Can HP-Flex Enhance Load Flexibility of Heat Pumps, Lower Costs, Support Grid Reliability, & Maintain Comfort?

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1 Executive Summary

Executive Summary

This report presents a data-driven evaluation of HP-Flex, a model predictive control (MPC) strategy for heat pumps, based on nearly a year of field testing at the Western Cooling Efficiency Center (WCEC) on the UC Davis campus. The primary objective was to analyze how HP-Flex performs under real-world conditions across different seasons and pricing schemes, with a particular focus on its potential to enhance HVAC load flexibility and reduce electricity costs, all while maintaining thermal comfort for building occupants.

This work is timely and important as California continues to electrify its building stock and faces increasing pressure to manage peak electricity demand, reduce greenhouse gas emissions, and ensure equitable access to clean energy technologies. By enabling smart control of heat pumps, HP-Flex aims to shift or shed HVAC loads in response to time-varying electricity prices - offering a pathway to grid-interactive, efficient building operations.

The analysis relied on high-resolution time-series data collected under three control strategies: Baseline (static schedule), Time-of-Use (TOU), and Demand Flexible or Demand Response (DF/DR). To ensure fair comparisons, a matched-day methodology was used to pair days with similar outdoor conditions across interventions. While DF control focused on shifting load in response to dynamic price signals, TOU control aimed to minimize peak demand charges, which dominate costs under TOU tariffs. Performance was evaluated using five core metrics: peak load reduction, load shed, energy savings, electricity cost savings, and thermal comfort deviation.

Results show that HP-Flex consistently reduced peak demand and improved cost performance across all seasons, while maintaining or even improving thermal comfort. The strongest performance was observed in Winter and Spring, with daily peak load reductions exceeding 5 kW and cost savings reaching over 20% relative to baseline. Statewide scaling analysis further suggests that deploying HP-Flex across California's small commercial building sector could reduce peak load by up to 1.2 GW and enable over 2 GW of load shift potential.

Based on these findings, we recommend prioritizing deployment in colder seasons and disadvantaged communities, where benefits to the grid and to residents are greatest. Recommendations are grounded in observed field performance, cost analysis under DR and TOU pricing, and scalability estimates derived from statewide building stock data.

2 Project Background

2.1 Brief History and Context

California faces major grid flexibility issues, with peak demand for electricity reaching 48 GW [6]. Small and medium commercial (SMC) buildings represent almost half of the state's commercial space, which is approximately 4.39 billion square feet, yet remain highly unused for demand flexibility solutions. The project looks into how advanced HVAC control can support the grid while reducing energy costs and maintaining comfort.

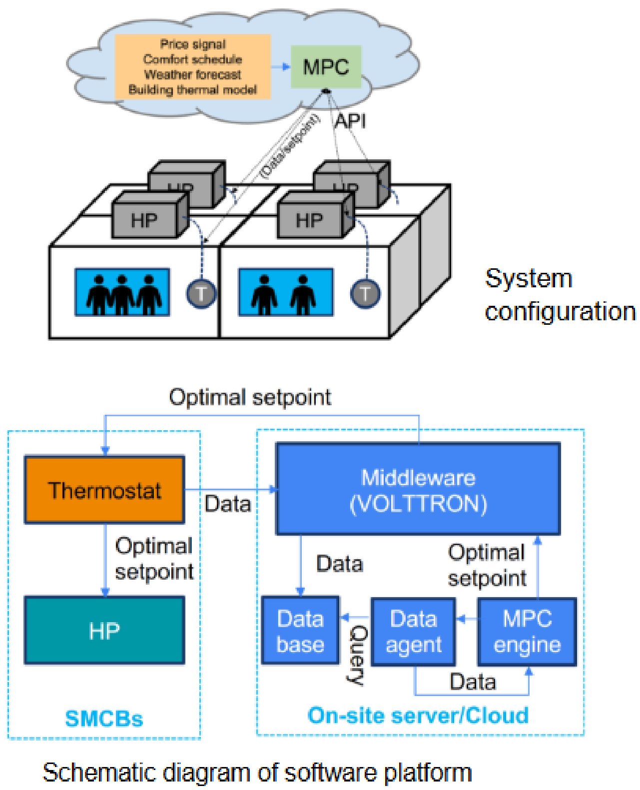


Figure 1: The figure shows how HP-Flex uses real-time data and an MPC engine to optimize heat pump operation by coordinating setpoints between thermostats and a central control platform.

