Journal
ASHRAE Journal, 66(8)

Authors
Cheng, Hwakong
Raftery, Paul
Wendler, Patrick

Publication Date
2024-08-01

Re-optimizing Optimal Start and Morning Warmup

Hwakong Cheng, PE, Member
Paul Raftery, Ph.D., Member
Pat Wendler, Associate Member

Conventional wisdom and standard industry practice is to setback zone temperature setpoints when commercial buildings are unoccupied at night. The HVAC systems then operate in warmup mode to recover zone temperatures prior to the start of occupancy, sometimes with an optimal start algorithm. These strategies were intended to reduce HVAC energy consumption when originally developed decades ago but are due for re-examination given the significant changes in HVAC systems that have since occurred. In particular, the changes currently underway with the movement toward electrification present new design considerations and priorities. Warming up a building as fast as possible may not be the best strategy in terms of energy use, operating cost, or carbon emissions. This article discusses some of the downfalls of conventional morning warmup practices, suggests an improved strategy, and shows the results from a pilot field demonstration test.

Conventional practice

Conventional control strategies aim to minimize building envelope losses in cold weather by reducing the amount of time that buildings are maintained at comfortable temperatures (setback) and to reduce building energy use by minimizing the system operating hours (optimal start). Required by building energy codes[1, 2, 3], optimal start strategies use learning algorithms and real time measurements to wait as long as possible before starting HVAC systems and typical control strategies then attempt to recover temperatures as fast as possible.

The control sequences described in ASHRAE Guideline 36 *High Performance Sequences of Operation for HVAC Systems*[4] include a range of actions to minimize recovery time. Below is a description of responses for typical variable air volume reheat systems, but the principles apply similarly to many other HVAC system types. When warmup mode begins, the zone heating setpoint rises from the unoccupied to the occupied value (Figure 1a). The sudden control error from this setpoint step-change forces control loops to wind up, simultaneously pushing all zones into full heating, with many hot water reheat valves driven fully open and airflows driven to heating maximums. This also often coincides with the heating plant first starting up each day, adding the load to warm up all of the water in the piping system to the hot water supply temperature setpoint. Recovering as fast as possible results in creating as large of a peak heating load as possible (Figure 2a).

