and preference for autonomy over controlling thermostat. Additionally, the interview transcripts revealed the following noteworthy observations:

- Households that are satisfied with their existing indoor thermal environments are less motivated and are more cautious to participate in DF programs than households unsatisfied with their existing HVAC system performance, thermal comfort, or energy bills.
- Households with at least one adult resident willing to learn new technology are more open to participating in DF. Households that find the HVAC control to be too complex are less willing to participate. This observation underlies the importance of thermal comfort autonomy in DF participation.
- In addition to indoor comfort, other factors that influence households' willingness to participate in DF include environmental or social good, and impact on energy bills.

Table 2: Key Findings from Thematic Analysis of Pre-Study Data

Themes & Categories	**CoolFIT**	**DHP**
Sociodemographic of Participant Households		
Gender	Male: 4 Female: 3	Male: 3 Female: 5

Age	Below 18: 2 18-65: 1 Above 65: 4	Below 18: 4 18-65:5 Above 65: 0
Ethnicity	White: 2 Black : 3 Asian : 2	White: 8
House Characteristics		
Type	Multi-family apartment unit: 5	Single-family detached: 3
Ownership	Rent: 5	Own: 2, Rent: 1
Household Energy Use		
Typical space heating/cooling source	Space cooling- HVAC: 4, Fan: 1	Space Heating- HVAC: 3
Typical thermostat use pattern	Infrequent daily setpoint adjustment: 2 Frequent daily setpoint adjustment: 2 Rarely uses air-conditioning: 1	Infrequent daily setpoint adjustment: 2 Somewhat frequent daily setpoint adjustment: 1
Thermal Comfort		
General satisfaction (before technology intervention)	Satisfied: 3 Unsatisfied: 2	Satisfied: 1 Unsatisfied: 2
Main factors that influenced indoor comfort (self-reported)	Poor envelope insulation, building orientation, HVAC system location and sizing	Non-uniform HVAC service quality between rooms, poor envelope insulation, single-pane window, window size and orientation, HVAC system location and sizing
Attitudes and Preferences		
First priority	Environment: 1 Comfort: 4	Energy Cost : 1 Comfort: 2
Second priority	HVAC control autonomy: 5	HVAC control autonomy: 2 Comfort of dependents: 1

Study phase: This phase involved conducting DF experiments and collecting detailed indoor environment, thermostat use, and comfort data over an eight-week period for the CoolFIT study, and 20-week period for the DHP winter study (please see Table 1 for details). The DF experiments varied in event duration and temperature offset. In addition, we tested the impact of typical DF rebound reduction strategies like pre-heating, pre-cooling and ramped setpoint offsets. The DF experiments were scheduled two to four weekdays per week; weekends and major holidays were exempted. While we randomly chose the DF event days, we conducted the experiments in the afternoons of those days to coincide with typical peak demand hours.

The comfort-surveys were sent out on most DF event days and occasionally on baseline days. Comfort surveys last less than a minute and include questions regarding how participants felt "right-now" about their thermal sensation and thermal preference. Responses are recorded as thermal sensation votes (TSV) on a Likert scale with options *-3: Cold, -2: Cool, -1: Slightly Cool, 0: Neutral, 1: Slightly Warm, 2: Warm, 3: Hot.* Thermal preference votes (TPV) are recorded as preferring *cooler, no change,* or *warmer* thermal conditions. Additionally, in cases when respondents selected *warmer* or *cooler* TPV; they were directed to the thermostat preference question asking whether they would like to *adjust the thermostat, wait for some time, or choose to take no action*.