HP-Flex: HP-Flex is a model predictive control (MPC) based heat pump control system that optimizes HVAC operations using real-time pricing signals and weather forecasts. It schedules or predicts the HVAC use to balance occupant comfort, grid demand and cost efficiency without any hardware retrofits. Unlike traditional thermostatic control, HP-Flex dynamically shifts HVAC operation away from peak price periods while maintaining thermal comfort.

2.2 Problem Description and Motivation

California is facing growing electricity needs, especially as more renewable energy is added to the grid. To keep things running smoothly, it is important for buildings to use energy more efficiently and be flexible about when they use it. But small and medium commercial buildings are often left out of the picture. They usually do not have the tools or systems needed to shift their energy use during busy times.

That's where HP-Flex comes in. It is a smart control strategy that helps the heat pumps in these buildings to adjust in real time to price signals and grid conditions. The goal is to cut down on energy use when it is most expensive or in highest demand, without making people uncomfortable. By giving these smaller buildings the ability to participate, HP-Flex makes energy use more affordable, more flexible, and better for the environment.

2.3 Literature Review

Recent literature highlights the growing importance of demand flexibility in grid management. Liu et al. [1] established a comprehensive framework for benchmarking electricity demand flexibility in grid-interactive efficient commercial buildings, emphasizing the need for standardized metrics to evaluate performance across diverse building types. Their work demonstrates that properly implemented demand flexibility can reduce peak loads by 10-30% without compromising occupant satisfaction.

Model Predictive Control has emerged as a promising approach for optimizing building HVAC operations. Casillas et al. [2] demonstrated that MPC algorithms could effectively manage thermal energy storage integrated with heat pump systems, achieving significant load shifting capabilities. Their research on generalized sizing and control algorithms provides a theoretical foundation for the HP-Flex approach, showing that predictive control can optimize across multiple objectives simultaneously.

The integration of demand response with existing building systems has been explored extensively by Nordman et al. [3] through the OpenADR 3.0 framework. This work establishes communication protocols and standardization approaches essential for scaling demand response programs. Similarly, Gerke et al. [4] projected California's demand response potential through 2050, identifying heat pump systems as critical contributors to the state's shed and shift resources.

3 Methodology

3.1 Major Considerations, Constraints, Assumptions and Metrics

The system was tested at the UC Davis Western Cooling Efficiency Center (WCEC) across 9 thermal zones, collecting minute-by-minute data for all the four seasons over the span of 13 months. Real-world sensor data, including HVAC power, indoor/outdoor temperature, and control setpoints were collected at minute-level resolution. This rich dataset enables precise evaluation of HP-Flex performance.

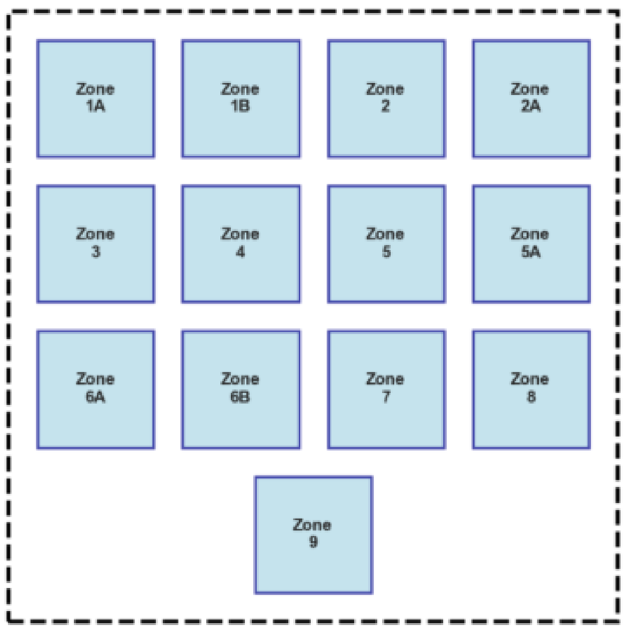


Figure 2: WCEC 9 thermal zones with individual heat pumps

In the project, we evaluated HP-Flex's performance across three control strategies:

- **Baseline:** Follows a static 24/7 schedule where heating and cooling setpoints are fixed. There is no flexibility to reduce the energy use during peak hours. It also does not know about the electricity prices.
- **Demand Response (DR/DF):** Designed to reduce electricity demand during peak periods by shifting load in response to a dynamic price signal such as the CalFlexHub CFH signal whihc was used during our DR testing. This signal provides 24-hour ahead pricing, allowing the HP-Flex MPC to optimize heat pump operation by minimizing both energy costs and peak demand. Since higher prices coincide with peak load times, this naturally shifts energy

use from peak load times to non-peak load times, resulting in demand reduction during peak periods.