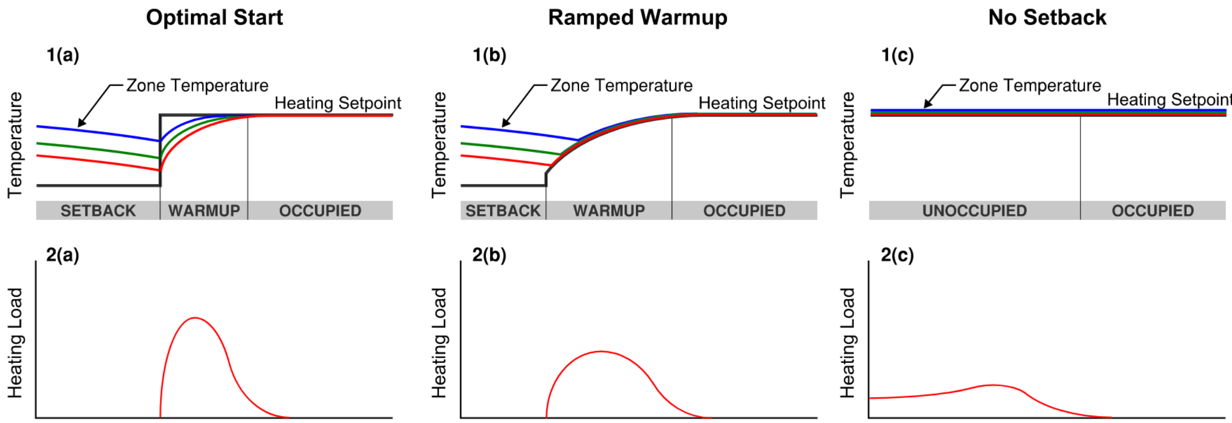

Figure 1 - Morning Warmup Strategies

Figure 2 – Associated Heating Loads

Simplified illustrations of different warmup strategies and the associated heating loads. Conventional morning warmup incurs a step change in heating setpoint prior to occupancy (Figure 1a) to recover space temperatures as fast as possible, resulting in a high peak heating load (Figure 2a). In Figure 1b, the warmup mode begins earlier and employs a ramped setpoint rise, which reduces the peak heating load (Figure 2b). In the extreme case with no night setback (Figure 1c), a constant heating setpoint is maintained, eliminating the morning recovery load (Figure 2c).

Issues with conventional practice

Warming up a building as fast as possible, however, may not be the most energy efficient or cost-effective strategy with modern HVAC systems. Much of the original research around night setback and optimum start is decades old, based on studies of buildings with relatively poor envelopes, prior to the widespread use of modulating capacity control in HVAC equipment, like variable speed drives for fans and modulating boilers. In newer construction, envelope losses are minimized with high-performance glazing, improved insulation, and sealing. Fans and heating systems generally also operate more efficiently at part load conditions.

There are potentially many downsides with conventional morning warmup practices that may outweigh their intended benefits:

- Brief periods of peak heating demand may drive a hot water plant to stage on additional equipment, with negative efficiency impacts if the lag equipment then cycles off quickly. In addition to pre- and post-purge losses for boilers, significant heating energy is required to warm up the thermal mass and water in a lag boiler, and that heat is then lost to the environment if the lag boiler stages back off soon after[5].
- Peak heating demand can drive hot water supply temperature setpoints to reset up to the maximum limit (e.g., when using demand-based setpoint reset logic per Guideline 36), resulting in lower equipment efficiency for condensing boilers (due to higher boiler entering water temperatures that prevent or reduce condensing) or air-to-water heat pumps (due to lower efficiencies at higher leaving hot water temperatures). Data gathered from a broad collection of buildings with condensing boilers shows that many operate at temperatures above the condensing region for most or all of the time[6]. Previous research also determined that losses through hot water distribution piping may make up a significant fraction of total hot water loop energy and are greater at higher supply water

temperatures[7, 8]. Depending on where and when these losses occur, they may be detrimental to energy performance.

- Where heating is provided by electricity (particularly electric resistance), heating loads during morning warmup may set the building peak electrical demand and may strain regional electric grids, with a potentially significant impact on first cost for increased electrical service in winter-peaking climates, and on energy costs depending on utility rate structures (e.g., high peak demand charges or ratcheting rates). Already a risk today in regions dominated by electric heat, this is likely to become an increasing concern as more buildings transition to have all-electric HVAC systems.
- Building heating loads generally peak during the warmup period. If warmup loads can be consistently reduced, designers can potentially be more aggressive in equipment sizing, particularly in retrofits of existing buildings where measured loads may be available. Conventional practice for sizing heating equipment assumes unrealistically conservative conditions, sometimes with additional safety factors[1], and with designers subsequently selecting the “next-size-up” boiler equipment. By conventional practices, there is little incentive for designers to “right-size” boilers as the incremental first cost for larger equipment is minimal whereas the consequence of having insufficient capacity is readily obvious to building occupants and operators. However, "right-sizing" boilers may appreciably improve annual efficiency and equipment longevity by reducing the amount of time spent short cycling at loads below minimum turndown limits. Data gathered from hundreds of boiler plants across the country indicates that a majority operate at very low part loads, with many likely cycling below minimum turndown limits for much of the time[6]. The same dataset shows that the vast majority of these are oversized for the actual peak heating load encountered in the building, typically by a factor approaching two. For air-to-water heat pump plants (AWHP), equipment sizing has a much more significant impact on first costs and space requirements, and may also affect electrical system service sizing.

