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Assessing Thermal Comfort and Participation in Residential Demand Flexibility Programs

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ABSTRACT

Residential space-conditioning-based demand flexibility (DF) has become an increasingly sought-after method for demand-side load management to enhance grid reliability and facilitate integration of renewable energy generation. However, predicting the effectiveness and flexibility of residential DF resources is challenging due to the variability in household energy use behaviors. Current estimates show that only 50% of projected savings from DF resources are actualized due to regulatory, technological, and social barriers. From a household perspective, concerns over thermal comfort during space conditioning-based DF events significantly impact participation decisions. Currently, there is a very limited understanding of how thermal comfort during space-conditioning-based DF events in real-world settings impacts household energy use behaviors and, consequently, the success of DF programs in achieving targeted savings. This paper proposes a method to comprehensively assess the thermal comfort implications of DF strategies and presents results of their impacts on DF event participation decisions and demand savings. The proposed method was applied to a heat pump DF field study in Cordova, Alaska. The study's key findings are: 1) DF event setpoint offsets that maintain indoor operative temperatures between 18 to 22°C (65 to 71°F) may be preferred in Cordova, Alaska; 2) Household-level thermal comfort is more sensitive to the duration of the DF event than to the degree of temperature offset from baseline conditions; 3) The delayed impact of changes in indoor operative temperature in response to setpoint offsets, both during and after a DF event, influences occupants' thermal comfort perceptions and willingness to persistently participate in events. The findings from application of the proposed method can help inform future larger-scale occupant-centric DF programs as it can capture information not readily available through utility and device-level energy use data. Thus, it can supplement these sources and help program administrators develop occupant-centric DF strategies, enabling more accurate predictions of participation rates and savings estimates for space-conditioning-based DF programs.

Keywords: Demand side management, Residential demand flexibility participation, Indoor thermal comfort evaluation, Household energy use decision making, Winter demand flexibility, Heat pumps, Demand side management in underserved rural community.

Highlights:

- A novel method for place-based assessment of thermal comfort effects of space-conditioning based DF events.
- An assessment of the implications of thermal comfort of various DF strategies on household-level event participation.

- Examples of proposed method applications to inform development of region-specific occupant-centric DF strategies.

Introduction

In the United States, residential and commercial buildings collectively utilize 40% of the total energy produced (EIA, 2023a). Despite recent 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 from a current estimate of 14% in 2022 to 22% by 2050 (EIA, 2023b). This increase is attributed to the projected growth in electricity demand due to increased uptake of air conditioning and electric vehicle charging, as well as electrification of space and water heating, signaling a greater 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 (California Energy Commission, 2021; The White House, 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 United States 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 et al., 2019). Current estimates predict that efficient demand-side management of U.S. building loads could save $100-$200 billion in electric power costs, improve grid reliability, 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 (EIA, 2023c). These end-uses are inherently controllable and flexible (Masters, 2013); hence they are a major focus of demand-side management programs. However, the external control of residential space heating and cooling during a DR event loads impacts service quality as the delivery of heating and cooling is temporarily curtailed this may cause building occupant discontent by impacting their comfort and satisfaction (Pallonetto et al., 2020). The EIA data on the potential vs. actual utilization of DF in the residential sector for 2021 shows that the actual savings realized (3.8 TW) was less than 50% of the 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 (Carmichael et al., 2014). This variability stems from differences in a) socio-technical characteristics between households and b) people's willingness to accept changes in indoor thermal environment during DF events (Hanmer et al., 2019; Martin-Vilaseca et al., 2022; Sweetnam et al., 2019). However, there is limited literature that examines thermal comfort during space conditioning-based DF events and the associated impact on DF participation decisions of households. This insight is critical as space-conditioning- based DF has high potential to meet grid needs. Additionally, DF implementation strategies that take into account the thermal comfort of building occupants can encourage persistent participation of residential households in DF events (Nagy et al., 2023); thereby leading to more reliable outcomes for DF programs.

We propose a comprehensive approach to assess the impacts of changes in the indoor thermal environment during DF and its implications on household decisions on persistent event participation. We tested the approach in a field study conducted on a small sample of residences in the cold-weather climate of Alaska with the aim of using study findings to inform the development of occupant-centric and place-based winter DF strategies for future larger-scale deployment in the region.

This paper begins by describing the study's motivation, summarizing literature that addresses residential DF's potential in meeting grid needs, and identifying key challenges in leveraging DF's full capacity and the role of thermal comfort in encouraging persistent participation of households in DF events. Following descriptions of the mixed-method approach applied in a field study, and key findings and insights, we offer recommendations of how findings can inform occupant-centric DF strategies for future programs.

Background

Demand Flexibility and 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 et al., 2019). Residential buildings are strong candidates for demand flexibility due to several reasons. First, buildings have thermal mass acting as thermal storage that delays the rate of heat conduction through them. This phenomenon can be exploited to pre-heat or pre-cool the building to shift 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 devices and appliances 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 home appliances and devices. Interoperable APIs with standardized communication protocols allow external agents to program temporary changes to the setpoints or duty cycles of thermostatically 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 (Hanmer et al., 2019). Finally, curtailable building loads respond more quickly to demand flexibility needs, and are more environmentally friendly than back-up peaking power plants in managing the electric grid's supply-demand balance (Masters, 2013).

In the U.S., the estimated peak demand load reduction capacity of buildings is 10.2 GW (Satchwell et al., 2021), however actual savings from current load-management activities are 50% less than this estimated potential (EIA, 2022). Researchers have reviewed barriers leading to under-utilization of building-based demand flexible resources (Weck et al., 2017). For the residential sector, Weck et al. (2017) classified these barriers into technological, economic, and social. Technological barriers include i) low adoption of advanced-metering infrastructure needed for measuring electricity customers' hourly energy consumption to quantify demand reduction compared to a baseline (Safdarian et al., 2019); ii) grid-interactive and DF-enabled devices and technologies like smart thermostats, home energy management systems and heat pumps that are equipped to enable automated load management in response to a demand response signal (Safdarian et al., 2019; Weck et al., 2017); and iii) challenges in appliance-to-grid communications due to lack of standardized communication protocols, interoperability between demand-response enabled technologies, and inefficient algorithms for automated control of flexible loads (Satchwell et al., 2021). 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; for example, restrictive market rules that limit or disincentivize aggregators to facilitate participation of distributed demand flexible resources (Satchwell et al., 2021). Social barriers include customer inertia, fear of loss of privacy and autonomy, distrust toward utility companies, lack of motivation, risk averseness and distrust toward digital technologies, described in detail in the 2020 systematic review by Parrish et al (2020).

Beyond initial enrollment, the success of a DF program relies on the persistent participation of households in multiple DF events and throughout the entirety of a given multi-hour DF event (EPRI, 2014). In the case of DF events involving temporary adjustment to space heating or cooling appliance operation, the willingness of a household to persistently participate can be influenced by the impact of curtailment on their thermal comfort (Hanmer et al., 2019; Martin-Vilaseca et al., 2022; Sweetnam et al., 2019). Studies have identified direct and latent factors impacting participation including household composition (Bird, 2015), daily routines of energy consumption (Fell et al., 2014), thermal comfort preferences (Martin-Vilaseca et al., 2022; Sweetnam et al., 2019), level of interaction with thermostats or home energy management devices (Naghiyev et al., 2022), outdoor temperatures, DF event duration, and impact of the 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 residents in warmer climates are more likely to participate than those in 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 that households without dependents or pets are more flexible, and events lasting up to one hour are preferable to 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 an increase in household size. A study in the U.S. found that households participating in DF events generally reduce their electricity consumption when prices are higher, and the enabling technology has automation features (Gillan, 2017). A study in Sweden investigated the sensitivity of customers to information sharing with peers and their willingness to give away control over home appliances and thermostats. They found differences in sensitivity based on age, household size, and DF event type (Broberg and Persson, 2016). Martin-Vilaseca et al. (2022) found that people notice DF events through thermal sensation, the surface temperature of various objects, and equipment noises, and their responses to such triggers impact the 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 (EPRI, 2015; NV Energy, 2015) emphasizes the role of thermal comfort during DF events on the willingness of residential households to persistently participate in DF programs.

