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Heat Pumps with Phase Change Thermal Storage: Flexible, Efficient, and Electrification Friendly

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ABSTRACT

As we continue to electrify space- and water-heating, the electricity demand profile of many buildings will change significantly, and periods of high electricity demand will likely not align with renewable energy generation. We expect electricity demands will increase substantially in the winter, annual maximum electricity demands will increase, and more regions will experience annual peak electrical demands – and higher wholesale electricity prices – in the winter. This is especially important for cold climates where 60% of site energy use in buildings is for heating, and where heat pumps perform least efficiently. This paper focuses on one promising solution among the many paths to electrification: the use of phase change materials (PCM) for compact low-cost thermal energy storage (TES). We present the design and simulation of a combi heat pump and phase change thermal storage system used for space- and water-heating in a multifamily residence in a cold climate. To assess the benefits of this technology, we compare its annual performance to that of a current state-of-the-art air-to-air heat pump and separate heat pump water heater. Simulation results for IECC Climate Zone 6A reveal that the combi heat pump with phase change thermal storage can reduce the design size for heat pumps by 40-60%, reduce maximum electric demand by 30-50%, reduce electricity use during 4-12-hour load shed periods by 50%, and avoid the need for auxiliary electric resistance for both space- and water-heating. Tariff structures are highly varied between different utilities and currently reflect higher wholesale market prices for electricity during summer days. Consequently, although this system design provides large electric demand reductions during hypothetical 4-12-hour load shed periods, it does not provide energy cost reductions with current winter residential time-of-use tariffs.

Introduction

Heat pumps offer a pathway to reduce use of on-site fuel combustion and inefficient electric resistance for space- and water-heating. However, a broad transition to heat pumps (HP) will add substantial end-use electricity demands with time-of-use (TOU) patterns that do not align with the availability of intermittent renewable electricity generation. In certain circumstances, a transition to heat pumps for space- and water-heating could increase greenhouse gas emissions compared to on-site combustion. Moreover, the added electricity loads from a transition to heat pumps could shift system-wide peak electricity demands to the winter, increase peak electricity demand, and require costly upgrades to electricity system transmission and distribution capacity (Liang 2022, Vaishnav 2020, Deetjen 2019). These issues are especially acute in wintertime in cold climates (Satchwell et al. 2021).

Grid-scale storage can effectively shift some renewable energy to better align with end-use demands, but it does little to reduce the impact that broad electrification will have on end-use electricity demand profiles, electric system distribution capacity requirements, and time-of-use electricity costs. Thus, there is a need for on-site energy storage to facilitate broad adoption of heat pumps without stressing grid capacity, and without burdening consumers with high costs from time-of-use electricity rates. Distributed on-site electrochemical storage could flatten net loads on the grid, but electrochemical storage capacity would need to be large if it is to buffer the large energy use for space- and water-heating, and rated power output from electrochemical storage would need to be large enough to compensate for the maximum power input for heat pumps – and auxiliary electric resistance heat – sized to match the annual peak coincident space- and water-heating loads.

In view of these multifaceted challenges, thermal energy storage (TES) offers several potential advantages. In addition to providing the grid balancing and electricity distribution capacity benefits provided by other energy storage technologies, TES could also: reduce required heat pump size, avoid auxiliary electric resistance, improve space- and water-heating heating efficiency, and reduce on-site electric service capacity.

In this paper we present simulation results that explore the potential benefits of integrating HPs and TES. We focus on phase change materials (PCM) in a TES tank, paired with an air-to-water heat pump that is used for both space heating and domestic hot water (DHW). Although this combi heat pump system with PCM TES may be appropriate for many building types and climates, our example analysis for this paper focuses on one multifamily building in one cold climate (IECC Climate Zone 6A, Minneapolis MN). We assess the potential for this technology to: (1) reduce design heat pump capacity, (2) reduce energy use during different hypothetical peak demand periods, and (3) reduce maximum electricity demand.

Methods

The analysis presented in this paper compares a baseline all-electric mechanical system to that of a combi heat pump system with PCM TES. We modeled both systems for a multifamily building in a cold climate (IECC Climate Zone 6A, Minneapolis MN).

Explanation of model environment and parametric simulation framework

For this investigation, we used a recently developed parametric simulation framework that facilitates rapid evaluation of many different HP + PCM TES system architectures and system sizing options for different building types, climate regions, and electricity tariff structures. We used the open-source JModelica software (Åkesson et al. 2010) to compile and simulate the buildings, systems, and controls in Modelica – a multi-physics, object-oriented, equation-based language with an open specification that offers hierarchical and dynamic modeling of integrated energy systems and controls (Mattsson and Elmqvist 1997). We utilized open-source models for system subcomponents and controls from both the Modelica Buildings Library (Wetter et al. 2014) and IDEAS (Jorissen et al. 2018). User definition of alternate design parameters, management of parametric simulations, and results post processing are packaged within a portable docker, which we developed using the publicly available docker environment for JModelica (Docker 2020). The design and function of our parametric simulation tool is described in greater detail by Helmns et al. (2021b).