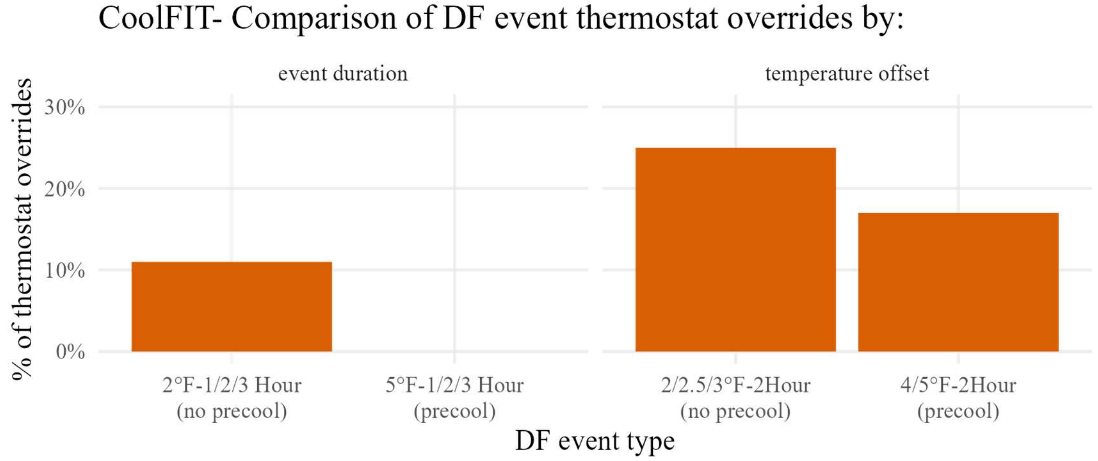

Figure 1: CoolFIT- percentage of thermostat override comparison by precool vs no precool DF events.

Key Findings: Figure 1 shows a summary of the CoolFIT summer study DF events and a comparison of the percentage of thermostat overrides by event duration and temperature offset. Events preceded by a pre-cooling period generally resulted in lesser overall thermostat overrides than events without precooling.

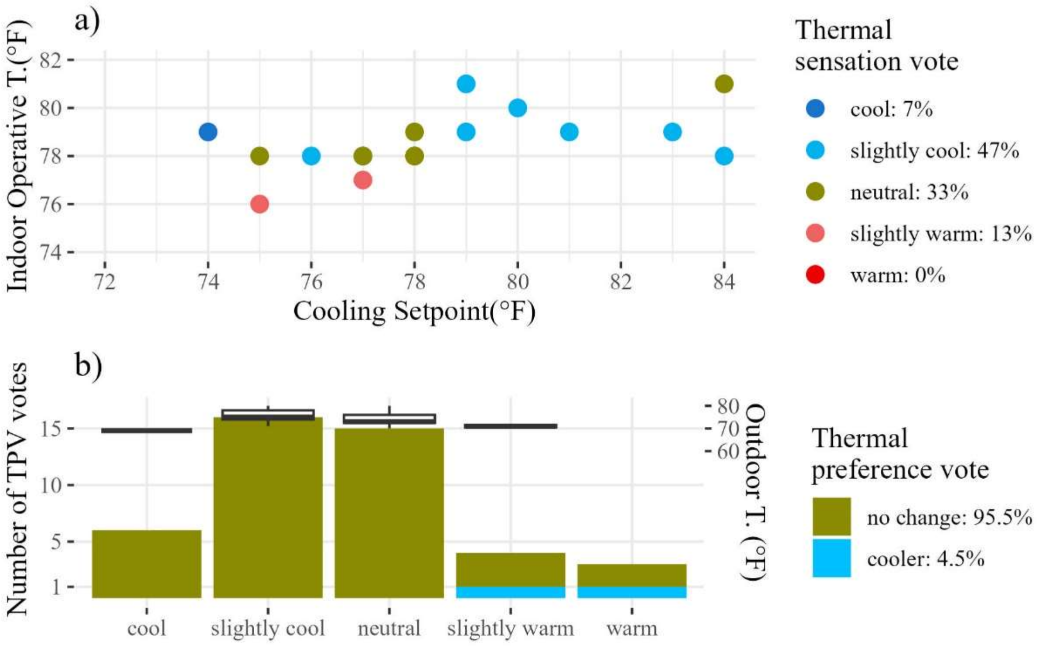

Figure 2: Comfort survey results- CoolFIT study. a) 47% *slightly cool*, 33% *neutral* Thermal sensation votes. b) 95% *no change* Thermal preference votes