Limitations and gaps in current DF thermal comfort assessment methods

Space conditioning-based DF often involves temporary changes to the indoor thermal environment through external control, which can lead to a perceived loss of control over household comfort. Parrish et al. (2020) found that comfort and convenience during DF affect peoples' willingness to continue participating in future events (Parrish et al. 2020). Occupant expectations and preferences for thermal comfort influence building energy use (Yang et al., 2014). However, assessing thermal comfort is challenging because thermal comfort adaptation behaviors are heterogeneous (Brager and De Dear, 1998; Parker, 2013), and currently available thermal comfort models have low prediction power (Cheung et al., 2019). Moreover, comfort standards (ASHRAE, 2023, p. 55; CEN, 2012; ISO, 2005) focus on conditions to maintain steady-state indoor thermal conditions; offering limited guidance for transient conditions. These standards are predominantly based on laboratory studies, aimed at sedentary office workers; failing to address real-world transient thermal conditions, (Arens et al., 2006) especially in non-sedentary and residential settings. Hence, the optimum method to address some of the existing gaps in thermal comfort in residential DF studies, particularly in settings not addressed by current literature, is to collect and analyze empirical data. Insights from field experiments are extremely limited for residential DF in general (da Fonseca et al., 2021; Parrish et al., 2019), and cold-climate regions in particular.

With regards to DF field studies and technology pilots, most studies focus on technology maturity or peak demand savings, with little attention to thermal comfort (Gaur et al., 2021; Parrish et al., 2020). Some studies use retrospective surveys to evaluate overall satisfaction, asking questions like “Was the program comfortable?” or “How was comfort affected?” (EPRI 2017; NV Energy 2015). However, these methods are inadequate for evaluating thermal comfort, especially during multi-hour DF events with temperature offsets, as comfort conditions can vary considerably with event progress and recollection may be biased (Zhang, de Dear, and Candido 2016 (Aghniaey and Lawrence, 2018; Zhang and de Dear, 2015). Open-source thermostat use data has been analyzed to understand thermostat setpoint preferences and to predict thermostat over-ride behaviors (Sarran et al. 2021). However, they do not address the relationship between changes to the thermal environment and DF participation decisions. Finally, researchers have conducted field studies with limited sample sizes to monitor changes in the physical environment during demand response events (Martin-Vilaseca et al. 2022; Sweetnam et al. 2019). Results from these studies highlight the importance of comfort practices in DF event success. However, the limited sample calls for further research for results generalizability.

To address the limitations highlighted above, we propose a mixed-methods-based approach combining qualitative and quantitative data that build on the concepts discussed above. This approach aims to improve existing DF thermal comfort data collection methods and enhance our understanding of the implications of thermal comfort on residential DF participation decisions. The following sections present the details of this method through the example of a DF field study conducted in Cordova, Alaska. A key contribution of this article is an empirical data-collection and analysis effort that focuses on enabling a ‘place-based’, and reproducible method to capture region-specific insights for DF program implementation.

Methodology

Ductless Heat Pump (DHP) Study

The DHP study is a residential DF field study to examine the potential of CTA-2045-enabled ductless heat pumps (DHP) as a grid resource in a cold climate and rural region of Cordova, Alaska. Cordova is a small city of approximately 2,600 residents that experiences a subpolar oceanic climate with moderately cold, extremely snowy winters. The outdoor temperature in the winter months reaches lows ranging from -3 to 3°C (27 to 37°F). In addition to evaluating the technology potential of the ductless heat pump and CTA-2045 communication protocol, this pilot study aims to evaluate occupant-centric and region-specific strategies to promote market transformation in rural cold-climate areas. The evaluation is based on local energy use behaviors and comfort practices. The goal is to help the local community and similar communities elsewhere to achieve energy security by transitioning from costly and inefficient fossil-fuel-based home heating to electric heat pumps powered by locally generated hydroelectricity or other regional renewable resources. As existing studies on occupant-centric winter DF strategies for cold weather are limited and large-scale studies in remote regions can be technically and economically challenging, the focus of this study is on conducting a comprehensive evaluation of various DF event types on a small study sample and apply the findings to inform larger future deployment efforts.

Three single-family homes (two occupant-owned and one rented) participated in the DHP study. The study participants have lived in Cordova for most of their lives. The participating household members ages range from new-born to less than 65 years; two of the three families also have pets. For this study, the homes were retrofitted with ductless Mitsubishi heat pumps featuring CTA-2045-enabled universal communications modules provided by e-Radio. The heat pumps replaced the study participants' original fuel oil-based primary heating source and were studied for their DF potential under Cordova's cold weather conditions. 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). It 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. DF event days were selected randomly and scheduled at a frequency of one to three events/week between 5 pm and 9 pm local time. The duration of the DF events lasted one to three hours, during which time the heating setpoint was reduced by 0.56°C (1°F) to 3.3°C (6°F) relative to pre-event (baseline) setpoint. Some events were pre-conditioned by increasing the setpoint by 1.1°C (2°F) relative to baseline setpoint for 1 hour immediately before the DF event. The winter study period lasted from November 2023 to April 2024. A total of 60 DF events were scheduled for a combined total of approximately 400 test hours across all homes.

Due to the rural and remote location of the study sites, the study set-up needed to enable remote dispatch of DF events, and data collection. This setup reflects typical utility and third-party aggregator-based residential DF program administration. Additionally, the study setup aimed to automate processes to minimize human errors in data collection, reduce the risk of missing data points and establish a reproducible proof of concept for future studies. A schematic of the physical setup of the remote DF dispatch and data collection approach is shown in Figure 1.

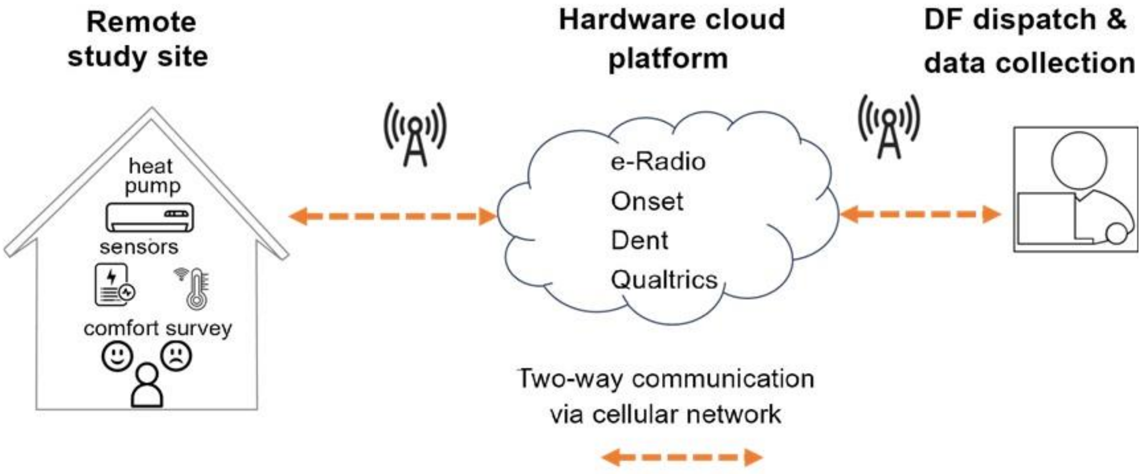

Figure 1: Study set-up schematic. DHP study set-up showing data flow management between heat pumps, sensors, and comfort survey participants in remotely-located study sites and off-site research team, using vendor-specific cloud platform services.