- **Time of Use (TOU):** Designed to reduce electricity costs by focusing on lowering peak demand charges, which are a major part of utility bills under Time-of-Use (TOU) pricing. Unlike DR signals that encourage shifting energy use to cheaper times, TOU rates don't change much throughout the day. So instead of shifting loads, the strategy focused on avoiding high peaks by making sure not all heat pumps run at the same time. Therefore, only buildings with more than two controllable heat pumps can be eligible for this control approach.

3.2 Analysis Approach

3.2.1 Comfort Zone Analysis

Thermal comfort was quantified by monitoring whether zone temperatures remained within predefined comfort limits. A violation is recorded when the zone temperatures exceed the upper or lower setpoints.

The average violation rates were calculated for each thermal zone across all the control strategies and seasons, providing a viable metric to compare comfort performances.

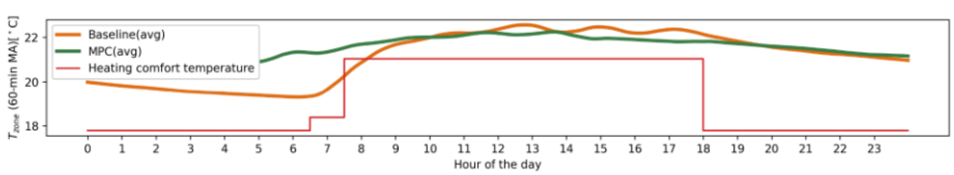


Figure 3: Summer Cooling Comfort Plot

This figure compares the zone temperatures under baseline and MPC throughout the day. As we see, MPC maintains temperature closer to the comfort band and doesn't even exceed it, thus reducing comfort violations compared to baseline.

3.2.2 Price Sensitivity Analysis

For analysing how well the control strategies adapt to time based pricing we did day matching to ensure fair comparisons between baseline and the intervention days. Days were selected to have similar outdoor temperatures profiles to isolate the effect of pricing response. For DR and TOU, hourly prices were applied in all simulations to guide the HVAC properly. This also allowed a detailed examination of how control strategies responded to pricing fluctuations throughout the day.

Steps to Address Equity

HP Flex addresses the energy burdens and health risks faced by underserved communities.

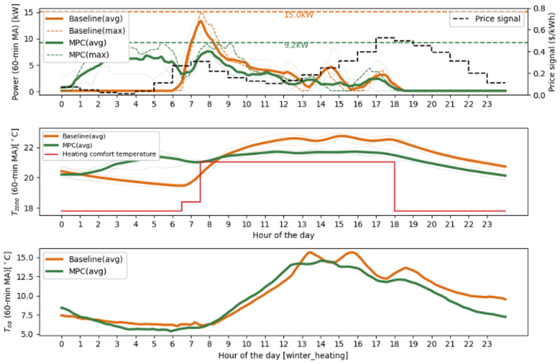
- Through the use of model predictive control, the system has the ability to make smart, real-time decisions about heat pump operations, reducing energy costs and staying responsive to the grid. This makes it affordable and a smarter option for everyone.
- The use of heat pumps, in general, can improve indoor air quality and reduce pollution. Traditional heating systems rely on indoor combustion, which can be harmful. Heat pumps prove a clean solution. This greatly helps low-income communities, many of whom might be living in older buildings that have poor ventilation systems.
- HP Flex and other such technologies can help address the issue of energy cost burden by reducing the share of income a household spends on electricity. By optimizing heat pump usage, HP-Flex can reduce monthly electricity bills and ease financial stress.

When implemented with equity in mind, smart control systems like HP-Flex have the potential to deliver both climate and community benefits.