In practice, optimum start algorithms often are not tuned or set up correctly, resulting in a high frequency of installations where the logic is disabled in favor of fixed, conservatively early start times to consistently ensure recovery in time at the expense of increased annual energy consumption.

A Better Approach

Considering the driving factors for avoiding peak heating loads during morning warmup, a practical alternative is to employ a ramped setpoint trajectory (e.g., exponential decay) that gradually increases the heating setpoint from the unoccupied to the occupied level (Figure 1b). Starting warmup earlier and gradually ramping the heating setpoint allows for a slower, paced recovery with a reduced peak heating load (Figure 2b). With this approach, each individual zone will enter heating mode at a different time depending on when its temperature intersects with the ramped setpoint, thereby further spreading out the heating demand (as opposed to having every zone simultaneously enter heating mode). This alternative approach may reduce fan energy by allowing VAV systems to operate at lower airflows, and reduce heating energy use by allowing for operation at lower water temperatures (with the associated improvement in equipment efficiency and reduction in distribution losses), and potentially avoiding cycling on lag equipment.

[1] The 2021 ASHRAE Handbook of Fundamentals suggests that oversizing factors of 20 to 25% for warmup and safety are common.

In the extreme edge case, maintaining a constant heating setpoint at all times (Figure 1c) completely avoids the morning recovery load (Figure 2c). The peak heating load is greatly reduced with just a smaller peak corresponding to envelope losses and perhaps conditioning outdoor air during the coldest time of day. However, this strategy does result in increased envelope losses from the space to the outdoors during the unoccupied periods since higher space temperatures are maintained.

For buildings considered for electrification retrofits, a major barrier is delivering sufficient heating capacity with the lower supply water temperatures that heat pumps can produce, typically around 130°F (54°C) compared to 180°F (82°C) for gas-fired boilers. Replacing distribution piping and heating coils to accommodate lower supply temperatures may be prohibitively expensive and disruptive. However, these modified morning warmup control strategies offer the potential to avoid these costly replacements by reducing peak heating coil loads and recovering more slowly instead at lower supply water temperatures.

Field Testing

Figure 3 – Demonstration Site
(photo: Los Medanos College)

Three alternative morning warmup strategies were tested at an academic building in northern California (ASHRAE climate zone 3B) in the spring of 2023. Constructed in 2020, the building houses classrooms, laboratories, faculty offices, and a student center in separate wings across the single story, 55,000 ft^2 (5100 m^2) facility. Each of the four wings is conditioned by a separate VAV reheat system with airside economizers, with hot water generated by a plant with two condensing boilers. The laboratory HVAC system operates 24/7 with 100% outdoor air and was excluded from the intervention, though its energy use is included in the monitoring data. The three strategies tested were:

1. Setback: The first strategy evaluated was the setback and warmup control strategy that was programmed in the existing control system. Though this approach included a setpoint ramp per Figure 1b, the ramp was not tuned and the warmup mode was limited to 1.5 hours prior to the start of occupied mode so the recovery was effectively compressed into a relatively short time period.
2. Long Warmup: This approach used the same ramped control logic, but the warmup period was extended to 3 hours and the optimal start tuning was adjusted to utilize the full period.
3. No Setback: As an edge case, the unoccupied heating setpoint was set equal to the occupied heating setpoint to effectively eliminate setback operation and the morning recovery load.

Figure 4 shows the heating setpoints (solid lines) and actual zone temperatures (dashed lines) for the three control strategies evaluated. Data are from days with similar average morning temperatures of about 48°F as indicated in Figure 5. The setpoint ramps for the Setback and Long Warmup approaches vary slightly each day based on ambient conditions and the resulting heating loads also vary based on how much each zone needs to recover. Note that the full setpoint step-change that is the dominant standard practice was not evaluated because the testing was performed with only setpoint and parameter adjustments for simplicity and the control system was already configured for “ramped” warmup per Figure 1b.