Comfort survey results for CoolFIT study are shown in Figure 2. Figure 2a) shows that thermal sensation votes collected on DF events are dominantly *slightly cool* (47%) and *neutral* (33%). The corresponding indoor operative temperature at the time of the *slightly cool* and *neutral* responses range from 78 to 81°F (25.5 to 27°C), and thermostat cooling setpoint ranged from 74 to 84°F (23.3 to 29°C). Figure 2b) shows that 95% of all recorded responses for thermal preference votes correspond to *no change*. 4.5% of votes preferred *cooler* in response to feeling *slightly warm* or *warm* thermal sensation. The indoor temperature, setpoint or outdoor temperature data did not provide sufficient explanation for these responses. However, further analysis of the comfort surveys and time- series of thermostat data tracked to a single participant. This participant had previously expressed dissatisfaction with the general thermal comfort of their home. They noted that the house had a large west-facing single-pane window that caused glare and discomfort. Additionally, they frequently interact with their thermostat throughout the day in efforts to optimize comfort. Apart from evidence that these habits may have continued; compared to other participant homes no notable changes were identified in indoor temperatures during DF events in this participant house. This observation highlights the importance of typical thermal conditions while targeting candidate households for DF programs.

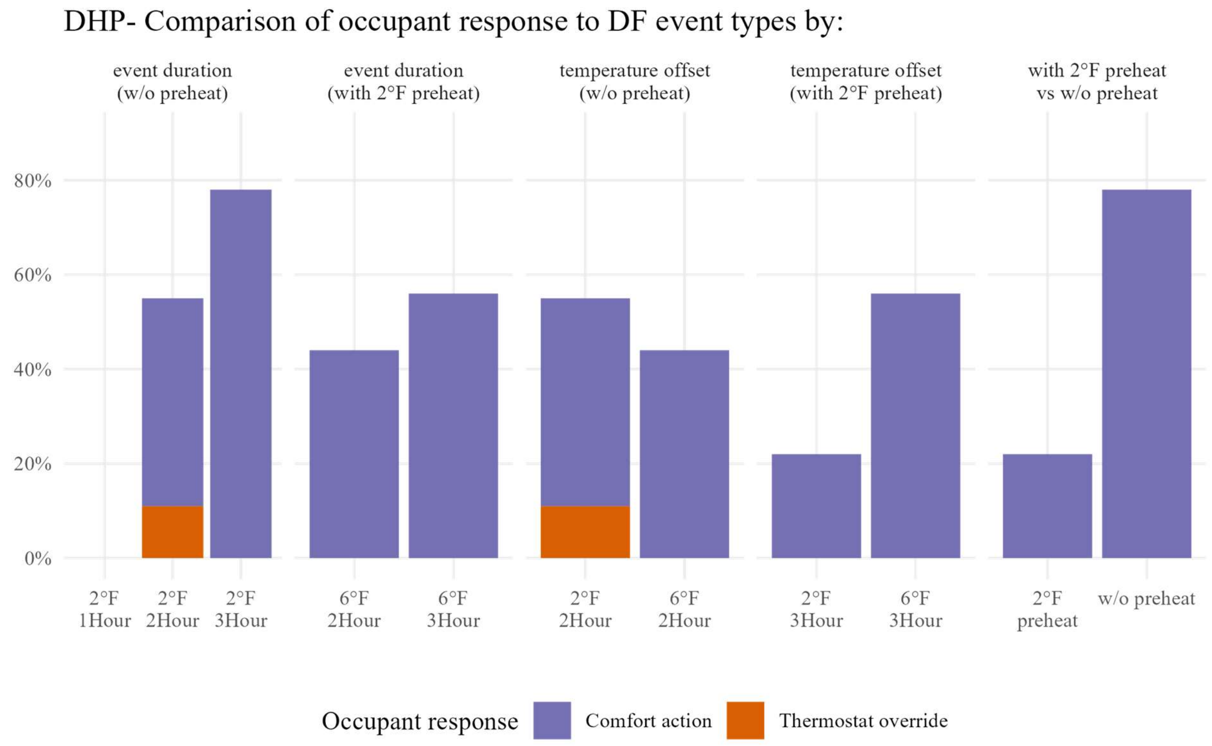

Figure 3: DHP DF events- thermostat overrides and other comfort actions by event type