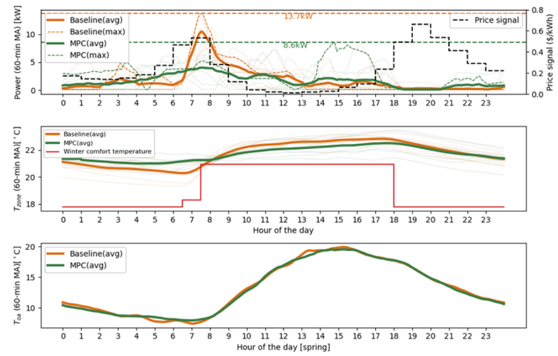
4 Results & Discussion

4.1 Main Results Relevant to Scope

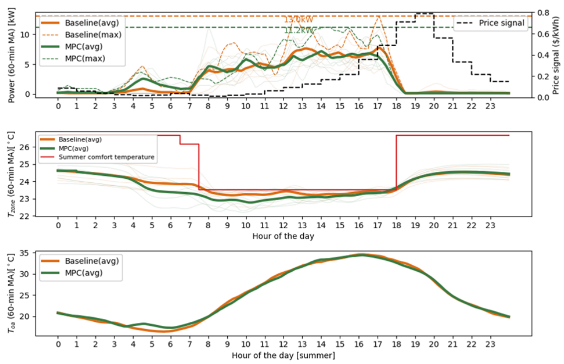
HP-Flex Demand Flexibility (DF) control strategy demonstrated strong and consistent performance in enhancing HVAC load flexibility across all four seasons: Spring, Summer, Fall, and Winter. Load shifting and shedding in response to dynamic pricing was clearly achieved, as illustrated in the average hourly performance plots (see Figure 4).



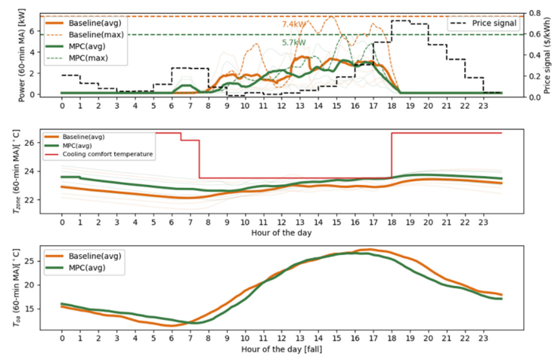
(a) Winter Heating



(b) Spring Heating



(c) Summer Cooling



(d) Fall Cooling

Figure 4: **Comparison of HVAC Power Demand, Price Signal, Indoor Temperature, and Outdoor Temperature Across Seasons.**

These plots show the daily average HVAC power demand, dynamic price signal, indoor zone temperature, and outdoor air temperature under demand response (DR) and baseline conditions. Data are based on matched day pairs - equal numbers of DR and Baseline days selected for similar weather conditions to ensure fair comparison. Matched day counts per season are: Winter heating – 8 pairs; Spring heating – 8 pairs; Summer cooling – 6 pairs; Fall cooling – 4 pairs.

Five key performance metrics were evaluated: peak load reduction, load shed, electricity cost savings, energy savings, and comfort deviation reduction. A summary of these metrics is presented in the heatmap figure (see Figure 5) with each cell showing both the absolute change and percent improvement relative to the baseline.

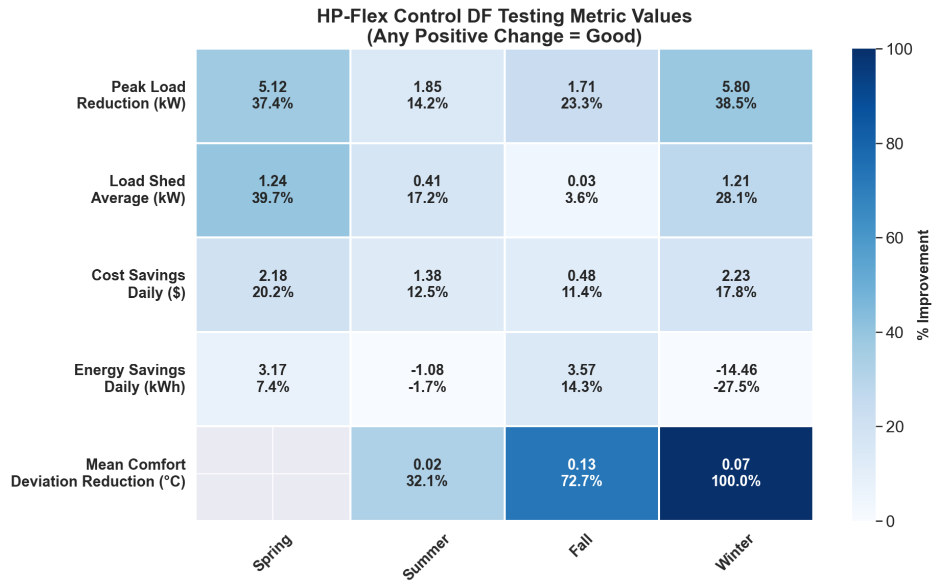


Figure 5: Summary heatmap of HP-Flex DF performance metrics across seasons.