Explanation of baseline system

The baseline system for this analysis is a state-of-the-art all-electric mechanical system without energy storage: a split air-to-air heat pump used for space heating and cooling, and a separate heat pump water heater (HPWH) used for DHW. The multifamily building we modeled uses individual storage water heaters in each apartment, not central water heating. Both heat pumps in this baseline system include auxiliary electric resistance.

Explanation of proposed system

The proposed system is a combi air-to-water heat pump paired with a PCM TES tank and hydronic terminal heating and cooling. This system, shown in Figure 1, is designed to provide all heating, cooling, and DHW with a single HP and no auxiliary electric resistance. The air-to-water heat pump can heat or cool the space through the hydronic terminal systems, or it can heat the PCM TES. The PCM TES includes two tanks with different phase change temperatures (48°C and 58°C). Each of these PCM TES tanks are comprised of two finned-tube heat exchanger circuits embedded in a reservoir of salt-hydrate PCM. When heating the PCM TES, the HP can heat either of the PCM TES tanks independently, or heat both tanks in series. For space heating, the system can avoid heat pump operation by extracting heat from the lower temperature (48°C) PCM TES. For DHW, the system extracts heat from both the lower temperature (48°C) and higher temperature (58°C) PCM TES. Additional details on the development of models for PCM TES are described by Helmns et al. (2021a).

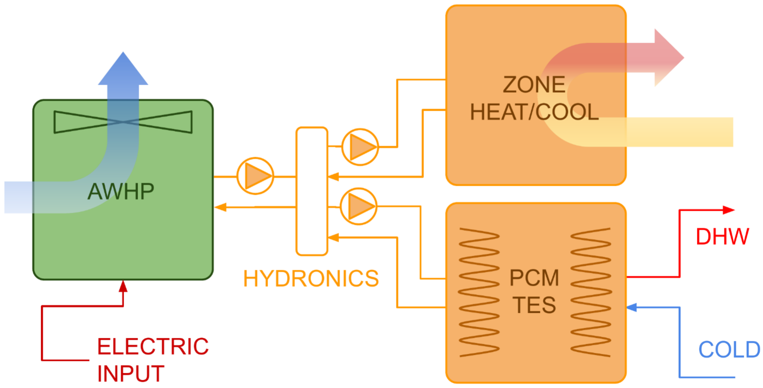

Figure 1: Conceptual schematic for the combi air-to-water heat pump with phase change thermal storage for space- and water-heating

The potential technical advantages of this system design include the ability to:

- Consolidate heat pump equipment
- Reduce required heat pump size
- Avoid electric resistance
- Reduce circuit ampacity compared to other all-electric pathways
- Reduce maximum electricity demands, and enable demand flexibility
- Shift electricity use for heating to periods with lower electricity prices, low greenhouse gas emissions, or high renewable penetration
- Improve COP by shifting HP operation to warmer periods
- Reduce space compared to water thermal storage
- Displace combustion heating in cold climates where heat pumps often rely on supplemental combustion heat.

Building model

We simulated the two mechanical systems in a single zone apartment in a multifamily building, with construction properties, heat gains, setpoints, schedules, infiltration rates, and ventilation rates corresponding to the U.S. Department of Energy Commercial Reference Building Model for a new construction mid-rise multifamily building (Deru et al. 2011). We developed DHW draw patterns for the single apartment using a publicly available stochastic DHW event generator (Hendron, Burch, & Barker 2010). For both mechanical systems, the models include a supply and return duct, supply fan, heating coil, and cooling coil. Additional details about the envelope model, DHW draw patterns, air delivery system, air-to-water heat pump, hydronic system, HPWH model and controls are described in Helmns et al. (2021b). Figure 2 illustrates the baseline and proposed systems, as they might be located within a multifamily apartment unit.

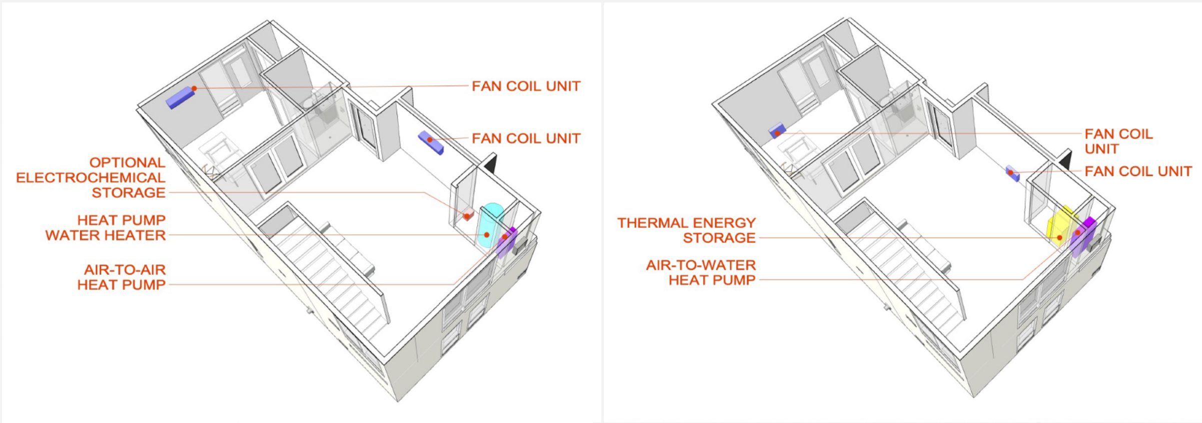

Figure 2: Illustrations of: (left) baseline heating and hot water system for multifamily and (right) proposed heating and hot water system for multifamily

Description of simulations performed

We performed simulations to assess the potential for the combi heat pump with PCM TES to reduce heat pump size needed in cold climates, reduce the maximum electricity demand for space- and water-heating, reduce total energy consumption, and reduce energy consumption during designated load shed periods when low electricity demand is preferred.