Typical DF event strategies used by utilities in residential DF programs differ in event specifications, as DF event types may vary by temperature offset, and event duration, and sometimes include pre-conditioning as a preventive measure to mitigate immediate energy rebound. Other studies on pre-cooling in summer DF events have looked at passive and active sources of thermal mass for pre-conditioning and potential for demand savings and minimize deviations from occupants' preferred setpoints (Chen et al., 2020). In this study, we tested DF events both with ("w/") and without ("w/o") preheat for winter DF. To understand the impact of event duration and temperature offset, we conducted tests with consistent temperature setback but varied event durations, as well as tests with consistent durations but varied temperature setbacks, both w/ preheat and w/o preheat. In case of events w/ preheat, the setpoint temperature increase of 1.1°C (2°F) was implemented for one-hour immediately before the DF event start. Prior experimental studies done on pre-conditioning found it to be an effective strategy to reduce DF discomfort for events lasting up to two-hours (Chen et al., 2020), indicating that comfort implications of pre-conditioned DF events may be felt more strongly in intermediate (two-hour) or longer-duration (more than two-hour) events. Hence for this study we choose DF events w/ preheat for two and three- hours to represent an intermediate and long-duration case respectively. Figure 2 illustrates the DF event types tested in the study. The selection of event days and non-event days (baseline) was randomized throughout the study period to improve the reliability of the results by reducing the effect of confounding variables (Montgomery, 2017). The randomization allowed the testing of various DF event durations, temperature offsets, and pre-conditioning to support diverse grid conditions that may trigger DF events. For instance, unscheduled or random deviations to net electricity demand or un-forecasted ramps in renewable energy production can be managed by calling DF events that can regulate, shed or shift energy demand (Olsen et al., 2013) per grid needs. For this study, local utility electricity load duration curve data was unavailable to the authors at the time of the study design; as a result the test events may not be fully represent actual grid conditions. However, the timing of the events was based around the late afternoon, which corresponds to typical daily peak demand periods in Cordova. Additionally, although the data collected may be combined with additional energy use data sources, to estimate the aggregate demand savings potential of DF-enabled residential heat pumps under various grid operational scenarios; this article focuses on occupant experiences during various DF event types; specifically, the impact of event characteristics like duration, setback offset and pre-conditioning on household DF participation decisions.

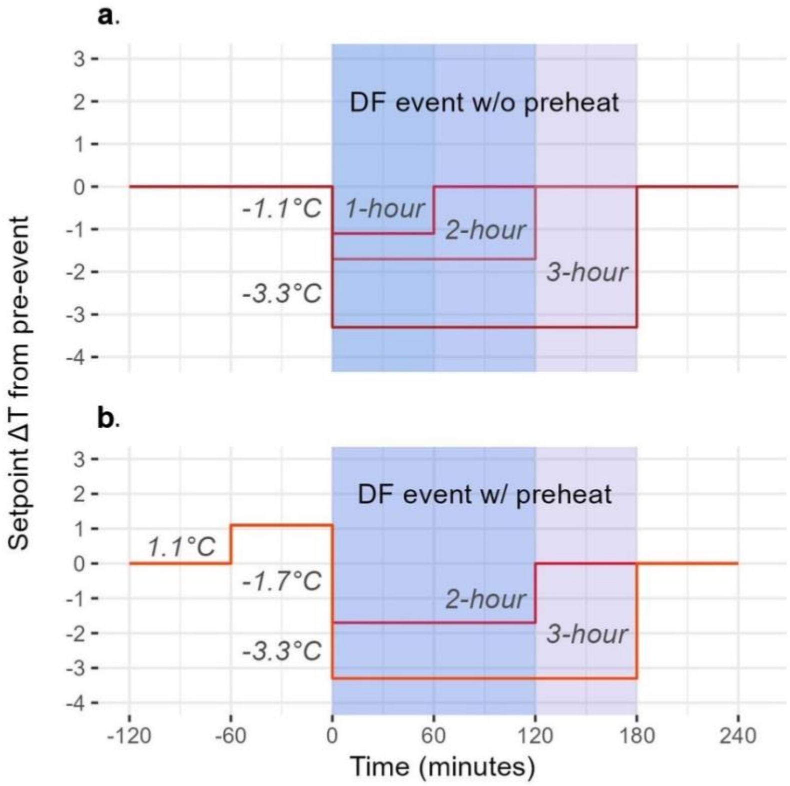

Figure 2: DF event types tested in the study. To analyze the impact of DF event duration and setback, we tested events with different (a) duration (one, two, and three-hours) and (b) setback (1.1Δ°C,1.7Δ°C, and 3.3Δ°C). Additionally, events were tested with and without preheat.

Proposed mixed method approach

The proposed method for DF thermal comfort assessment combines the use of qualitative approaches to capture contextual factors impacting thermal comfort perceptions and motivations or challenges to DF participation, and quantitative data to identify physical characteristics that influence the qualitative findings. This approach thus provided a comprehensive understanding of the interplay between subjective experiences and objective measurements. Figure 3 shows a high-level schematic of the proposed mixed-method approach.

The data collection step involves the collection of data from three sources: 1) continuously monitored indoor and outdoor temperature and humidity, device-level energy consumption, and thermostat setpoint data; 2) transcripts from guided interviews; and 3) point-in-time occupant feedback on thermal comfort during DF events, also known as right-now comfort surveys. Data from the three sources fill gaps and corroborate findings from individual sources, allowing for a holistic evaluation of thermal comfort impacts on household DF participation decisions.

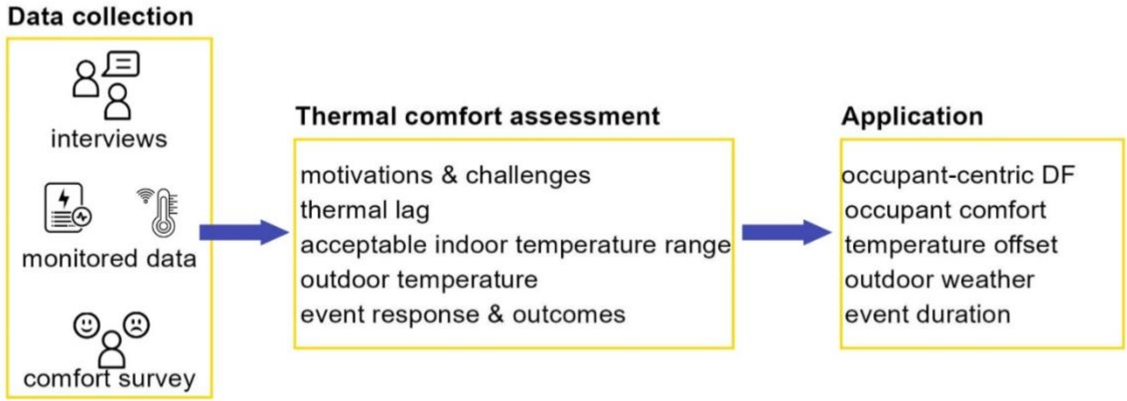

Figure 3: Schematic of proposed mixed method. Data collected from three sources are analyzed for a comprehensive assessment of thermal comfort and its impact on event participation. Findings inform recommendations for occupant-centric DF strategies.

Data Collection

Data for this study is collected from three sources. First, a qualitative assessment is performed with guided interviews and site visits. Separate guided interviews are conducted at the start and end of the study period. This information is used to assess the building's physical characteristics, study participant socio-demographics, households' energy use behaviors, and comfort experiences with the space conditioning systems.

Data includes:

- physical information on house type, year of construction or major renovation, floor 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;
- household demographic characteristics including study participant ages, gender, ethnicity, number of dependents and pets, time of house move-in, and occupation of study participants;
- behavioral information about 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; and
- thermal comfort related questions including preferred thermostat setting, 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, 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.