HP-Flex consistently improved performance across all five metrics evaluated: peak load reduction, load shed, cost savings, energy savings, and comfort deviation. Winter and Spring generally showed the strongest improvements, but meaningful gains were also observed in Summer and Fall. Load shifting and shedding were evident in all seasons, especially during peak hours. While energy use increased in Winter and Summer due to strategic pre-heating and pre-cooling, cost savings were still achieved by avoiding high-priced periods. Importantly, HP-Flex maintained or improved thermal comfort throughout, demonstrating its effectiveness in balancing grid demands and occupant well-being.

While HP-Flex achieved meaningful cost reductions under time-of-use (TOU) pricing, the main economic benefit of TOU control compared to the baseline was the reduction in peak demand charges. Unlike DR pricing, which features steep and dynamic price signals that incentivize load shifting, the TOU price curve is relatively flat. This limits opportunities for shifting energy consumption to lower-cost hours. As a result, HP-Flex's strategy under TOU primarily focuses on reducing the building's peak demand, which determines the monthly demand charge.

Figure 6 highlights this distinction.

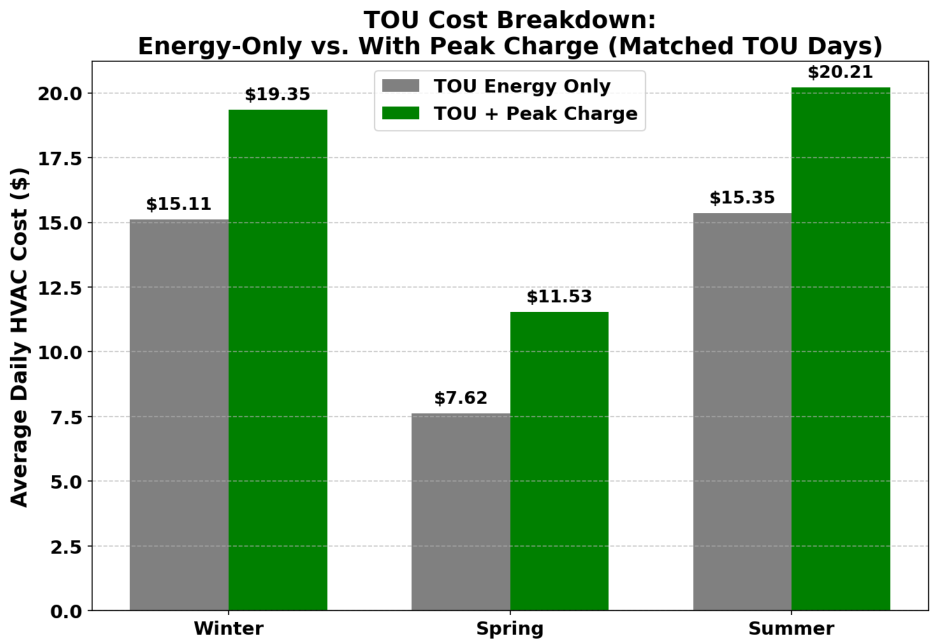


Figure 6: Average daily HVAC costs under TOU pricing, with and without peak demand charges, across Winter, Spring, and Summer.

This plot shows the average daily HVAC cost under TOU pricing, both with and without peak demand charges, across Winter, Spring, and Summer. To account for the fact that our testing was performed on a day-by-day basis rather than over complete calendar months, the monthly demand charge was normalized by dividing it by 30 and adding it to each day's cost. The figure clearly shows that peak demand charges significantly raise daily HVAC costs - by $3.91 to $4.86 on average - making them a major cost driver under TOU tariffs. This underscores the importance of explicitly managing peak demand when operating under TOU-based utility structures.

