Challenges and Opportunities for HVAC + Phase Change Material Thermal Energy Storage in Buildings

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ABSTRACT

Phase-change material (PCM) thermal-energy storage (TES) integrated with HVAC and domestic hot water (DHW) can shift a large share of building thermal loads. By flattening and shifting loads, PCM TES reduces peak electricity use, eases stress on local and grid infrastructure, and lowers costs. It can also defer costly upgrades to service panels, distribution, and transmission. Higher energy density relative to chilled or hot water storage makes PCM TES practical for small, space-limited, and retrofit projects, while packaged HVAC-integrated systems expand cost-effective load shifting to commercial buildings that previously lacked options.

Despite this promise, deployment faces barriers. This paper presents challenges, opportunities, and lessons learned from lab and field integrations of PCM TES with packaged HVAC systems. Key challenges include misalignment between default heat pump controls tuned for direct-to-load operation and TES charge/discharge objectives, PCM properties that diverge from manufacturer claims and evolve with cycling, and high integration and deployment costs with off-the-shelf products. These studies underscore the need for factory-built, integrated systems that arrive as prepackaged modules with proven controls, reducing design and installation effort and delivering predictable performance across projects.

The paper outlines steps to enable viable and scalable PCM TES HVAC and DHW systems, including 1) validated methods that can be used to characterize PCM properties and TES system performance, 2) supervisory controls that optimize charge/discharge scheduling, and 3) factory-integrated packaging that eliminates bespoke field engineering.

Introduction

The Load Shifting Opportunity

The U.S. building sector accounts for approximately 40% of national primary energy consumption, with roughly 60% directed toward thermal end uses: space heating, cooling, and domestic hot water (DOE 2021). The high cost of electric rates is primarily driven by infrastructure costs. The infrastructure has to be able to support the highest peak demand and is underutilized the rest of the time, typical US utilization factors are between 50 and 60% (DOE 2024). This creates a mismatch between utility costs and the energy that they charge customers (per kWh or BTU). There is a large opportunity to lower the rates paid by utility customers (and thus reduce their bills) by increasing utilization by shifting loads from peak times to off-peak times (Norris 2025). Thermal energy storage (TES) offers a direct solution by decoupling the time that energy is taken from the grid from when it is used in a building.

Building HVAC System Architectures and Thermal Storage

A "combi" (combination) system consolidates space heating, cooling, and domestic hot water onto one or more heat pumps (HP), which include air-to-water heat pumps (AWHPs) with hydronic distribution, or air-to-air. Hydronic systems are preferred for HP+TES integration because water provides a convenient heat transfer medium between the HP, TES, and multiple end uses (space heating, cooling, DHW) through simple valve switching (Woolley et al. 2024). Thermal storage can be added to a combi system using water tanks or, at higher energy density, PCM modules that charge and discharge through the same hydronic loop. This allows a single HP to serve space conditioning and hot water loads while shifting consumption to off-peak periods (Helmns et al. 2022).

The Deployment Gap

Despite these advantages, PCM TES remains far from mainstream deployment. Among 75 customer discovery interviewees across the multifamily building value chain, 55% cited upfront cost as the primary barrier to HP adoption, and 69% of building owners identified first cost as the dominant decision factor (TRC/LBNL 2024). A 2024 DOE-sponsored meeting with approximately 80 stakeholders, identified the lack of standardized TES metrics as a top-level barrier (Gluesenkamp et al. 2025).