To assess this, we conducted simulations of the combi heat pump and PCM TES with different heat pump sizes, and with different load shed periods. The proposed system was controlled to avoid heat pump operation during the designated load shed periods by drawing heat from the PCM TES for space- and water-heating. Then, at the end of the load shed period, the heat pump was allowed to charge the PCM TES. The baseline system was not controlled to provide any load shifting; the heat pump water heater was controlled to heat anytime the tank temperature dropped below setpoint, and the ducted split air-to-air heat pump was controlled to follow an indoor air temperature setpoint schedule. We ran the baseline simulation first, then used the combined design size for the baseline space- and water-heating heat pumps as the reference for sizing the combi heat pump for the proposed system. Then, we ran simulations of the proposed system with various smaller heat pump capacities, as described in Table 1 below.

Our parametric simulations covered the full factorial combination of the following:

- Heat pump size: 100%, 80%, 60%, 40%, 20%
- Load shed period: 4-hr (4pm-8pm), 8-hr (1:30pm-9:30pm), 12-hr (11am-11pm)

Table 1: The values of input variables for parametric simulations in IECC Climate Zone 6A

System and description	Heat pump size	Load shed period
Baseline *Ducted split air-to-air heat pump* *Heat pump water heater*	100% (5.437 kW) *Space heating: 3.137 kW* *Water heating: 2.300 kW*	No load shifting scheme
Proposed System *Combi air-to-water heat pump* *48°C PCM TES: 42.0 kWh-th (0.645 m^3)* *58°C PCM TES: 10.5 kWh-th (0.171 m^3)*	100% (5.437 kW)	4-hr (4pm-8pm) 8-hr (1:30pm-9:30pm) *and* 12-hr (11am-11pm)
	80% (4.350 kW)	
	60% (3.262 kW)	
	40% (2.175 kW)	
	20% (1.087 kW)	

Results

We simulated the baseline and proposed systems in IECC Climate Zone 6A for each combination of heat pump size and load shed period described above. Table 2 summarizes key results from all simulations, including: the maximum HVAC electricity demand (kW), annual HVAC energy use (kWh), HVAC energy use during designated load shed periods (kWh), the time-weighted deviation from indoor temperature setpoint and hot water temperature setpoint (K·h), and the maximum deviation (K) from setpoint encountered throughout the annual simulation.

Table 2. Summary of key simulation results in IECC Climate Zone 6A

System	Heat pump size	Load shed period (hours)	HVAC max electric demand (kW)	HVAC energy use during load shed period (kWh)	Annual HVAC energy use (kWh)	Indoor space weighted deviation from setpoint (K·h)	Indoor space max deviation from setpoint (K)	Hot water weighted deviation from setpoint (K·h)	Hot water setpoint max deviation (K)
Baseline	100%	4	2.74	213	2326	94	0.80	1151	17.14
		8		301					
		12		368					
Combi HP + PCM TES	100%	4	2.81	103	3063	72	0.57	919	0.62
		8	2.88	144	3136	72	0.56	920	0.62
		12	3.00	175	3212	73	0.55	921	0.62
	80%	4	2.33	105	3046	98	1.05	919	0.62
		8	2.50	141	3116	99	1.05	920	0.62
		12	2.50	176	3193	100	1.05	921	0.62
	60%	4	1.83	99	3029	174	1.93	918	0.62
		8	1.90	138	3089	179	1.92	920	0.62
		12	1.90	178	3164	180	1.92	924	0.62
	40%	4	1.31	115	2973	999	3.60	923	0.65
		8	1.31	147	3034	957	3.55	932	0.66
		12	1.31	190	3115	966	3.88	1078	5.80
	20%	4	0.71	85	2625	7524	8.90	4511	14.66
		8	0.71	80	2624	7841	9.22	7313	16.40
		12	0.71	55	2595	8418	9.43	17181	17.41

Table 3 presents the percent difference between key performance metrics for the baseline and proposed systems. Positive values indicate that the proposed combi heat pump with PCM TES performs better than the baseline system (e.g., annual energy savings, demand reduction, etc.). Negative values indicate that the proposed system performs worse than the baseline for that metric (e.g., increased energy use, etc.); these are also highlighted in red.