4.2 Sources of Uncertainty

Multiple factors could influence the interpretation and reliability of the results presented in this study. First and foremost, while matched-day analysis was used to control for external variability, additional factors such as humidity, solar radiation, or wind speed could potentially have been accounted for to further improve the alignment of environmental conditions between matched days. Furthermore, the limited number of matched days in some seasonal interventions - such as only four days for Fall cooling - reduces statistical robustness and may not fully capture the variability in building performance. Sensor accuracy could also present a source of uncertainty, as slight deviations in temperature or power measurement can impact the calculated metrics for energy use, comfort, and peak load. Additionally, simplifications in the cost analysis introduce potential discrepancies. For instance, for time-of-use (TOU) pricing, peak demand charges were approximated by dividing the monthly fee evenly across 30 days. However, in practice, this charge is based on the single highest 15-minute interval each month, meaning our approach may either understate or overstate the economic impact of peak demand. Finally, the way the model predictive controller (MPC) is tuned can also affect the results. The controller relies on certain settings like how strict the comfort temperature range is, or how accurate the weather and price forecasts are. These settings might work well in one season or building, but not as well in another. So, differences in how the MPC was tuned could lead to different levels of performance across seasons or building types. While the results overall demonstrate strong performance, these uncertainties highlight the importance of cautious interpretation and the value of further long-term testing.

4.3 Discussion of Equity Implementation Successes and Challenges

Multiple equity considerations arise in the deployment of HP-Flex. As previously mentioned,heat pumps eliminate indoor combustion, improving air quality. This is a benefit, particularly in low-income households which are often located in older, poorly ventilated buildings. Prioritizing HP-Flex in disadvantaged communities could reduce energy burden while improving indoor environmental conditions.

However, the technical complexity of MPC-based systems may present challenges for smaller facilities that lack on-site building engineers or facility managers with control system experience. Addressing this challenge means designing user-friendly tools that don't require advanced expertise, offering simple setup options, and providing ongoing support and training to ensure that even the smallest or least-resourced buildings can benefit from HP-Flex. Additionally, ensuring equitable access to real-time pricing and demand response programs is necessary for inclusive benefits.

To enable equity-focused deployment, utility programs should incorporate enhanced support programs, technical assistance, and performance guarantees tailored to disadvantaged communities. Effective implementation depends on intentional program design that accounts for capacity, accessibility, and fairness.

5 Recommendations & Conclusions

5.1 Future Work

Future work may focus on expanding HP-Flex deployment across diverse building types and climate zones to evaluate broader applicability. Enhancing the controller with adaptive learning algorithms and occupant-specific comfort models could further improve performance and responsiveness. Long-term field validation will be valuable for capturing full billing cycles, particularly for peak demand charges under TOU structures. Additionally, aligning HP-Flex with utility programs and equity goals, especially in under-resourced buildings, will be a meaningful improvement. Exploring scalable financing models and targeted support programs can reduce upfront costs and make HP-Flex adoption more accessible across diverse building types.

5.2 Identification of Additional Equity Challenges

Future efforts must consider additional equity challenges to ensure inclusive deployment of HP-Flex. Gaps in internet access and building automation create barriers for smaller or under-resourced facilities, calling for offline-capable and tiered control solutions. Demand response programs must also account for buildings with inflexible loads due to critical operations. Finally, language and cultural differences in diverse communities highlight the need for multilingual interfaces and tailored outreach strategies.

5.3 Impact Analysis

To understand the broader implications of HP-Flex deployment, we conducted a statewide impact analysis focused on small-to-medium commercial (SMC) buildings in California. This analysis estimates the potential grid-level benefits - specifically peak demand reduction and load shift capacity - that could be achieved if HP-Flex were scaled across the state's SMC building stock. By leveraging seasonal performance data from our WCEC test site and combining it with statewide building energy statistics, we extrapolate the impact of widespread adoption of demand-flexible heat pump control strategies. The following sections outline the assumptions, calculations, and resulting estimates.

Two primary benefits were quantified: statewide load shift potential and peak load reduction, using the methods described below.

Load Shift Potential:

$$L_{\text{shift}} = A_{\text{SMC}} \times i_{\text{shift}} \tag{1}$$

Where A_{SMC} is total statewide floor area and i_{shift} is the WCEC-observed seasonal load shed intensity (W/ft^2).