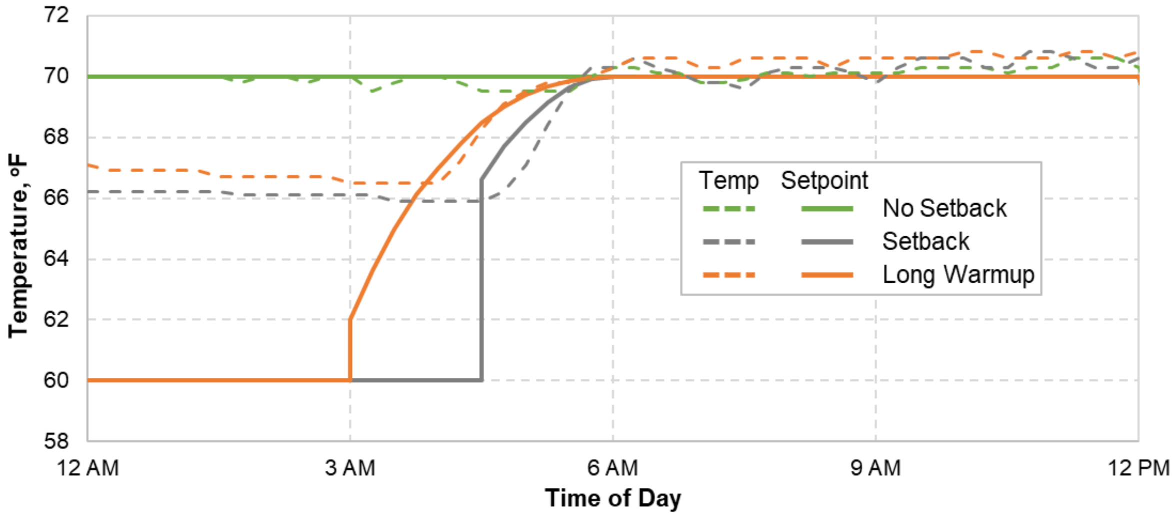

Figure 4 - Three Warmup Strategies

Zone Heating Setpoints for the three different warmup strategies in solid lines. Dashed lines show actual temperatures for a given day for each approach. Occupancy begins at 6 am.

As expected, the Long Warmup and No Setback approaches both reduced peak heating load compared to the baseline Setback approach. Figure 5 shows the peak heating load for the whole building plotted against the average outdoor air temperature (OAT), with each data point evaluated over the period from midnight to 6 am each day. The peak heating load correlates well with the average OAT for the Setback approach (shown in gray). Though there were only a few days where the No Setback approach was tested, the results consistently show (in green) a dramatic reduction in peak heating load of about 18 Btu/h-ft^2 (57 W/m^2) compared to the baseline Setback approach. This roughly represents the maximum reduction in peak heating load that can be achieved based on modified warmup control strategies. The Long Warmup approach also significantly reduced peak heating load, but more so on colder mornings. The diminishing reduction for warmer mornings is because the optimal start delays the onset of warmup mode on those days. Note that the absolute heating loads are relatively high in all cases here because they include the ventilation and recovery loads for the laboratory system, which operates continuously but does employ night setbacks. Again, the laboratory system controls were unchanged throughout the study.