Table 3. Summary comparing key simulation results in IECC Climate Zone 6A

System	Heat pump size	Load shed period (hours)	Max HVAC electric demand savings	HVAC energy use reduction during load shed	Reduction in indoor space setpoint discomfort	Reduction in max deviation of indoor space	Reduction in hot water setpoint discomfort	Reduction in max deviation of hot water

			(%)	period (%)	(%)	setpoint (%)	(%)	setpoint (%)
Baseline	100%	4	-	-	-	-	-	-
		8	-	-	-	-	-	-
		12	-	-	-	-	-	-
Combi HP + PCM TES	100%	4	-3%	52%	24%	29%	20%	96%
		8	-5%	52%	24%	29%	20%	96%
		12	-10%	53%	23%	31%	20%	96%
	80%	4	15%	51%	-4%	-32%	20%	96%
		8	9%	53%	-4%	-32%	20%	96%
		12	9%	52%	-6%	-32%	20%	96%
	60%	4	33%	54%	-84%	-142%	20%	96%
		8	31%	54%	-90%	-141%	20%	96%
		12	31%	52%	-91%	-141%	20%	96%
	40%	4	52%	46%	-958%	-352%	20%	96%
		8	52%	51%	-914%	-345%	20%	96%
		12	52%	49%	-923%	-387%	6%	66%
	20%	4	74%	60%	-7868%	-1017%	-292%	15%
		8	74%	74%	-8204%	-1057%	-535%	4%
		12	74%	85%	-8815%	-1084%	-1393%	-2%

Figure 3 shows the space heating profiles for the baseline system and combi system with PCM TES for the five different HP sizes tested. Figure 3 presents results for the 8-hour load shed period. In the proposed system, space heating thermal power is provided by the combined HP and TES tank, which is a function of both the downsized capacity and available PCM state of charge.

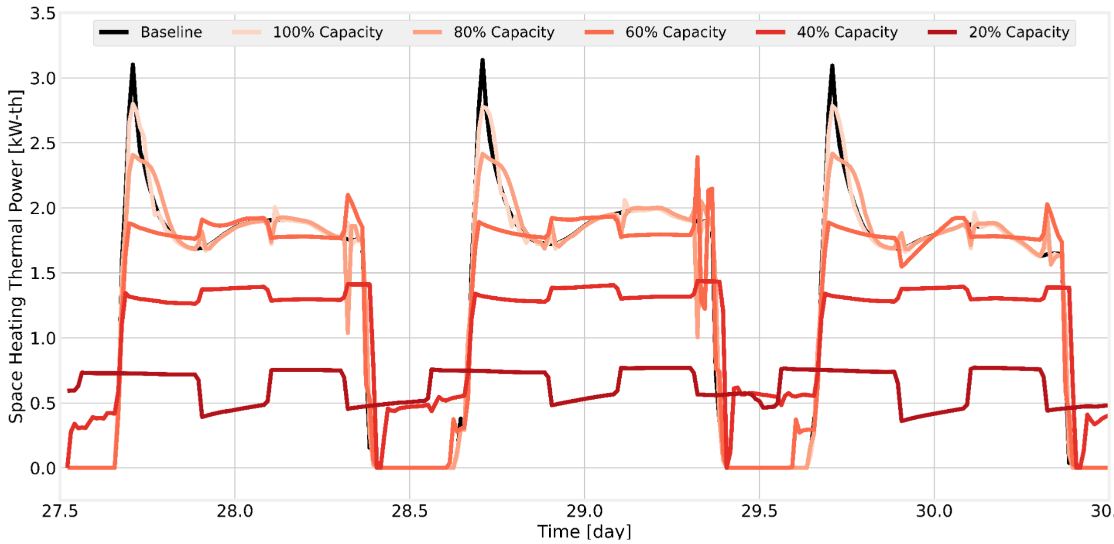

Figure 3: Time series results for space heating for the 8-hour load shed duration in IECC Climate Zone 6A for a period of three days (January 27 - January 30) in winter

Figures 4-6 show the temperature and electric power results across all simulations in IECC Climate Zone 6A. The top panel in each figure shows the indoor temperature for each simulation, plus the indoor temperature setpoints, and the outdoor temperature. The combi system with PCM TES is controlled to meet these setpoints if it has adequate thermal energy and power to do so. Across the 4-hour, 8-hour, and 12-hour duration load shed periods, several of the smaller capacity systems are unable to meet setpoint and this is exacerbated by longer duration discharge. The bottom panel in each figure shows the electric power required for HVAC and DHW by both the baseline and proposed systems. The blockier nature of the electricity demand of the combi system with PCM TES is due to the controls implemented for charging. These are meant to deliver thermal energy at a relatively constant rate to charge the PCM TES. All scenarios have the same charging duration and same PCM TES size noted in Table 1. The PCM state of charge impacts the electric demand profile; greater utilization requires more charging by the HP in the next available charge period.