Paper Scope and Contributions

This paper makes three contributions to the emerging field of building-integrated PCM TES. First, it documents specific technical challenges encountered during field deployment of HP+TES systems, providing practical lessons that are absent from the simulation-focused literature. Second, it identifies opportunities for overcoming these barriers through validated testing methods, supervisory controls, and factory-integrated system design. Third, it offers actionable recommendations for manufacturers, utilities, and researchers to accelerate the transition from bespoke prototypes to scalable products. The findings draw on two field deployments and supporting laboratory and simulation research:

1. The LBNL/Stanford HVAC+PCM TES prototype deployed at the Agramonte Ranch Research and Conservation Center (ARC), a microgrid-connected site in Half Moon Bay, California. The microgrid context amplifies the consequences of control decisions, as every kWh of misaligned demand directly affects system stability and distributed energy resource coordination (Dutton et al. 2026).
2. The DOE Cost Compression for Cold Climate HPs (CCC) project, which included a residential combi system pilot in Colrain, Massachusetts, and supporting cost analysis and system design work (Woolley et al. 2024).

Background and Prior Work

Phase-change materials store and release thermal energy through solid-to-liquid phase transitions at substantially higher energy density than sensible (water) storage. Salt hydrates and organic PCMs with transition temperatures between 20 and 60°C are suitable for building HVAC applications (Akamo et al. 2023; Li et al. 2022). Despite growing R&D interest, the gap between laboratory demonstrations and field-validated HVAC-integrated systems remains large. Most published work reports simulation results or component-level tests; few studies document the practical challenges of integrating PCM TES with HPs in occupied buildings.

Recent field and laboratory work has demonstrated HP+TES systems across a range of scales and climates. Field demonstrations include grid-interactive HP+TES in commercial buildings achieving 46% average annual load shift savings (CEC 2025), residential pilots in Maine and California (GridWorks 2024a), and M&V studies of hot water TES with HPs (NREL 2025). Valuation studies indicate that current utility methods undercount TES benefits by 38 to 57%

(WCEC 2024). However, few of these projects have published detailed accounts of integration challenges encountered during deployment.

Domestic hot water is a compelling application for combi HP+TES, especially in cold climates where AWHP heating capacity decreases at low ambient temperatures. PCM TES bridges the capacity gap by charging whenever the HP has spare capacity (off-peak or part-load) and discharging during peak demand, decoupling heat-pump output from instantaneous load (Helmns et al. 2022).

Systems and Field Deployments

LBNL HVAC+PCM TES Prototype at Stanford ARC

The first system is a HVAC+PCM TES prototype developed by LBNL and deployed at the Agramonte Ranch Research and Conservation Center (ARC), a single-family residential structure on a microgrid-connected campus in Half Moon Bay, California. The system uses dual PCM TES units: one with a high melting point (~50°C) for storing heat, and one with a low melting point (~11°C) for storing cooling capacity. This dual hot/cold configuration enables year-round load shifting for both heating and cooling modes (Dutton et al. 2026).

System Architecture

The system comprises three main subsystems: (1) a Viessmann AWHP (Viessmann 2025) with 6 kW heating and 5 kW cooling capacity (Vitocal 100-AW AM2V 020028; heating rated at 7°C OAT, 35°C supply, ΔT 5°C; cooling rated to AHRI 550/590); (2) Briza Jaga fan coil units (JAGA 2025) for air-side heat exchange; and (3) a hydronic rig containing balance of plant, including hot and cold PCM TES, pumps, valves, and controls (Figures 1 and 2). The thermal storage consists of two Sunamp PCM units (Sunamp 2025): one at 11°C for cold storage (Ester-based PCM) and one at 50°C for hot storage (sodium acetate trihydrate-based Plentigrade). The controls architecture uses a WAGO PLC (WAGO 2025) interfaced with an Intel NUC mini-PC running the supervisory control algorithm in Python via the PyModBus library.

Figure 1: Indoor view of the structure (left) with thermal energy storage and controls systems and fan coil unit; and outdoor view (right) with HP unit. Note the default PTAC unit (through wall) that the experimental HP TES replaces.

The system operates across eleven implemented PLC modes: Standby (M0); Charge Hot (M1), Use Hot TES (M2), Hybrid Charge Hot (M3), and Hybrid Use Hot (M4) for hot-TES operation; Charge Cold (M5), Use Cold TES (M6), Hybrid Charge Cold (M7), and Hybrid Use Cold (M8) for cold-TES operation; and Baseline Heat (M10) and Baseline Cool (M11) for direct heat-pump operation. The supervisory control determines one of four high-level actions: do nothing, charge hot PCM, charge cold PCM, or prioritize discharging PCM. The ARC site includes solar PV and a battery-inverter system, providing a controlled microgrid environment for evaluating HP+TES dispatch.