Peak Load Reduction:

$$P_{\text{reduction}} = P_{\text{SMC,HVAC}} \times R_{\text{peak}} \tag{2}$$

$$P_{\text{SMC,HVAC}} = P_{\text{peak}} \times s_{\text{commercial}} \times s_{\text{SMC}} \times f_{\text{HVAC}} \tag{3}$$

Where:

- P_{peak} is California's system-wide peak electricity demand. For the 2024–2025 period, the annual maximum occurred on September 5, 2024 at 4:59 PM, reaching approximately 48 GW [6].
- $s_{\text{commercial}}$ is the commercial sector's share of the total peak demand.
- s_{SMC} is the fraction of the commercial building floor area attributed to the small and medium commercial (SMC) segment.
- f_{HVAC} is the share of HVAC systems in the SMC segment's peak demand.
- R_{peak} is the observed peak reduction ratio from site-level testing of HP-Flex.
- $P_{\text{SMC,HVAC}}$ is the portion of statewide peak demand attributed specifically to HVAC systems in the SMC building stock.

Table 1 presents the estimated statewide seasonal impacts of HP-Flex deployment, including both load shift potential and peak load reduction, based on normalized performance data from the WCEC site.

Table 1: WCEC-Based Statewide Load Shift and Peak Reduction Estimates by Season

Season	Load Shift Potential (MW)	Peak Load Reduction (MW)
Spring	972.4	1249.3
Summer	323.5	474.1
Fall	21.4	779.5
Winter	948.4	1289.3

Table 2 presents the key input parameters used in the statewide impact analysis of HP-Flex. It includes fixed constants related to building stock and load allocation, as well as season-specific values for peak load reduction ratios and load shift intensities derived from WCEC testing results.

Table 2: **Input Parameters Used for Statewide Impact Analysis of HP-Flex**

Constants Used Across All Seasons		
California system peak demand, P_{peak}	48 GW	
Commercial share of peak demand, $s_{\text{commercial}}$	0.35	
SMC share of commercial floor area, s_{SMC}	0.498	
HVAC share of SMC peak load, f_{HVAC}	0.4	
Total SMC floor area, A_{SMC}	4.39 billion ft^2	
Seasonal Values		
Season	R_{peak}	i_{shift} (W/ft^2)
Spring	0.374	0.22150
Summer	0.142	0.07367
Fall	0.233	0.00487
Winter	0.3855	0.21603

The results presented in Table 1 highlight the substantial system-level potential of HP-Flex deployment in California's SMC building stock. Both load shift and peak reduction impacts are especially pronounced in Spring and Winter, where favorable HVAC dynamics and strong controller performance led to statewide peak reductions exceeding 1.2 GW. While Fall shows more modest load shift potential due to limited demand flexibility during that season, its peak reduction remains significant. Overall, these findings highlight HP-Flex's ability to deliver meaningful grid benefits - especially when deployed at scale - by easing peak demand, enabling load flexibility, and supporting decarbonization goals, all while keeping building occupants comfortable.

6 Conclusion

Our study has demonstrated that HP-Flex control strategy effectively enhances the demand flexibility of heat pump systems in small commercial buildings. Across all seasons, HP-Flex consistently reduced peak HVAC loads - up to 38.5% in Winter - and lowered daily energy costs, with the greatest savings observed in Spring (20.2%). Even when energy use increased in Winter and Summer due to a greater emphasis on load shifting during these seasons, thermal comfort was maintained or improved, with comfort deviations reduced by as much as 100%.

Statewide impact estimates based on WCEC data suggest that deploying HP-Flex across California's small commercial (SMC) building stock could yield substantial benefits. Depending on the season and intervention, the strategy has the potential to reduce daily peak demand by 470 - 1,290 MW and shift 20 - 970 MW of HVAC load during peak hours - all without compromising occupant comfort. These results highlight HP-Flex's potential as a powerful demand-side strategy which is capable of scaling to support grid stability and emisisons reduction as California accelerates its transition to all-electric buildings. As far as equity is concerned, more discussions are needed. Smaller buildings and disadvantaged communities may face barriers to adopting such complex systems due to limited resources, technical capacity, or access to supportive programs. Ensuring that the benefits of HP-Flex are equitably distributed will require intentional outreach, inclusive policy design, and sustained stakeholder engagement.

Overall, HP-Flex offers a scalable solution to improve grid-interactive building performance. With continued development and equity-centered program design, this approach can play a key role in California's path toward a cleaner, more flexible, and more equitable energy future.

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