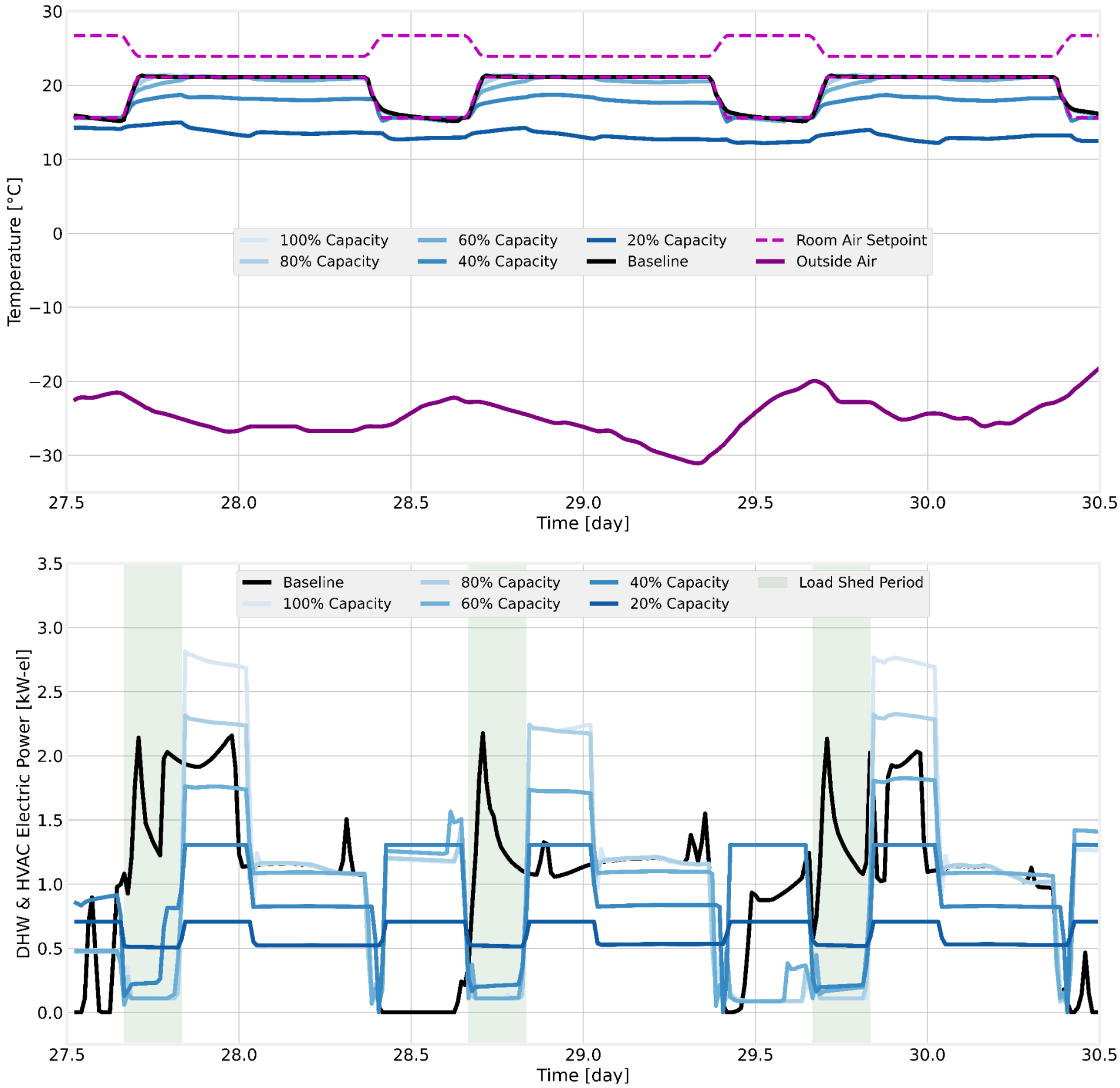

Figure 4: Time series results for (top) space temperatures, setpoints, and outdoor air temperature and (bottom) HVAC electricity demand (kW) comparing baseline and proposed system with 100%, 80%, 60%, 40%, 20% heat pump size for the 4-hour load shed scenario in 6A for a period of three days (January 27 - January 30) in winter