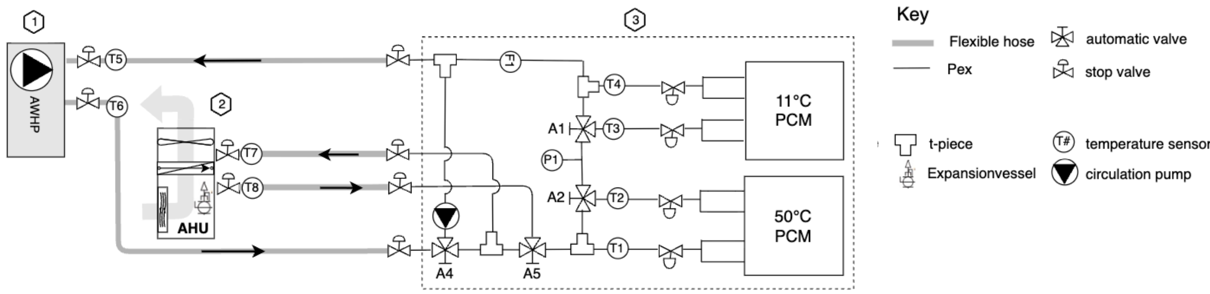

Figure 2: Schematic of the LBNL ARC HVAC-PCM TES prototype showing pipes, pumps, valves, and sensors between AWHP (1), fan coil in air-handling unit (AHU) (2), and dual hot and cold PCM TES (3).

ARC Field Testing

The rule-based control (RBC) algorithm manages TES charge/discharge using an "urgency score" framework that combines a calibrated building thermal model with solar generation forecasts (Fan et al. 2025). At each control interval, the algorithm evaluates zone temperatures, TES state of charge, predicted solar availability, and time-of-use rate periods, then makes discrete switching decisions to select among operating modes (e.g., direct heating, TES charging, TES discharging). By comparing forecast load profiles against available stored energy, the controller shifts consumption toward off-peak and solar-surplus periods without requiring continuous optimization. The measured hot TES capacity is approximately 6.9 kWh and the cold TES capacity approximately 4.7 kWh; further performance metrics are reported in Dutton et al. (2026).

An example of operational performance is shown in Figure 3. In the morning, when the night setback ends and heating is demanded, the TES is prioritized to heat the space, when that's depleted, the heat pump heats the space and charges the hot TES simultaneously (hybrid hot charge mode, with the air-to-water heat pump sized for the combined load at the 50°C hot-TES supply). After the setpoint is reached, the heat pump charges the hot TES exclusively. Once solar gain warms the structure, the system shifts to meeting cooling demand and charging the cold TES. In the evening, with no on-site power generation and a lower ambient COP, the system uses the hot TES exclusively for heating. This sequence is the intended operation: storage is charged when the heat pump can run efficiently and is discharged when conditions are less favorable.

Two further behaviors on the same day are worth flagging separately. The first was an unintended interaction that has since been corrected. In the midday cooling period the zone temperature tracked the cooling setpoint rather than dropping below it, because the system could not fully meet the cooling load: the cold TES and the AHU could not absorb cooling fast enough, so the loop water returning to the heat pump arrived already cold. The heat pump's internal controller saw no thermal load and held the compressor off, even though the supervisor was calling for cooling, while the circulation pump continued to draw cooling capacity out of the cold TES back into the heat pump and AHU. Supervisory logic has since been added that only permits loop water to enter the TES when it is colder than the TES (and the analogous rule on the hot side), preventing the TES from bleeding its stored capacity into a heat pump that is being held off. Additionally, an emergent benefit rather than a fault: the cold TES was charged on this heatingdominated day to act as a buffer that reduces heat-pump short cycling, taking advantage of an unseasonably warm winter day.