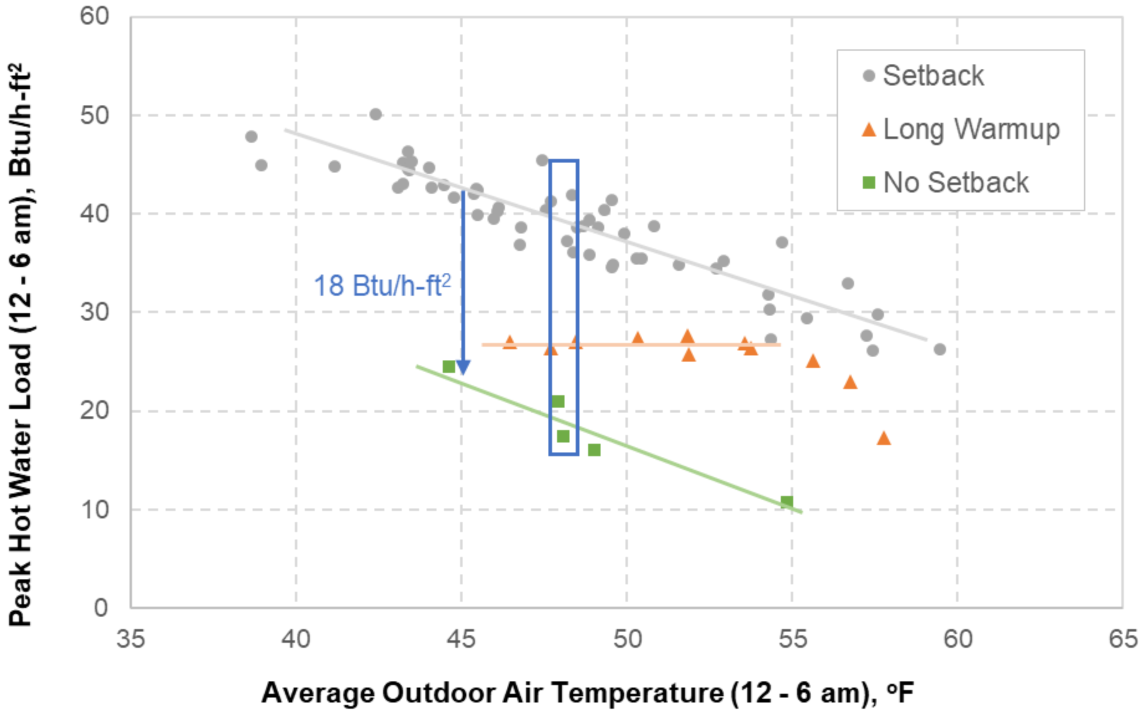

Figure 5 – Peak Heating Loads as a Function of Average Outdoor Air Temperature

Though the scatter plot in Figure 5 shows clear reductions in peak heating loads, it is easier to visualize and understand the impact of the different warmup strategies by observing the heating load profiles (Figure 6). So that the recovery loads are comparable across the different strategies, the load profiles shown are for weekdays where the average morning outdoor air temperatures were about 48°F (identified by the blue box in Figure 5). The Setback approach incurs the highest peak loads, with peaks just prior to the start of Occupied mode. Though only two days of data were available, the heating loads for the Long Warmup mode were consistent, starting earlier and with a significantly reduced peak. The heating load for the No Setback approach was nearly flat with the recovery load effectively eliminated (except for the laboratory wing) and achieved even further reductions in the heating peak.