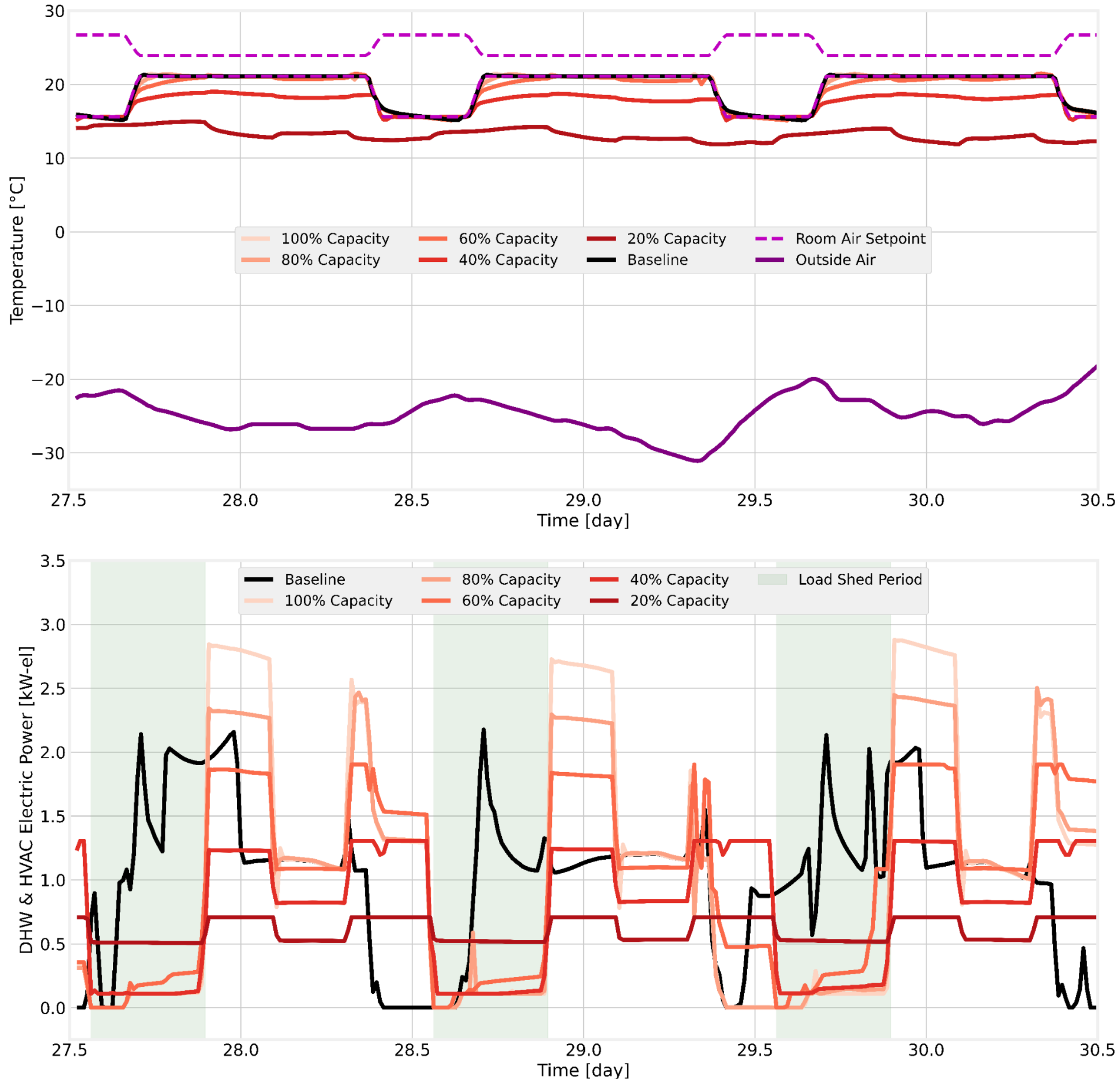

Figure 5: Time series results for (top) space temperatures, setpoints, and outdoor air temperature and (bottom) HVAC electricity demand (kW) comparing baseline and proposed system with 100%, 80%, 60%, 40%, 20% heat pump size for the 8-hour load shed scenario in 6A for a period of three days (January 27 - January 30) in winter