The second is that when charging the hot TES, the state-of-charge (SOC) initially drops as water that was warm but cooler than the hottest part of the TES, was able to enter the TES, reducing the SOC briefly. This behavior has since been addressed by ensuring that all three available temperature measurements in the TES are considered rather than using an average TES temperature to determining if the valve that allows TES flow should be opened.

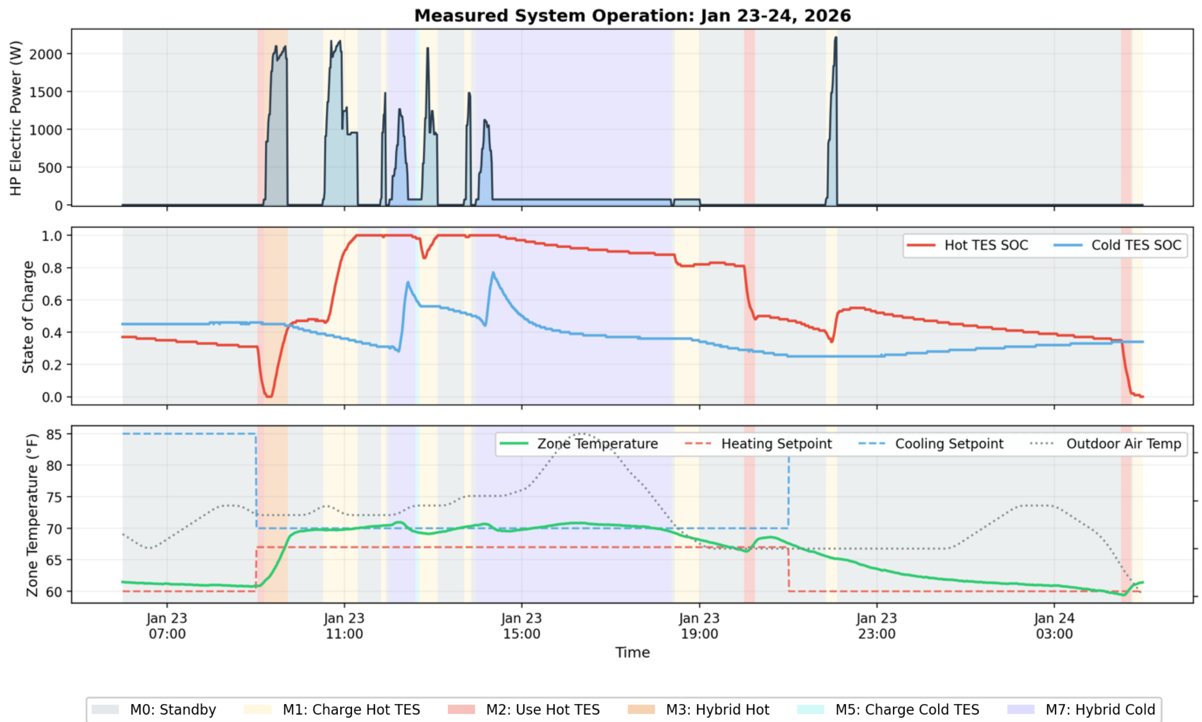

Figure 3: Measured 24-hour system operation at the ARC test site, 23–24 January 2026. Heat-pump electric power (top), hot and cold TES state of charge (middle), and zone air temperature with heating and cooling setpoints and outdoor air temperature on the right axis (bottom). Vertical shading indicates the active operating mode see legend.

More exhaustive details of system design, control issues and control resolution and performance are to be published prior to the publication of this paper, see Dutton et al 2026.