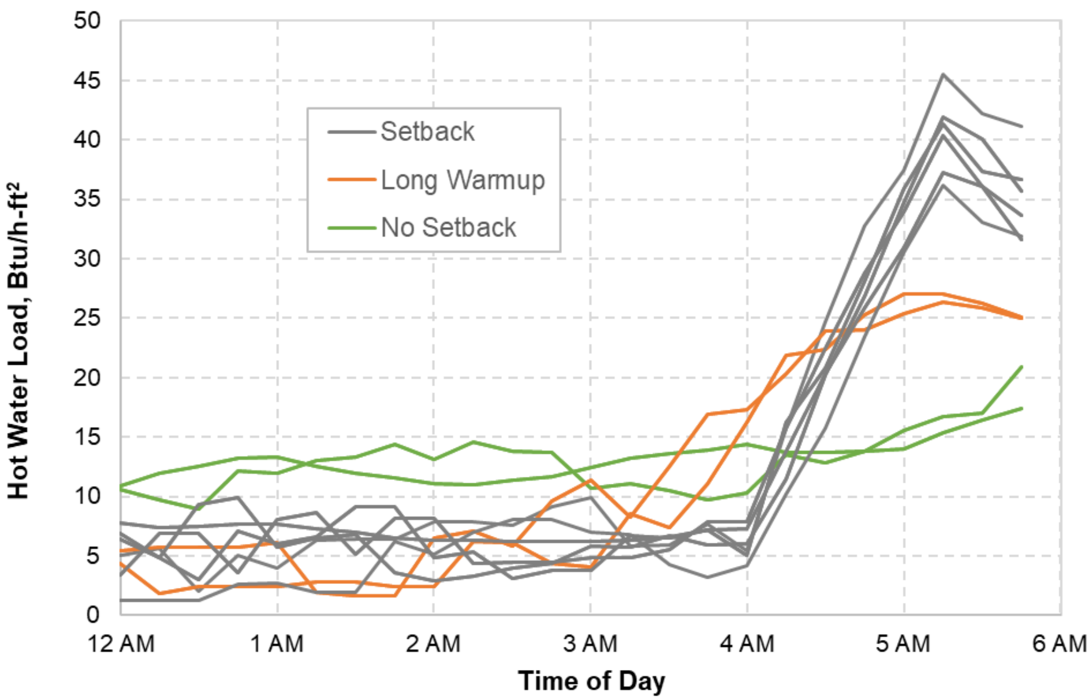

Figure 6 – Heating Load Profiles for the Three Warmup Strategies

The heating energy consumption was also evaluated for the different warmup control strategies. Figure 7 shows the total overnight (9 pm to 6 am) heating energy use as a function of the average outdoor air temperature. As expected, the No Setback approach incurs significantly higher heating energy use to overcome the increased envelope losses. Though only limited data are available, there was little difference in heating energy between the Long Warmup and baseline Setback approach. Though the Long Warmup approach did not measurably *reduce* heating energy use in this testing, this is an important result because this strategy achieved a significant reduction in peak heating load without incurring a measurable *increase* in heating energy. The reduction in peak heating load would likely be greater if evaluated against a conventional step-change setpoint approach (Figure 1a), whereas the baseline Setback strategy here employed some degree of a ramped setpoint change (Figure 1b). Also, the hot water plant controls were not altered or tuned during this intervention to take advantage of the increased opportunity for improved plant performance, and the existing settings largely prevented condensing operation. For buildings with electric heat, the reductions in peak heating load have the potential to reduce operating costs through reduced peak demand charges.