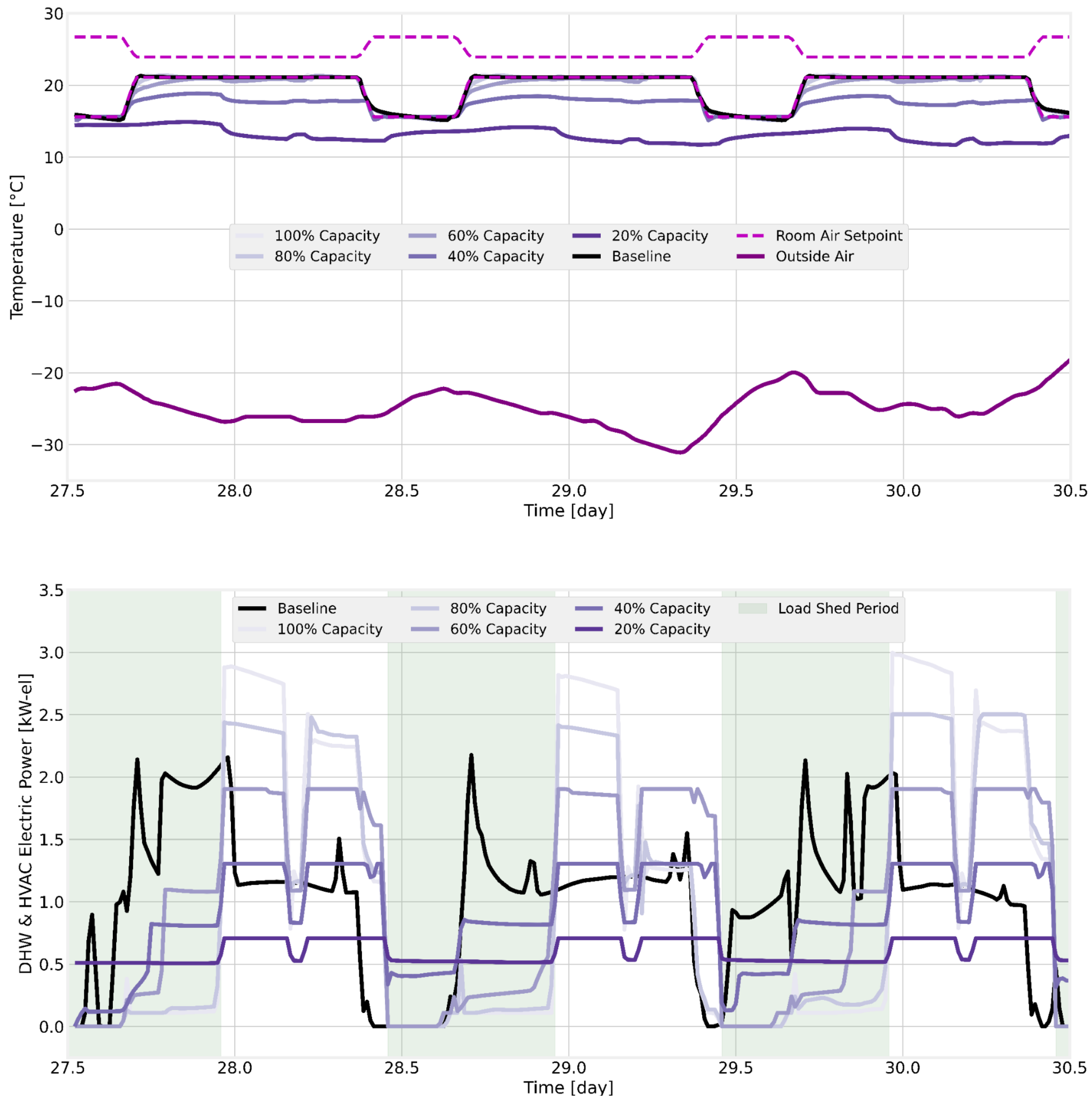

Figure 6: Time series results for (top) space temperatures, setpoints, and outdoor air temperature and (bottom) HVAC electricity demand (kW) comparing baseline and proposed system with 100%, 80%, 60%, 40%, 20% heat pump size for the 12-hour load shed scenario in 6A for a period of three days (January 27 - January 30) in winter

Figure 7 shows the domestic hot water temperature results across all simulations in IECC Climate Zone 6A. The combi system with PCM TES is controlled to meet the DHW setpoint if it has adequate thermal energy and power to do so. Across the 4, 8, and 12-hour duration load shed periods, the 20% capacity systems are unable to meet the water setpoint and this is exacerbated by longer duration discharge. For water-heating, the baseline HPWH is outperformed by the proposed system with 40% combi HP capacity and higher.

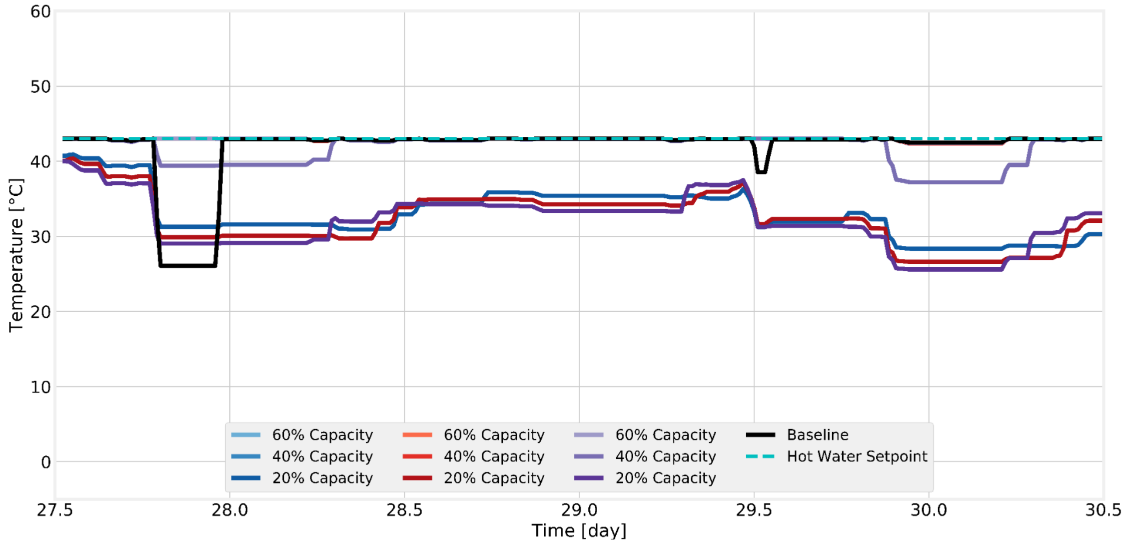

Figure 7: Time series results for DHW temperatures comparing baseline and proposed system with 60%, 40%, 20% heat pump size for the 4 (blue), 8 (red), and 12 (purple) hour load shed scenarios in 6A for a period of three days (January 27 - January 30) in winter

Figure 8 shows the state of charge for the high and low temperature phase change thermal energy storage devices in the proposed combi system. The timeseries results show the impact of the heat pump capacity limits (100%, 80%, 60%, 40%, 20%) and load shed durations (4, 8, and 12-hours). The state of charge of the PCM TES should ideally vary between 0 and 1 to remain in the latent heat transfer regime. This is what makes the technology energy dense. However, sensible heat transfer can also occur in the phase change material, either superheating in the liquid state or subcooling in the solid state. Figure 8 gives greater insight to why some of the scenarios are unable to meet space- and water-heating setpoints. The 20% and 40% capacity heat pumps struggle to charge the PCM TES and, thus, its discharging proves inadequate to meet the space- and water-heating setpoints shown in Figures 4-7 above.