The end-of-study guided interviews aim to capture retrospective reflections about occupant's experience with the DF-enabling technology and DF events. The responses to the interviews are used to identify key motivations and challenges to household DF participation as summarized in Table 1.

Table 1: Key Motivations and Challenges to DF Participation

Themes	
Typical thermostat adjustment frequency in winter months	Infrequent – set and go: 2 homes Somewhat frequent daily adjustment: 1 home
General satisfaction with thermal comfort (before technology intervention)	Satisfied: 1 Unsatisfied: 2
Main factors that negatively influence indoor thermal comfort (self-reported)	Non-uniform HVAC service quality between rooms, poor envelope insulation, single-pane window, window size and orientation, HVAC system location and sizing
Main factors that influence household energy use behaviors (self-reported)	Energy cost, thermal comfort
Main factors that influence household decision to switch to DF enabled heat pumps	Environment - switch from propane to locally generated electricity, HVAC control & responsiveness, improved thermal comfort

The second data source is the minute-level monitored data collected from each participating site. Energy data is collected at one-minute intervals using DENT power loggers (ELITEpro, DENT Instruments, USA), Mitsubishi heat pump thermostat setpoint data at one-minute intervals via e-Radio API (CTA-2045, e-Radio, USA) and one-minute interval indoor and outdoor temperature and humidity data through Hobo sensors (MX1101 and MX2301, Onset, USA). This data is quantitively assessed to understand the physical impacts of the DF events on the thermal environment, energy use, and occupant responses.

The third data source -study participant responses collected using a bespoke version of the right-now surveys (Duarte Roa et al., 2020), is administered through the Qualtrics platform and disseminated via text messages to adult study participants. The comfort surveys collect study participants' real-time subjective responses of thermal comfort. The comfort surveys last less than a minute and include questions regarding how study participants felt "right now" about their thermal sensations and thermal preferences. Thermal sensation votes (TSV) are recorded 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; the survey logic directed the respondent to a thermostat preference question asking whether they would like to *adjust the thermostat*, *wait* for some time, or choose to take *no action*. Quantitative assessment of the subjective responses is used to gain further insight into occupant thermal comfort preferences and identify relationships between occupant comfort preferences and indoor and outdoor temperatures.

Results and discussion

The following are the key findings from the thermal comfort assessment across various data sources:

Study Participant interviews: Interviews provide valuable perspectives on motivations, challenges, preferences, and attitudes of households toward DF (Bresa et al., 2024). Improved thermal comfort and reduced environmental impact were study participants' common motivating factors to switch from existing fuel oil-based heating systems to heat pumps. Study participants felt their existing system was inadequate to meet winter thermal comfort needs and was unreliable and expensive as the fuel-oil required to run the existing space heaters had to be transported from distant sources. Hence, households were also motivated by the prospect of lower costs and environmental impacts of their energy use. However, study participants were initially skeptical of the thermal comfort impact of DF events, particularly on dependents/children. Further investigation revealed that this skepticism stemmed from their belief that the physical characteristics of their houses (e.g., orientation, room layouts, or window positions) inherently limited the ability of the heating system to consistently maintain thermal comfort. Study participants pointed out rooms and time periods when comfort was particularly challenging. The pre-study interviews also revealed that preferred thermostat setpoints and schedules varied between households. We took these findings into consideration while developing DF event strategies. For example, for this study, we decided to include only relative temperature setback offsets. Using absolute setpoint offset across all participating homes would likely negatively impact thermal comfort in at least some of the participating houses.

The interviews also pointed out that study participants highly valued autonomy over thermal comfort and factored in the ability to override as an important decision criterion in permitting external control. Therefore, the study participants were instructed to override the thermostat setting at any time they needed. Post-study interviews revealed that having autonomy over the thermostat helped build trust and motivated continued cooperation and persistent participation in DF events.

Monitored data: The monitored data was analyzed to understand the physical impacts of the DF events on the thermal environment, energy use, and occupant responses. Figure 4 compares the overall percentage of comfort actions, and energy demand savings for different event types. A comfort action refers to an occupant response that results in an indoor temperature increase by more than 0.3°C (0.5°F) during the DF setback event; indicating that thermal comfort conditions during such events are likely to trigger a comfort-driven response, potentially leading to the termination of the DF event. For this study, comfort actions taken by study participants include thermostat override action or activation of a supplementary heating source. It is estimated by calculating the event temperature change, i.e. – difference in indoor temperature at event start and event end. Figure 4 shows the percentage of DF events of a given type that resulted in a comfort action. Note that we assume a comfort action to have occurred if it occurred at any point between event start and end.

For this analysis, we adopt definition of baseline as the ‘estimate of what the load would have been in each interval in the absence of the curtailment’ (Goldberg and Agnew, 2003). Baseline energy for each site is estimated as the average of the heat pump energy on non-DF event weekdays during study period. Heat pump demand savings during DF event compared to baseline is computed as:

$$\overline{\eta_J} = \frac{1}{n}\sum_{i=1}^{n}\frac{\overline{E}_{base_i} - \overline{E}_{j_i}}{\overline{E}_{base_i}} \tag{1}$$

where $\overline{\eta_J}$ = is the average energy demand savings percentage for event-type *j* from all sites

$\overline{E}_{base_i}$ = is the average baseline energy demand for site *i*

$\overline{E}_{j_i}$ = is the average energy demand for site *i* for event-type *j*

Figure 4 shows the aggregated results from all homes across three or more occurrences of each DF event type tested during the study period. The results illustrate the effects of event duration, setpoint temperature changes, and the impact of pre-heating on heat pump demand savings and comfort actions. Positive demand savings indicate that the average heat pump energy during the event period was lower than on a baseline day. Conversely negative savings indicate higher heat pump energy compared to baseline during DF event hours. Comfort actions are presented as the percentage of events of each type that were overridden and are shown as a negative percentage. As described earlier, in order to capture all potential scenarios that may indicate study participant termination of a DF event, both thermostat overrides, and use of supplemental heating were considered comfort actions for this analysis.

Figure 4a shows the effect of event duration on i) 1.1°C (2°F) w/o preheat setback events of 1,2-, and 3-hour duration, ii) 1.7°C (3°F) w/ preheat events of 2-, and 3-hour duration events, and iii) 3.3°C (6°F) w/ preheat events of 2-, and 3-hour duration. As shown, comfort actions increase with event duration—no overrides were recorded for 1-hour events, but comfort actions progressively increased for 2- and 3-hour events for the 1.1°C (2°F) setback. Notably that the magnitude of demand savings for the 1.1°C (2°F) setback across 1-, 2-, and 3-hour events is not proportional to the increase in comfort actions. Post-study interviews indicated that some participants used supplementary heat sources (wood-fired stove, space heaters) during the 3-hour DF event, resulting in less impact on heat-pump demand compared to similar 2-hour events where participants chose to override the thermostat setpoint that led to a incomplete DF event. Comfort action also increased for 1.7°C and 3.3°C (6°F) w/ preheat for events of 3-hour duration compared to a 2-hour duration event of same type. This indicates occupant preference for shorter duration DF events and is in agreement with conclusions from other studies for optimal household participation for summer DF (Sarran et al., 2021) and DF event cost-benefit to an implementor (Zhang et al., 2020). Figure 4a also indicates that though all DF events saved energy, the magnitude of savings did not increase for larger duration events, emphasizing the role of occupant-comfort and actions taken in response to comfort changes during DF events on DF energy savings.