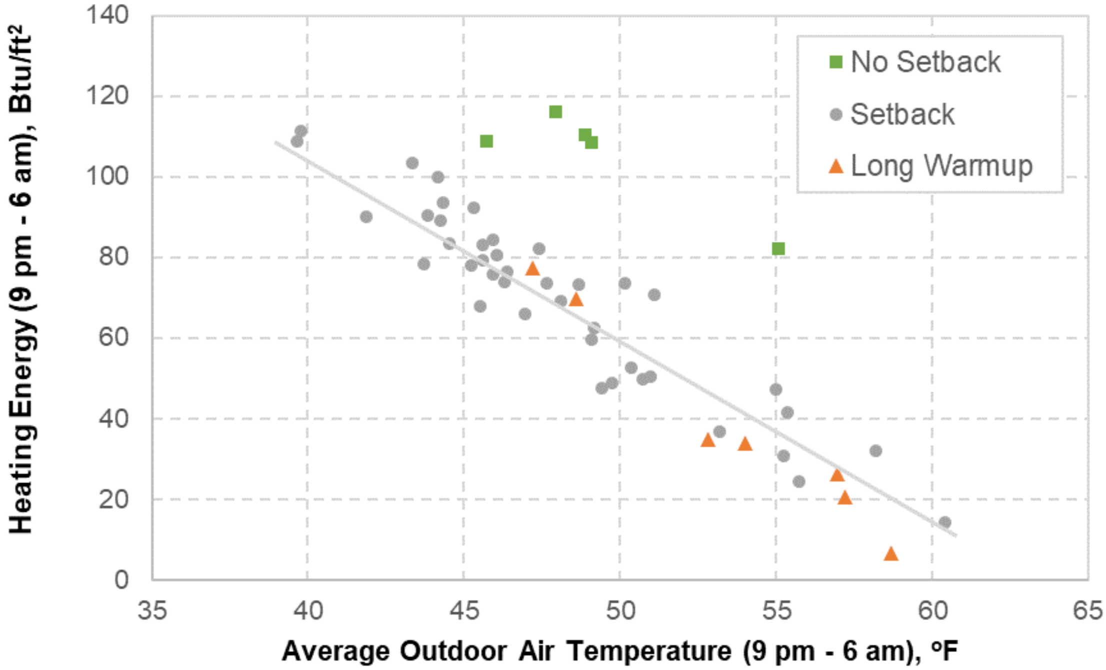

Figure 7 – Heating Energy Use for the Three Warmup Strategies

In addition to the impact on heating energy and loads, alternative warmup strategies present an opportunity to reduce fan energy. Figure 8 shows the total supply fan power for the different strategies across the same comparable mornings shown in Figure 5. The Long Warmup approach reduced fan power compared to the Setback approach, with about 10% fan energy savings (though based on very limited data). The No Setback approach had the lowest fan power but increased fan energy consumption because of the longer runtime.