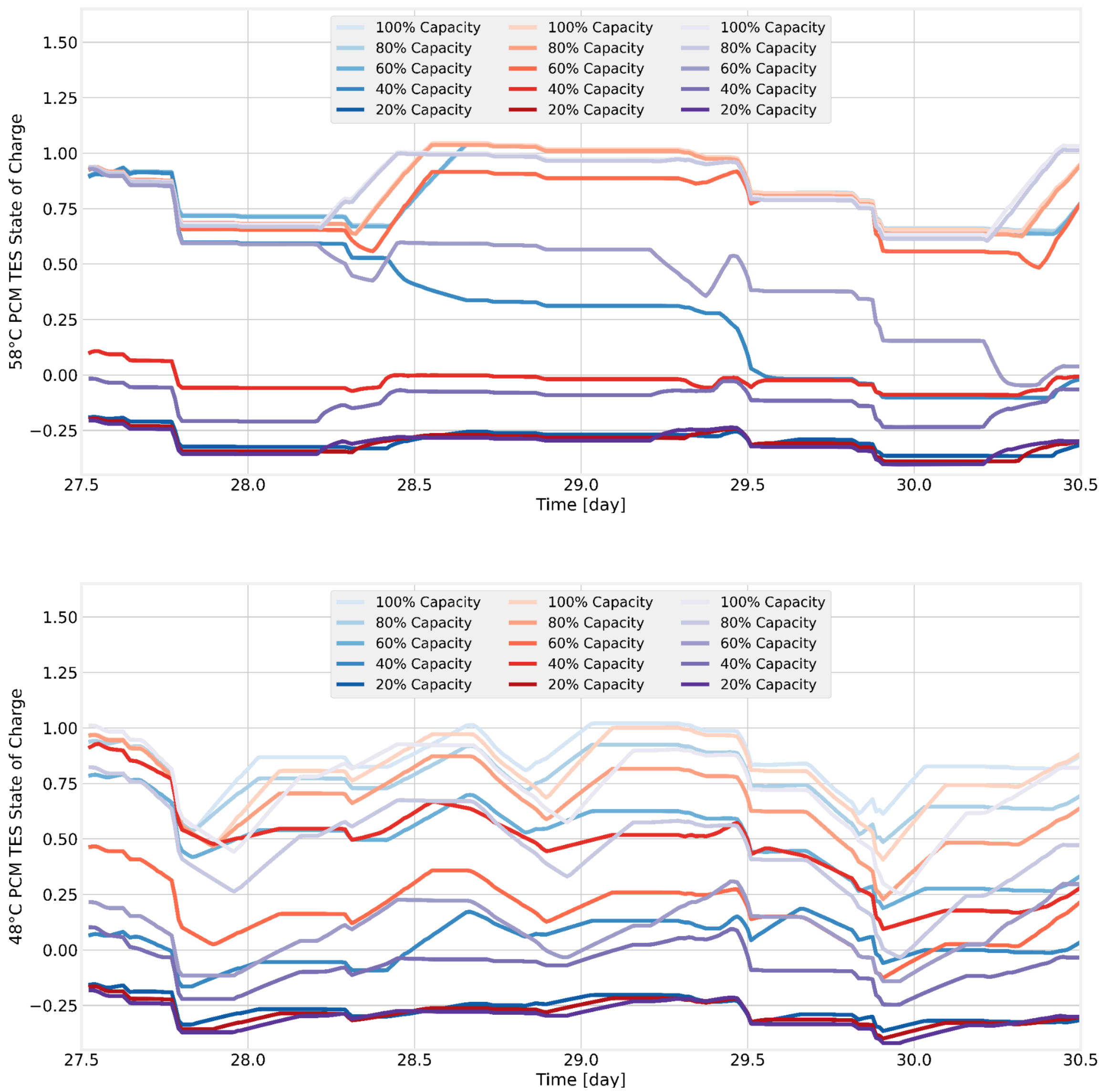

Figure 8: Time series results for state of charge for (top) high temperature storage and (bottom) low temperature storage in proposed system with 100%, 80%, 60%, 40%, 20% heat pump size for the 4 (blue), 8 (red), and 12 (purple) hour load shed scenarios in 6A for a period of three days (January 27 - January 30) in winter

Conclusions

In this paper, we explored the impact of a new load shifting system for a multifamily residential apartment building. We simulated models of the baseline and proposed combi HP with PCM TES in cold climates and presented time series data for visualization of system operation on peak days in winter for IECC Climate Zone 6A. Compared to the baseline system, we found that the proposed system can comfortably be downsized to 60% capacity while meeting space conditioning setpoints within a max deviation of 2°C. In fact, we also found that the proposed system at a combi HP capacity of 40% or higher with cascading temperature PCM TES performs better than the baseline system tank water heater at reliably delivering hot water. The annual HVAC energy use is higher in all scenarios with storage because the heat pump must operate at a higher setpoint and therefore lower coefficient of performance to charge up the PCM TES. This performance could possibly be improved through better alignment of HP operation with the warmest outdoor temperatures. Despite greater energy use overall, the proposed system is very effective at reducing energy use by half during 4, 8, and 12-hour shed periods. Furthermore, the downsized heat pump capacity enables significant electricity demand reduction across the year. This is extremely promising for an increasingly electrified grid.

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