Figure 3 is an overview of key DHP winter study DF findings. A larger study period enabled the testing of a wider range of DF event types repeated multiple times (3 minimum) thereby providing greater confidence in results. Figure 3 shows a comparison of the occupant responses during DF event periods as thermostat override rates and other comfort actions. Comfort actions refer to events when the indoor temperature increased by more than 0.5°F during DF event due to a thermostat override or activation of supplementary heating units in the homes. The comparisons are summarized for preheat vs no preheat DF events by event duration and temperature offset. Thermostat overrides and comfort action are generally higher for DF events with no preheat in comparison to DF with preheat. Occupant response rates (overrides and comfort action) increased with event duration with no overrides recorded for one-hour events and progressively increased rates for two- and three-hour events. The impact of temperature offset is less pronounced in the no preheat case but noticeable in the longer duration preheat case. These results indicate that for DF during heating season, residential participants may have a greater sensitivity to event duration than temperature offset for events that are less than two hour long. Events lasting more than two hours are sensitive to both duration and temperature offset Additional studies and larger sample sizes can help generalize these findings under other geographic conditions.

Figure 4 a), b), and c) show results of DHP study comfort surveys. Thermal satisfaction votes during DF events ranged from *cold (-3)* to *slightly warm (2).* Figure 4.a) shows more than 50% of TSV votes correspond to *neutral* – a self-reported verbal description of a sensation of feeling neutral- neither warm nor cool. Over 90% of the *neutral* votes correspond to indoor operative temperatures ranging from 67 to 71°F (19.4 to 22°C) and heating setpoint ranging from 67°F to 71°F (19.4 to 22°C). Heating setpoint temperature above 73°F (23°C) received *slightly warm* and *warm* votes corresponding to indoor operative temperature ranging from 66 to 73°F (19°C to 23°C). Figure 4.b) shows that the *cold* and *cool* TSV's correspond to events when outdoor temperatures were below 30°F (-1°C). Thermal preference votes – an indicator for desired change in thermal conditions during events when outdoor temperatures were below 30°F (-1°C) were *warmer*; indicating that DF during extreme cold days are not desirable. Indoor and setpoint temperature conditions during events that triggered a *warmer* thermal preference vote are shown in Figure 4.c). Though *warmer* thermal preference is indicated for a wide range of indoor temperatures, only indoor temperatures below 65°F (23°C) also received the *adjust the thermostat* votes.

From the results of both studies, it can be concluded that a better understanding of comfort preferences can provide flexibility to enable DR strategies over a range of temperature conditions. The data from DHP study indicates that DF events that allow maintaining indoor temperatures between 65 to 71°F (18 to 22°C) are preferable in Cordova, Alaska. In both studies preconditioning – preheat or precool reduced overall discomfort and improved reliability of the DF event. The DHP study indicates that DF event duration may be more sensitive than temperature offsets in triggering an occupant response (thermostat override or other comfort actions) though a larger sample size will be needed to confirm. However, the DHP study results reiterates findings from other studies that shorter duration DF events that are one to two hours are more reliable than DF events three hours or longer.