Cold Climate Combi HP + TES Pilot: Massachusetts Residence

The second system is a combi AWHP with PCM thermal storage, installed as a pilot in a single-family residence in Colrain, Massachusetts. This cold-climate site (IECC Climate Zone 6) provides demanding operating conditions for evaluating HP+TES performance, including low winter outdoor temperatures that derate AWHP heating capacity and COP, large heating loads characteristic of the climate zone, and the need to charge a PCM while serving load.

System Configuration

The system (Figure 4) comprises an LG Therma V variable-capacity AWHP (17 kW maximum heating capacity; LG 2025) coupled with two Sunamp UniQ PCM TES units (Sunamp 2025) and hydronic distribution serving both fan coils and radiant floor heating. A Caleffi HydroLink hydraulic separator (Caleffi 2025) decouples the HP and distribution loops, allowing independent flow control.

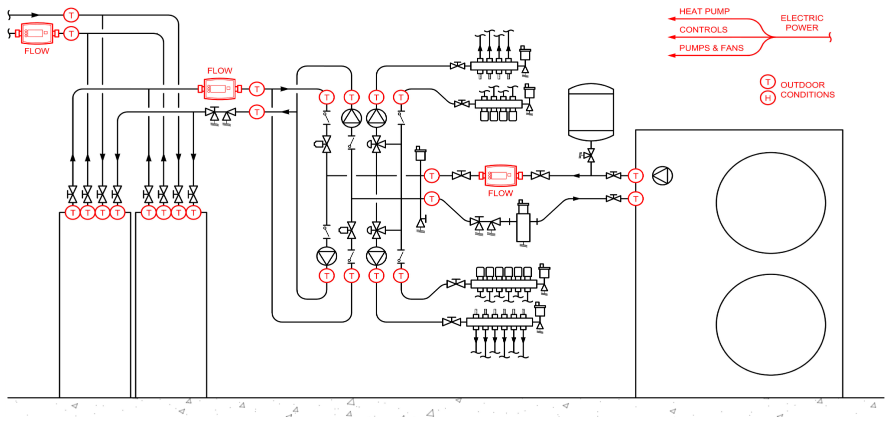

Figure 4: Schematic of the Massachusetts combi HP+TES system showing the AWHP (right), balance-of-plant with Caleffi Hydrolink (center), two Sunamp UniQ PCM TES units (lower left), radiant floor manifold M1 (lower center), fan coil manifold M2 (upper center), and DHW connections (upper left).

Phase Change Thermal Storage

The two Sunamp UniQ PCM TES units (Figure 5) use a proprietary sodium acetate trihydrate-based PCM with a phase change temperature of approximately 58°C. The sealed, factory-built construction avoids the air exposure and material degradation issues encountered with custom PCM assemblies (Woolley et al. 2024).

Figure 5: Massachusetts pilot installation. Left: LG Therma V R32 AWHP outdoor unit. Center: Sunamp UniQ PCM TES unit (white cabinet), Caleffi pump stations and balance-of-plant components. Right: JAGA Briza ductless hydronic fan coil unit.

Each unit is a Sunamp UniQ-12 providing approximately 12 kWh of storage; capacity was set by the availability of two donated units rather than by a load-matched calculation. Demand-shift hours are not reported because they depend on weather and load, and the charging challenges discussed below have prevented operational characterization.

Controls and Design Innovations

A notable innovation is the use of wireless communicating controls for all valves and pumps, enabling remote monitoring and supervisory control adjustments without on-site visits. This low-cost controls approach points toward practical supervisory control architectures for residential HP+TES see Woolley et al. 2024 for more details on this system.

Field Testing and Performance

The system was designed to operate in several modes: space heating (serving any combination of fan coils and radiant floor), water heating (charging the PCM TES while serving load), and PCM discharge. Of these, space heating and PCM discharge functioned as designed.

Charging the PCM TES has been the limiting issue, with two field-identified causes. The Caleffi Hydrolink hydraulic separator transfers heat between adjacent pipes, dissipating charging energy before it reaches the PCM and limiting how much heat-pump output actually lands in storage. The LG heat pump also exhibited unexplained control behavior during charging attempts, ramping up and then shutting off rather than holding output through the PCM phase change. As a result, the system does not currently fully melt the PCM TES, which limits available thermal storage capacity. These findings highlight how balance-of-plant choices and heat-pump control logic can constrain system-level performance in ways difficult to anticipate from component specifications alone.