Figure 4b shows the effect of setpoint temperature change on i) 2-hour events w/o preheat with 1.1°C (2°F) and 3.3°C (6°F) setback, and ii) 3-hour events w/ preheat with 1.1°C (2°F) and 3.3°C (6°F) setback. Results indicate that the impact of setpoint temperature change on comfort action (1.1°C vs 3.3°C) is less discernable in the 2-hour events. However, comfort actions increase for 3.3°C (6°F) in the longer duration (3-hour) preheated events. These findings indicate that for winter DF, residential DF program participants may have a greater sensitivity to event duration than temperature offset especially when DF events are of 2-hour or shorter duration. Events lasting more than 2 hours are sensitive to both duration and temperature offset. With regard to effect of setpoint temperature change on energy savings, Figure 4b shows that energy savings increase with larger setpoint temperature change; however, the magnitude of savings for both 1.1°C and 3.3°C is lower for longer duration and preheated (3 hour) events compared to shorter (2-hour) events.

Figure 4c shows a comparison of 1.1°C (2°F) 3-hour duration events w and w/o preheat.

As can be observed, comfort actions for 1.1°C (2°F) 3-hour event w/ preheat are significantly lower than that w/o preheat. Though not including in the figure, this study also found that pre-heated larger setpoint temperature change events had lower comfort action than similar events with no preheat. This indicates that pre-heating may be an effective strategy for mitigating the negative comfort impacts of larger duration events. Similar to Figure 4a, Figure 4c shows that the 3-hour, 1.1°C (2°F) event with preheating has lower comfort actions and achieves higher demand savings compared to the similar 3-hour, 1.1°C (2°F) event without preheating..

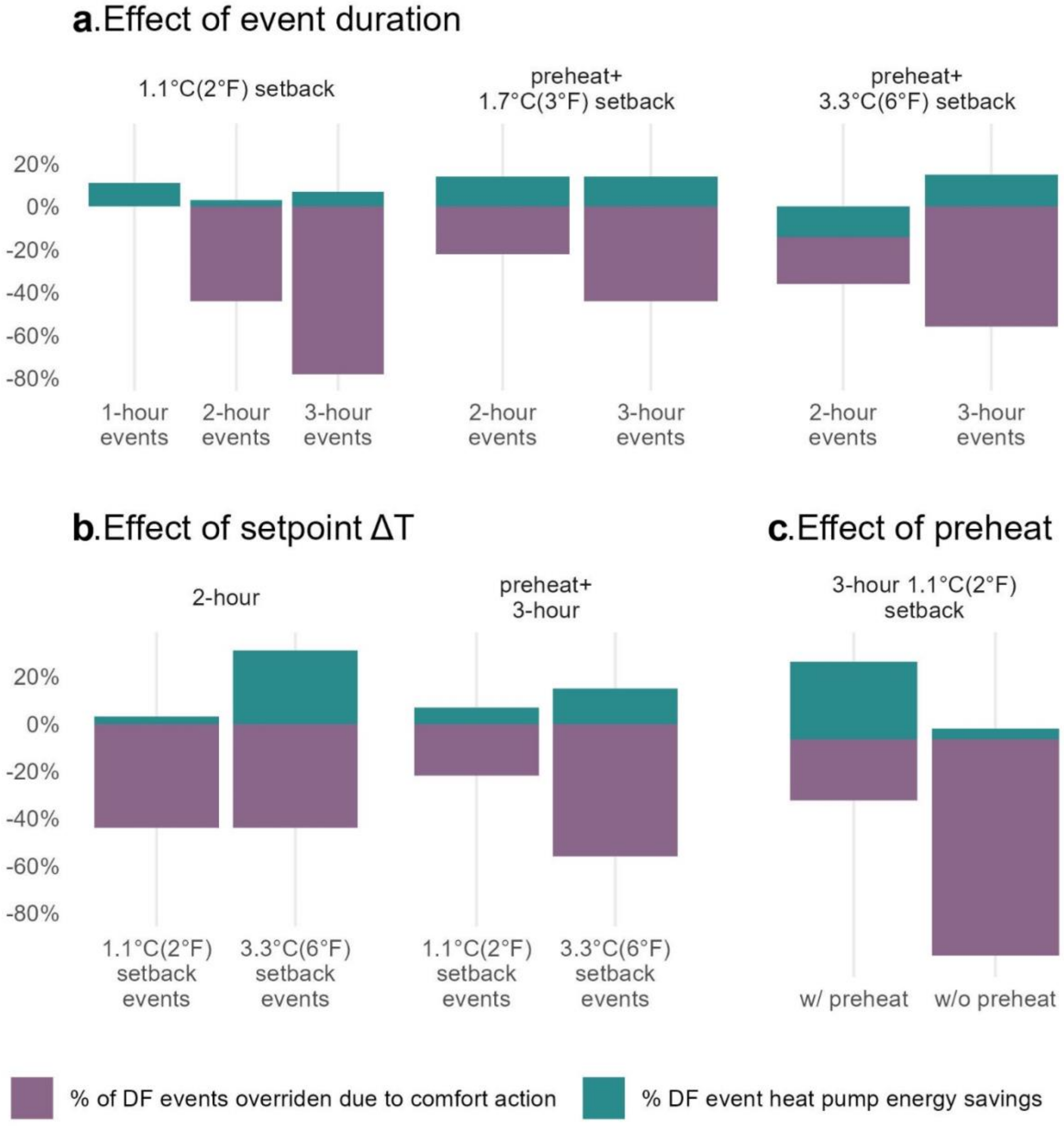

Figure 4: Effect of (a) event duration, (b) setpoint temperature change and (c) preheating on comfort action and DF event energy savings. a. Comfort actions increase with increase in event duration. b. Energy savings increase when setback temperature change is larger; however, if event duration is long, increase in comfort action reduces magnitude of energy savings. Larger setbacks are tolerated if event duration does not exceed 2-hours. c. preheating can help reduce comfort actions of longer duration events.

Comfort surveys: Next, we investigate the responses to the comfort surveys to better understand the thermal conditions triggering the comfort-driven sensitivities discussed above. Figure 5 a, b, and c show the results of the comfort surveys overlaid with the physical monitored data recorded at the time of each survey response. A total of 30 responses were recorded from all DF events tested across the study period from November 2023 to April 2024. Only adult study participants from each home were included in the comfort surveys. Recorded thermal satisfaction votes during DF events ranged from *cold* (-3) to *slightly warm* (2). Note in Figure 5a, that 8 out of 30 (more than 50%) of responses to TSV correspond to *neutral* – a self-reported verbal description of a sensation of feeling neither warm nor cool. 90% of all *neutral* TSV responses fall within indoor operative and heating setpoint temperatures ranging from 19.4 to 22°C (67 to 71°F). Heating setpoint temperatures above 23°C (73°F), correspond to indoor operative temperatures ranging from 19 to 23°C (66 to 73°F) – at these conditions TSV responses were *slightly warm* and *warm*. In Figure 5b, the bars shows the number of thermal preference votes (primary y-axis) corresponding to each TSV response category (x-axis). In the same figure, the box plots show the range of recorded outdoor weather (secondar y-axis) at the survey response time for each TSV category. Note that TPV is *neutral* when comfort survey response to TSV is *neutral, slightly warm,* or *warm.* Furthermore, Figure 5b shows that *cold* and *cool* TSVs correspond to events when outdoor temperatures were below -1°C (30° F). The corresponding TPV *warmer* indicates that study participants preferred *warmer* indoor conditions during these periods; indicating that DF during extreme cold days is not favored by study participants. Indoor and setpoint temperature conditions during events that triggered a *warmer* thermal preference vote are shown in Figure 5c. As can be seen, though *warmer* thermal preference is indicated for a wide range of indoor temperatures, only indoor temperatures below 18.3°C (65°F) also received *adjust the thermostat* votes. From the above findings, it can be concluded that study participants favored DF events that are conducive to maintaining indoor temperatures ranging between 18 to 22°C (65 to 71°F). The lower limit of this range is more flexible than the simulation-based study findings of (Alimohammadisagvand et al., 2017), which estimated that, for Finnish homes, the lowest acceptable indoor air temperature for demand flexibility is 19.4°C (67°F) (Alimohammadisagvand et al., 2017). The difference in findings may stem from variations in study methods – empirical vs simulation based, as well as potential differences in local thermal adaptation habits between the two regions. This highlights the importance of place-based empirical studies for evaluating thermal comfort to inform effective DF program design, as context-specific differences in preferred temperature ranges can significantly affect households' ability to be flexible and, consequently impacting the potential for actual energy demand savings.