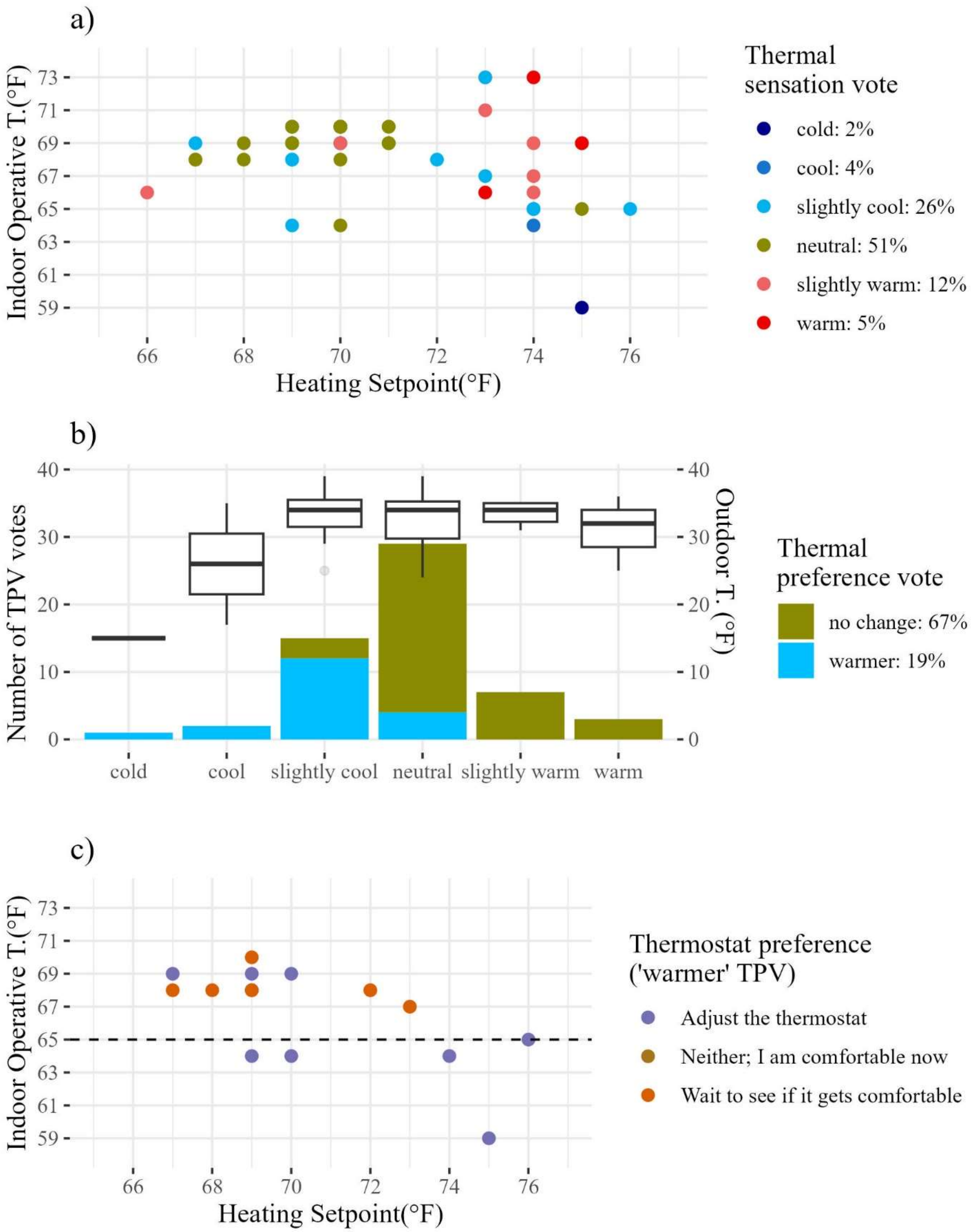

Figure 4: Comfort survey results – DHP study a) 51% *neutral* TSV. No *neutral* TSV votes when indoor temperature in above 71°F b) 67% *no change* TPV. c) Thermostat preference corresponding to *warmer* TPV is *adjust thermostat* when indoor operative temperature below 65°F.

Post-study phase: This is the wrap-up phase of the study. The monitoring devices were uninstalled and removed in this phase; additionally one-to-one guided interviews were conducted to gain further insights on the occupants' experiences and impressions about the technology and tests performed during the study-period. The participants were offered the option of keeping the new technology or denying them. All participants opted to keep the DF-enabled technology.