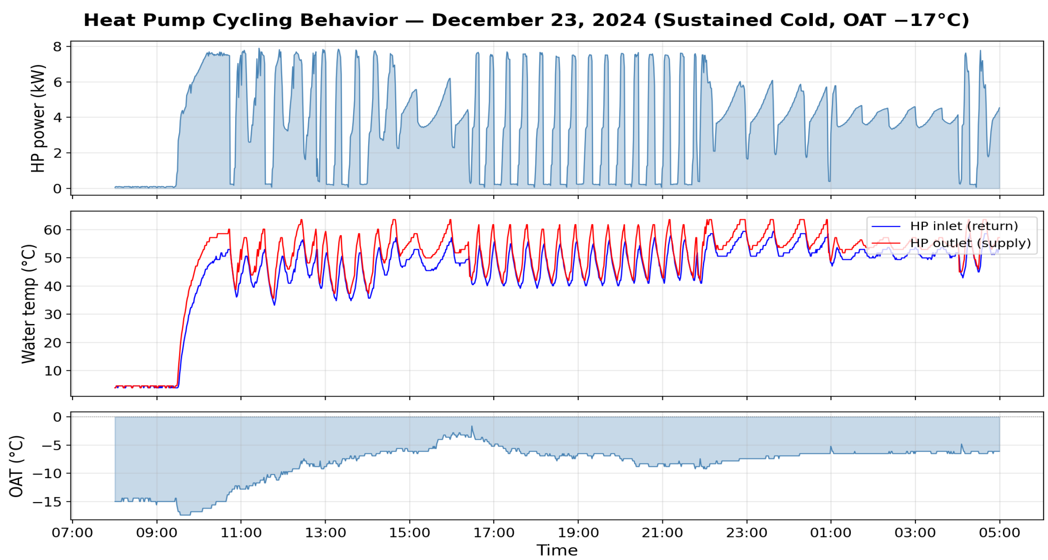

Figure 6: Field measured HP cycling at the Massachusetts pilot on a sustained cold day (December 23, 2024). Panels show (top) HP power, (middle) HP return and supply water temperatures, and (bottom) outdoor air temperature, which falls to approximately −17°C. Shaded fills under the power and OAT traces are for visual emphasis only.

The two pilots use different HP and PCM pairings: the LG (Massachusetts) is rated to 65°C maximum hydronic temperature and is paired with the 58°C Sunamp PCM, and the Viessmann (ARC) is rated to 60°C and paired with the 50°C PCM; both pairings are compatible by specification. The operational limitation reported here is on charging, not on discharging.

Challenges and Lessons Learned

This section presents five interrelated challenges identified through the field deployments and supporting research. Control misalignment (1) is exacerbated by PCM integration difficulties (2), both contribute to high costs (3), and all three are compounded by the absence of standardized metrics (4) and market barriers (5).

Controls Misalignment Between HPs and TES

The most pervasive technical challenge is the fundamental misalignment between off-the-shelf HP controls and TES integration requirements. Commercial HPs modulate compressor speed to maintain a thermostat setpoint, not to charge a thermal battery. The internal control logic is proprietary and unaware of TES state of charge, thermal demand forecasts, or grid price signals, creating a layered controls conflict: the supervisory control must work through (and often against) the HP's own logic.