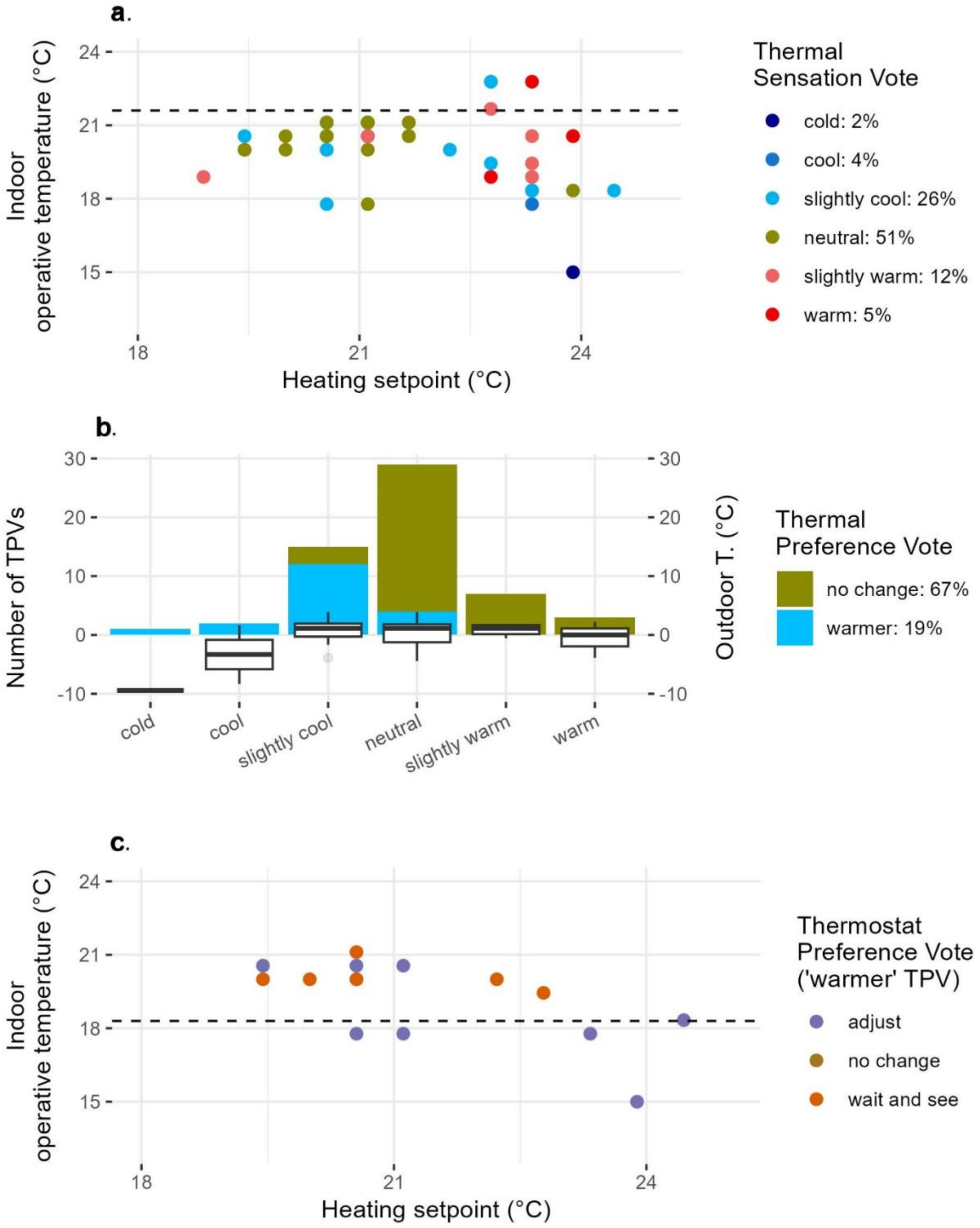

Figure 5:Comfort survey results overlaid over monitored indoor temperature and setpoint data. a. 51% of comfort survey responses to TSV correspond to *neutral* TSV. Indoor temperature for *neutral* TSV does not exceed 22°C. b. 67% responses to TPV recorded as *no change*. TPV is *warmer* when TSV is below neutral and outdoor temperature is below -1°C. c. Thermostat preference is *adjust* when indoor operative temperature is below 18°C.

Additional considerations for occupant-centric DF program implementation

Previous sections have identified key thermal comfort factors that encourage DF event participation, such as using relative thermostat setpoint offsets, maintaining autonomy over thermostat during the event, understanding preferred ranges of indoor and outdoor temperatures, and considering the impact of event characteristics like pre-heating, event duration and magnitude of setpoint temperature offset. In this section, we present additional considerations for occupant-centric DF implementation.

We explore the applicability of ANSI/ASHRAE Standard 55 (Standard 55) ramp rate recommendations as guidelines to determine DF setpoint temperature offsets in winter DF events. Standard 55 specifies the requirements for thermal comfort in buildings. It defines thermal conditions with asymmetries as “transients,” and provides recommendations to limit temporal transients. Table 2 shows the allowable ramp and drift rates per Standard 55; defined as monotonic, noncyclic changes in the operative temperature and cyclic variations with a period greater than 15 minutes. These recommendations are based on early steady-state-based lab studies (Berglund and Gonzalez, 1978; Kolarik et al., 2009; Nevins et al., 1975; Rohles et al., 1980).

Table 2: ASHRAE Standard 55-2020 Limits on Temperature Drifts and Ramps

Time, minutes	**15**	**30**	**60**	**120**	**240**
Maximum operative temperature change allowed °C (°F)	1.1 (2.0)	1.7 (3.0)	2.2 (4.0)	2.8 (5.0)	3.3 (6.0)

More recent research has shown that these steady-state studies are not representative of comfort in temporal transients in real-world conditions (Aghniaey et al., 2018; Kim et al., 2016; Vellei and Le Dréau, 2019; Zhang and de Dear, 2015; Zhang, 2003) and may be overly conservative. Moreover, the study conditions in early studies that inform the current transient limits in comfort standards are not good representations of demand response event conditions. For instance, experiments conducted by Nevins (1975) and Rohles (1980) took three hours to achieve steady-state conditions, whereas most DF events last only 1-4 hours. Additionally, from an application perspective, the recommendations based on operative temperature are not helpful for practitioners. This is because operative temperatures in homes may lag behind setpoint temperatures depending on the difference between indoor and outdoor temperatures and the characteristics of the building envelope. Additionally, the effectiveness of the heating system to achieve indoor operative temperatures at the level of thermostat setpoint temperature will also vary from one house to the next. For example, as seen in in Table 3, the difference between median indoor operative temperature and thermostat setpoints is larger 4°C for home 1, compared to 0 for home 3

Table 3: Range of Indoor operative and setpoint temperatures during testing period

Home #	**Indoor operative temperature °C (°F)**			**Thermostat setpoint °C (°F)**		
	25th percentile	Median	75th percentile	25th percentile	Median	75th percentile
1	17 (64)	19 (67)	20 (69)	21 (70)	23 (73)	24 (75)
2	19 (67)	20 (68)	20 (69)	20 (68)	21 (70)	23 (74)
3	20 (69)	21 (70)	21 (70)	21 (70)	21 (70)	22 (72)

Hence, to verify the applicability of ASHRAE Standard 55 operative temperature ramp rate recommendations for guidelines to determine DF setpoint temperature offsets, we analyze the thermal lag between the setpoint and operative temperatures from the DHP study sample. Additionally, we examine the thermal comfort implications of various DF types during and after event time to further understand the underlying reasons for the lower limits of occupant acceptability discussed in the previous section. This information will enable DF administrators to understand the contextual factors that impede event participation, which should be considered to set realistic program expectations or develop strategies to extend participation limits for example by providing additional financial participation incentives. Moreover, this examination provides insight into DF event participation potential of households based on existing construction practices, specifically building thermal mass and its potential contribution towards maintaining comfort under local weather conditions. Studies that focus on determining aggregate potential of DF resources assume that individual differences between households are normalized when participation numbers are high (Sajjad et al., 2016). However, for rural micro-grid-based communities, considering household heterogeneity is crucial as grids in these regions typically operate with a smaller cluster of distributed DF resources (Herman and Kritzinger, 1993). Accounting for variability in DF resource flexibility among participating households may enable better DF program planning (Jang et al., 2016).