Table 3: Key Findings from Post Study Interviews

	CoolFIT	**DHP**
Energy Use		
DF-enabled HVAC use during study period	HVAC + smart thermostat: 4/5 Smart ceiling fan : 5/5	DHP: 3/3 Supplemental heating: 2/3 (occasional use only)
Typical thermostat use pattern	Infrequent daily setpoint adjustment: 3/5 Frequent daily setpoint adjustment: 1/5 Rarely used air-conditioning: 1/5	Infrequent daily setpoint adjustment: 3 participants
Thermal Comfort		
General satisfaction (during technology intervention and DF testing)	Satisfied: 3/5 Unsatisfied: 2/5	Satisfied: 2/3 Unsatisfied: 1/3
Positive influence on comfort (self-reported factors)	Performance of smart fan: 2/5 Improved HVAC control autonomy: 4/5	Response time: 1/3 General Effectiveness: 2/3 No (diesel) odor: 1/3
Negative influence on comfort (self-reported factors)	Complexity of new technology: 2/5 Perceptible changes during DF events: 1/5	Figuring out optimal settings: 3/3 Inability to meet heating needs in extremely cold days: 3/3
Attitudes and Preferences		
Willingness to use DF enabled technology	Continue: 3/5 Unsure: 2/5 Discontinue: 0/5	Continue: 3/3
Factors that are likely to impact future DF program participation decisions	Comfort: 3/5 $ incentive: 0/5 Ability to override: 3/5 Environmental impact: 2/5	Supplementary heat: 3/3 Comfort: 3/3 Environmental impact: 2/3 Ability to override: 3/3 Utility cost reduction: 3/3

Key Findings: Key findings from post-study interviews are summarized in Table 3. The intervention technology – smart thermostat integrated with ceiling fan (CoolFIT) and ductless heat pump (DHP) were generally preferred over the participant's prior technologies in both studies. Participants in the DHP study noted a need for supplementary heating on extreme cold days when outdoor temperatures dropped below 30°F (-1°C). Participants from both studies noted the quicker responsiveness of the intervention technology in comparison to their post intervention systems as one of the main reasons they decided to continue usage. However, many noted a learning curve associated with operating the new system. Households with at least one adult resident willing to learn the new technology were more successful in using the technology optimally consistent with the author's intuition based on findings from pre-study phase findings. Participants who were not fully satisfied with the technology at the end of the study period attributed it to inherent issues with thermal comfort in their homes like poor envelope insulation, orientation of windows and floor plan layout. In both studies, participants stated that they did not perceive noteworthy changes during DF events and could not tell if a DF event was underway at any given time. As participants were provided full autonomy to adjust their thermostat at any time; they did not experience feeling "controlled". With regards to factors that will impact their future DF participation decisions, participants reported considerations for thermal comfort, energy cost, environment, autonomy over thermostat overrides and access to low-cost supplemental heating/cooling during extreme conditions as key criteria. These findings underlie the following:

- Whole building energy efficiency and weatherization are an important first step to residential DF program enrollment to ensure their reliability and persistent participation in DF events.
- Thermal comfort is a key factor influencing success and reliability of DF events. DF strategies that allow participants autonomy over control of their thermal environment can enable trust, leading to long-term commitments and persistent participation in DF programs.
- Additionally, DF strategies that consider participants thermal comfort boundaries have potential to be more reliable as they triggered lower levels of overrides and other energy-intensive responses in these studies.

Conclusions

Utilization of the demand flexibility potential of residential space heating and cooling devices can be valuable in balancing the demand on electric grids. To realize its full potential, a better understanding of the limitations and flexibility potential of DF strategies is necessary. From a participant's perspective, thermal comfort is an important consideration impacting households' decisions toward DF enrollment and persistent participation. In this paper we present evidence collected from two field studies that underline the importance of household-level information regarding energy use and thermal comfort in identifying candidate homes for DF enrollment. Some candidate homes may benefit from weatherization or energy efficiency upgrades further improving their ability to accept changes during DF events. Furthermore, region-specific data about thermal comfort preferences help identify acceptable ranges of indoor temperature for devising occupant-centric DF strategies. DF strategies within acceptable changes in temperature and event duration are unperceivable; hence less likely to be overridden prematurely. The case studies presented in this paper present a method to collect comprehensive thermal comfort data using low-cost sensors and qualitative comfort surveys to identify occupant-centric and efficient DF strategies.

Limitations and Future Research

The findings from this study may be not generalizable to different geographic regions with significantly different weather conditions. Additionally, due to the relatively small sample size, future studies and larger study samples are needed to corroborate some of our findings.

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