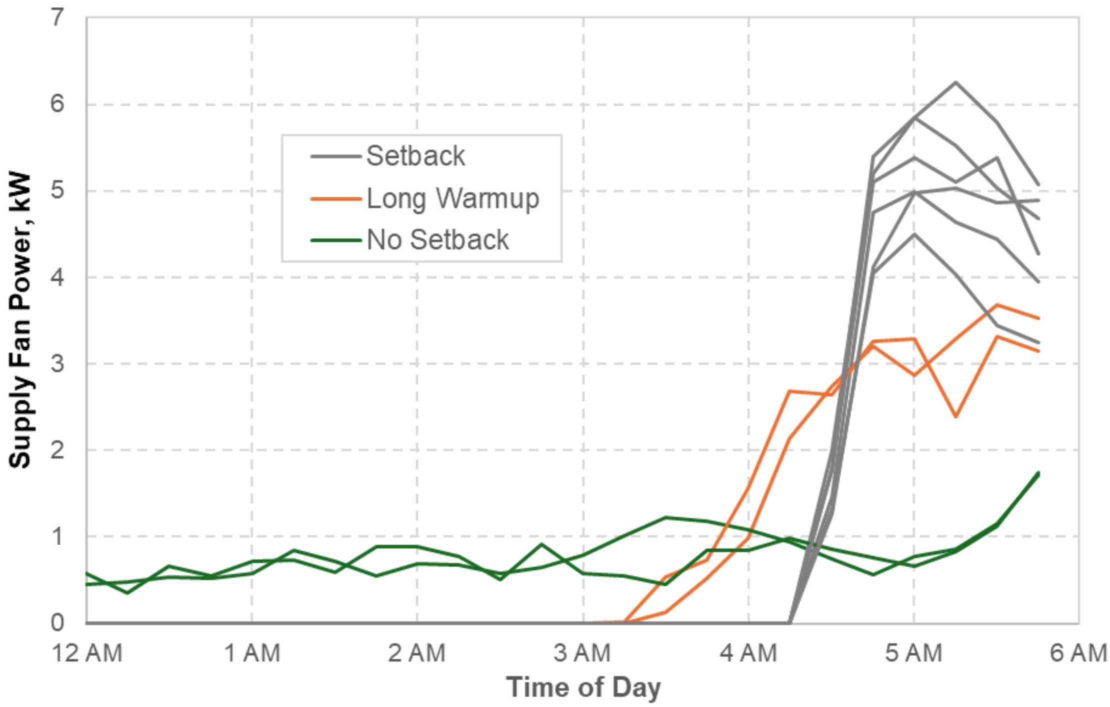

Figure 8 – Fan Power for the Three Warmup Strategies

Conclusions

This pilot testing was limited in duration and had relatively few days of operation for the two alternative warmup strategies because the study was initiated in spring and there were limited cool nights available for testing. Though more extensive study is needed to expand on this work and better understand its implications across different climates and HVAC system types, this limited field testing confirms the potential for significant reductions in peak heating loads. The ramped warmup strategy is the default approach in the building automation system installed in this test building – it is readily available for this platform and for replication in others but unfortunately in the authors' experience is often left untuned or adjusted to leverage its potential benefits. With basic tuning and a longer duration, the ramped warmup strategy can provide better assurance of achieving comfort by the start of occupied mode, potentially without the energy penalty of the step-change approach and without the risk of not recovering in time because of imperfect optimal start. Most building controls systems use the standard step-change approach, and this is what is described in Guideline 36, but these could be modified to use a ramped strategy with relatively simple programming changes.

Improving HVAC heating system performance in setback and warmup modes is of great urgency with increasing interest and mandates to reduce fossil fuel consumption in buildings, and with the rapid pivot to building electrification in some areas of the country. When deployed with effective heating plant control sequences (e.g., Guideline 36), there may be opportunities for improved heating efficiency as well. More importantly, the reduction in peak heating loads at both the plant and the zone levels may help overcome challenges with electrifying the building stock. The reduced plant peak loads may allow for more aggressive equipment sizing, reducing first costs, reducing equipment space requirements, and minimizing the impact on building electrical infrastructure. The reduced zone coil heating loads have the potential to allow existing hot water pipe distribution and heating coils to be reused for heat pump retrofits with lower supply water temperatures (avoiding prohibitively expensive and invasive distribution and coil retrofits). On the coldest days of the year in cooler climates where envelope loads alone may require all of the reduced coil capacities at lower supply water temperatures, applying the No Setback approach may even be an effective way to maintain comfort conditions without costly and disruptive infrastructure replacements. Lastly, for buildings with electric heat, the improved morning warmup strategies may reduce winter demand charges. In areas where time-of-use utility tariffs have morning peak periods in the winter (of which there will be more in the future as more buildings are electrified), improved morning warmup strategies have the opportunity to reduce both energy and demand charges, and reduce strain on electrical grids. Future study should examine how different warmup strategies may better achieve varying objectives, whether minimizing energy cost, peak heating load, peak electrical demand, or marginal carbon emissions, and consider suggesting revisions to Guideline 36.

Acknowledgments

The authors are grateful to Michael Schenone formerly at Los Medanos College and Tracy Marcial at the Contra Costa Community College District for supporting this research and generously allowing this testing to be performed at their facility.

This work was partially funded by the California Energy Commission through its PIR-19-013 grant to the University of California Berkeley.

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[1] ASHRAE. 2022. ANSI/ASHRAE/IES Standard 90.1-2022. Energy Standard for Sites and Buildings Except Low-Rise Residential Buildings.
[2] International Code Council. 2021. International Energy Conservation Code.
[3] California Energy Commission. 2022. Title 24, Part 6. Building Energy Efficiency Standards for Residential and Nonresidential Buildings.
[4] ASHRAE. 2021. ASHRAE Guideline 36: High Performance Sequences of Operation for HVAC Systems.
[5] Wang, J., Stein, J., Choi, K. Mustacich, P., Waltner, M., Achong, G. 2022. Boiler Research Project Final Report In Support of ASHRAE Standard 155P. PG&E.
[6] Raftery et al, in press
[7] Raftery, P., Geronazzo, A., Cheng, H., and Paliaga, G. 2018. Quantifying energy losses in hot water reheat systems. Energy and Buildings, 179: 183-199. https://escholarship.org/uc/item/3qs8f8qx
[8] Raftery, P., Vernon, D., Singla, R., and Nakajima, M. 2023. Measured Space Heating Hot Water Distribution Losses in Large Commercial Buildings. https://escholarship.org/uc/item/46h4h28q