Figure 6 shows the setpoint temperatures and corresponding changes in operative temperatures for two representative event types w/o preheat. Figure 6a shows 1.1°C (2°F) 2-hour events and Figure 6b shows 3.3°C (6°F) 2-hour events. For each event type, the top figure shows minute-level indoor operative temperatures from all events of that type covering the time-range from 3 pm to 10 pm local time. The shaded area from 5pm to 7 pm marks the DF event period. Red lines indicate events, with no comfort actions, which are further analyzed in the bottom plots to compare setpoint temperature changes with indoor operative temperature changes. Temperature changes are calculated by first averaging minute-level data over 15-minute intervals, then computing the difference between each interval. (See supplementary material for more details). Notably, operative temperature changes during the events in Figure 6a Figure 6b, do not exceed 0.5°C (1°F) and 1.1°C (2°F), respectively. This lag between operative temperature response and setpoint temperature offset underscores the impracticality of directly applying Standard 55 ramp rate guidelines for DF setpoint adjustments in winter.. Additionally, as can be seen in Figure 6a, there is a delay of over 30 minutes from the DF event start time before 0.5°C change operative temperature for the 1.1°C (2°F) 2-hour events. However, Figure 6b shows an almost immediate drop in operative temperature for the 3.3°C (6°F) event. Also noteworthy is the overshoot effect of some DF event types- for example the impact of the setpoint offset on operative temperatures during the DF events is observed even after the end of the event in Figure 6b.

This overshoot effect is more evident on DF event days where outdoor temperatures dropped below the normal low range of -3 to 3°C (27 to 37°F). Figure 7 shows 1.1°C (2°F) 2-hour events and 3.3°C (6°F) 2-hour events w/ preheat on days when daily average outdoor temperatures dropped below typical lows (-9.4°C (15°F) and -6.1°C (21°F) respectively). As can be seen in Figure 7, the operative temperature changed by 1.7°C (3°F) during the 3.3°C (6°F) event and the change lingered for almost an hour after event end, potentially due to the inability of the primary heating system to meet comfort needs under the extreme cold outdoor conditions. This finding explains the conclusion from comfort surveys that occupants do not favor DF events on colder-than-normal days, as these negatively impact thermal comfort, with effects lingering well after the event ends. Hence, when DF participation becomes a critical need for grid stability on extremely cold days, it is recommended that DF administrators dispatch low-intensity events to ensure reliable household participation. Additionally, it is advisable to have in place mechanisms to mitigate the lingering decline in thermal comfort using low energy use supplementary heating sources, such as electric or radiant heaters. Finally, these findings indicate that a weatherized home may have better DF flexibility potential.

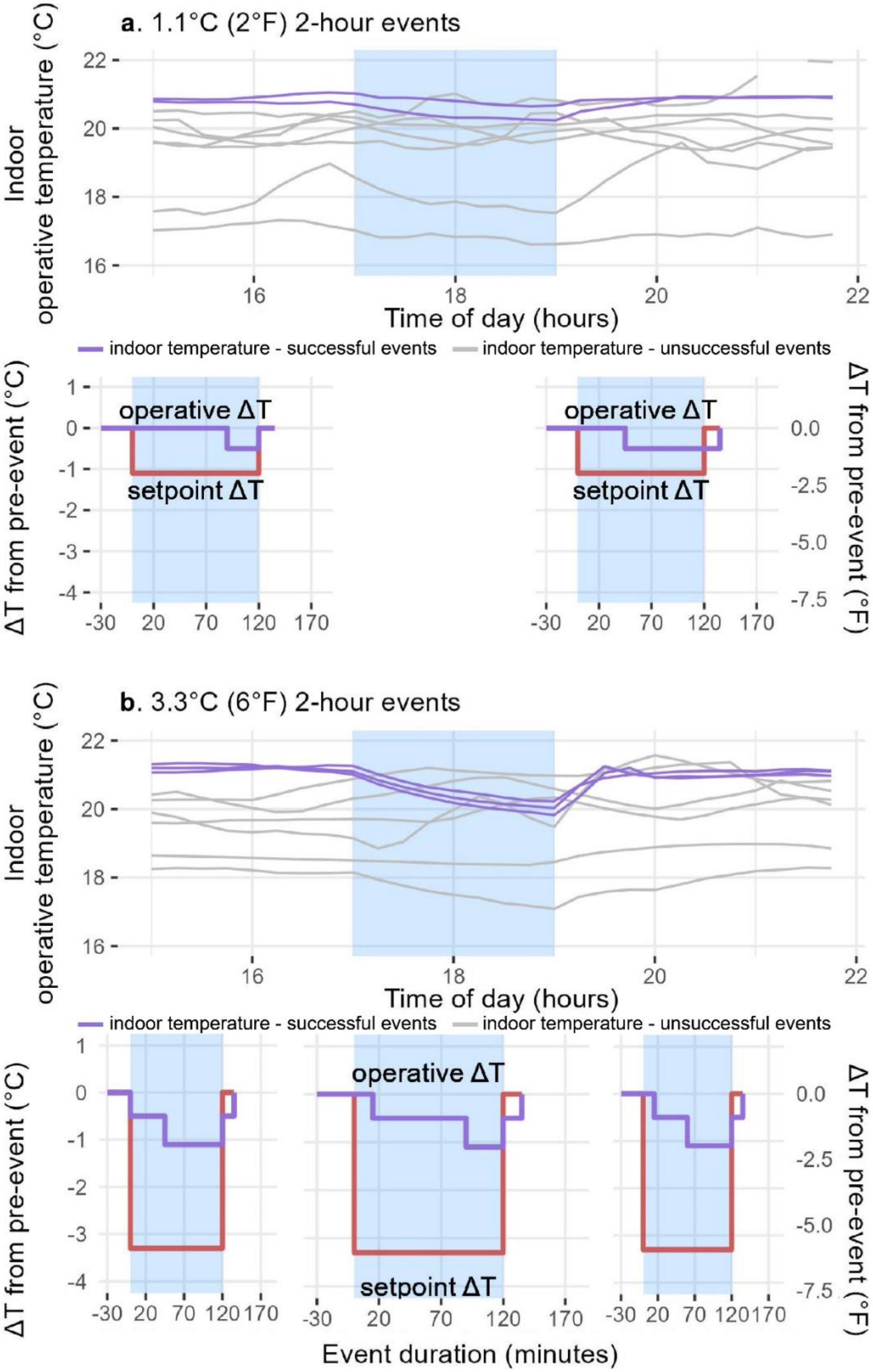
a. 1.1°C (2°F) 2-hour events
Indoor operative temperature (°C)
22
20
18
16
16
18
20
22
Time of day (hours)
indoor temperature - successful events
indoor temperature - unsuccessful events
ΔT from pre-event (°C)
1
0
-1
-2
-3
-4
-30
20
70
120
170
operative ΔT
setpoint ΔT
ΔT from pre-event (°F)
0.0
-2.5
-5.0
-7.5
b. 3.3°C (6°F) 2-hour events
Indoor operative temperature (°C)
22
20
18
16
16
18
20
22
Time of day (hours)
indoor temperature - successful events
indoor temperature - unsuccessful events
ΔT from pre-event (°C)
1
0
-1
-2
-3
-4
-30
20
70
120
170
operative ΔT
setpoint ΔT
ΔT from pre-event (°F)
0.0
-2.5
-5.0
-7.5
Event duration (minutes)

Figure 6: Comparison of indoor operative and setpoint temperature change during DF events. a. For 1.1°C (2°F) 2-hour events, operative temperatures does not reduce to 1.1°C throughout event period. b. For 3.3°C (6°F) 2-hour events, operative temperatures does not reduce to 3.3°C throughout event period. Operative temperature for these events reduced by maximum of 1.1°C. These comparisons of setpoint and indoor operative temperature changes during DF events suggest that it may not be practical to implement winter DF per ASHRAE 55 ramp rate recommendations.

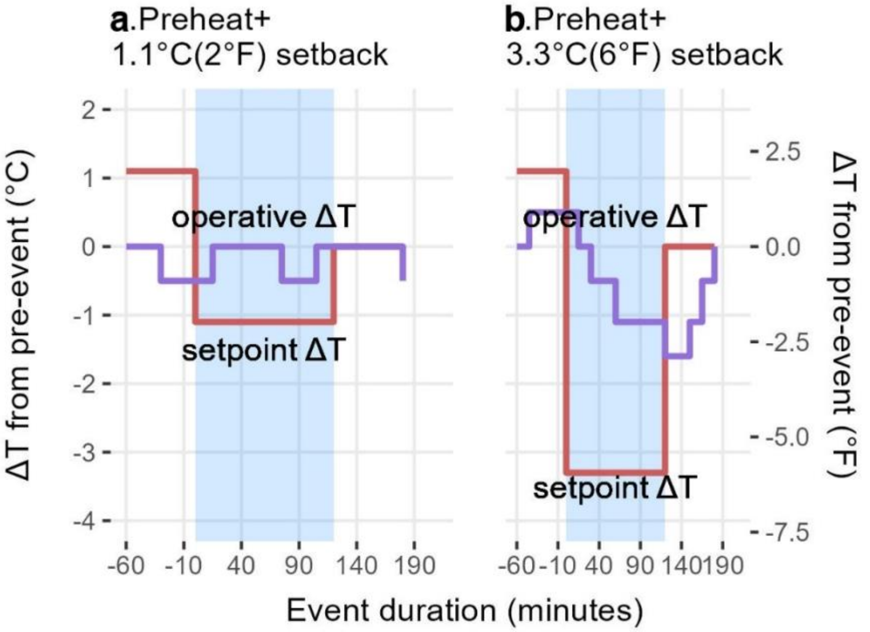

Figure 7: Overshoot effect of setpoint temperature reduction during DF on very cold days highlighting comfort-driven limitations on household participation in intense DF events on extreme weather days.

Conclusions and Recommendations

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 capability, a better understanding of the limitations and flexibility potential of DF strategies is necessary. The research presented in this article explores a method to quantify the utilization potential of DF flexibility in cold climate households by evaluating the complex interaction between the technology -DF-enabled device (heat pump), household dynamics -comfort preferences and physical characteristics of the buildings -thermal lag and outdoor weather conditions. We find that all three are important factors influencing the engagement levels of households in a DF program. From a household’s perspective, thermal comfort is an important consideration impacting decisions toward DF enrollment and persistent participation. We presented a method to assess comfort implications of DF event characteristics and its impact on persistent event participation tested with a field study in Cordova Alaska. The proposed method enables a comprehensive assessment of thermal comfort using data collected from interviews, surveys, and low-cost sensors.

The proposed method provides valuable information for developing the components of an occupant-centric DF program. First, interviews of potential DF participants help identify contextual factors that impact their daily energy-use behaviors to maintain indoor comfort. This information can help program administrators understand the bounds and flexibility potential of DF program participants- which should be taken into consideration if the reliability of DF resources is critical. For example, in the case study, we found that relative temperature offset is better than absolute offset for maintaining persistent DF program participation rates, and autonomy over the thermostat is key to building trust from the perspective of study participants. Data from physical environment monitoring supplemented with right-now comfort surveys can help determine the preferred indoor and outdoor temperature ranges conducive for setting bounds of DF strategies and event types. Findings from our study indicate that study participants prefer indoor operative temperatures ranging from18 to 22°C (65 to 71°F) are preferred. Additionally, DF thermal comfort is more sensitive to event duration than temperature offset for shorter duration events (2 hours or less). Residential participants sensitivity to DF event duration has been reported by previous studies for summer DF in the discussion section. This study validates the importance of event duration sensitivity for winter DF. Additionally, we found that for longer duration (3 hours or longer) winter DF events, participation rates are sensitive to both setpoint offset and duration. This study also found that pre-heating can be effective in mitigating the negative comfort impacts of high-intensity events (offsets greater than 1.1°C and duration more than 3 hours). In this study pre-heating period was scheduled for one hour immediately before the event to prevent overheating and prevent unnecessary heat pump energy consumption. From an implementation perspective, communication protocols like OpenADR and CTA-2045 already have signaling requirements to allow events to be initiated following a pre-conditioned period (Piette et al., 2013). However, as shown, the effectiveness of pre-heating can be influenced by factors such as the thermal envelope and outdoor weather conditions; therefore, we recommend accounting for these parameters when for efficient use of pre-heating in DF events. Finally, DF events on days when outdoor temperatures differ significantly from normal are not favored by occupants as existing heating systems may not be capable of maintaining comfort. Data shows that the negative impact of curtailment can linger for hours after the event ends. Though we could not establish the impact of this on next-day event participation, post-study exit interviews suggest that subjecting households to multiple intense DF events during extreme conditions may be impractical. Program administrators may consider additional nudge mechanisms, for example, financial incentives, to ensure participation or provide access to supplementary heating sources (Gaur et al., 2021) as encouragement if participation is critical for meeting grid needs on such days.

Though a detailed assessment as proposed in this paper may not always be feasible, it is valuable, particularly in remote or extreme weather regions, where prior empirical data is limited or unavailable. Moreover, empirical data focused on DF thermal comfort can supplement other existing DF data sources for example - typical residential energy-use load profiles available through utility data (Gerke et al., 2024), smart-thermostat datasets (Huchuk et al., 2021), and simulation-based energy use load profiles (Wilson et al., 2022) to fill current gaps in developing better estimation methods of DF program impacts. A better understanding of how household-level thermal comfort goals impact DF event participation can help in the development of DF program strategies that are occupant-centric and hence more reliable.

Limitations and Future Research

The findings from this study may be not generalizable to different geographic regions with significantly different weather conditions. Hence, future studies and larger study samples are needed to validate the proposed study method and corroborate findings for more diverse regions. The main goal of this research was to develop and test a place-based approach for informing winter DF strategies particularly to support programs in remote, rural areas that have traditionally not been well studied. To address these limitations, the next phase of this research project will evaluate the application of the methods introduced in this article in a larger study sample in extreme cold climate region of Alaska.

Credit authorship contribution statement

Chitra Nambiar: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Stefano Schiavon:** Conceptualization, Supervision, Visualization, Writing-review and editing. **Gail Brager:** Conceptualization, Supervision, Writing -review and editing. **Samuel Rosenberg:** Data curation, Funding acquisition, Project administration, Visualization, Writing – review and editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary Material

Sample data - Figure 6a
Additional data available upon reasonable request

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT to improve language and readability in some sections. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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