At the ARC site, this manifests as excessive HP cycling. Return water temperatures run high as the PCM melts (51 to 55°C against a 50°C PCM temperature), limiting thermal energy transfer given a 60°C supply setpoint. The HP reaches setpoint quickly, shuts off, the temperature drops, and it restarts, reducing efficiency and increasing compressor wear (visible in Figure 3). Additional complications include non-uniform PCM melting that reduces temperature measurement accuracy from the three embedded thermistors, valve and pipe residual temperatures introducing transient errors, and mode-switching penalties as the system transitions between hot and cold operation. During midday periods with warm afternoons yet cold nights, the system switches between meeting cooling demand and charging hot TES for nighttime use, creating transition dynamics and dead periods during which the system cannot respond to changing loads. The HP's internal controller modulates on return water temperature, so managing the return-temperature trajectory is the principal control challenge. With a 50°C PCM melting against a 60°C supply setpoint, achieving a low enough return temperature to keep the unit running requires high heat-exchanger effectiveness, making this both a control and a heat-transfer problem partly addressable by raising PCM-side mass flow. The cycling visible in Figure 6 is itself the wear indicator: start/stop transients are a known source of compressor stress.

This reflects a fundamental gap in the HVAC industry's experience base, not merely a software challenge. Systems are built and tested based on anticipated use, and need either more flexible controls or user configurable parameters to allow for a wide range of applications including PCM-TES integration.

PCM Integration and Heat Exchanger Challenges

The second challenge involves PCM material and heat exchanger reliability in field conditions. Importantly, this is primarily a problem with custom-built systems using research-grade materials, not a fundamental limitation of PCM technology. Both field deployments used commercial Sunamp units, which performed acceptably; the more severe issues described below arose from a separate CCC research effort that fabricated custom PCM and heat exchanger (PCM/HX) assemblies to explore lower-cost designs.

The CCC custom PCM/HX assembly encountered several field-identified failure modes. Bulk salt-hydrate PCM was exposed to air during transfer, altering moisture content and shifting phase-change properties. The team later learned the material required periodic superheating to approximately 70°C to reset performance, temperatures unachievable with R290 AWHPs. Separately, push-to-connect fittings in the custom heat exchanger failed, allowing PCM to leak into and contaminate the hydronic loop and requiring extensive remediation. PCM was ultimately excluded from the CCC life-cycle cost analysis: if PCM TES requires in-unit electric resistance elements for reset superheating, it eliminates the main cost-compression potential, since the high-wattage elements would trigger apartment panel upgrades, the very cost the design sought to avoid.

The contrast with commercial products is instructive. Like commercial PCM products generally, the Sunamp units ship in sealed factory enclosures that avoid the air exposure encountered with custom research assemblies, and Sunamp's Plentigrade material retains 95% of its capacity after 40,000 cycles (Oliver et al. 2021; Oliver et al. 2024). The lesson is that PCM TES reliability depends on the entire system (material sourcing, containment, manufacturing quality, hermetic sealing), not just on the PCM itself.

A related challenge applies even to commercial products: observability. The Sunamp units do not allow full PCM temperature measurement throughout the storage volume, which makes SOC estimation unreliable and complicates supervisory control. A research group has recently developed a pressure-based SOC measurement (P-SOC) that leverages PCM volume changes during phase transition and could address this observability gap if commercialized (Rendall et al. 2024).

High Integration and Deployment Costs

Current HP+TES deployments are fundamentally bespoke: each installation requires custom engineering of piping, controls, electrical distribution, and commissioning. As Woolley et al. (2024) noted: "A notable barrier to adoption of AWHPs in the US is their relative complexity and the burden of bespoke design and installation that currently rests on the installing contractor."

The CCC cost analysis for an 18-unit multifamily building shows lifecycle savings of 12% in Climate Zone 6 ($535K vs. $607K) and 22% in Climate Zone 7 ($590K vs. $763K), driven primarily by $55K in electrical infrastructure savings from demand consolidation (TRC/LBNL 2025). However, these savings hinge on avoiding apartment panel upgrades, "the pivotal variable," which can swing savings from 22% to just 2%. In comprehensive retrofit projects where panel upgrades are triggered by broader project scope, the cost advantage is muted. Beyond equipment, bespoke integration introduces substantial soft costs (custom controls development, heat exchanger design) that could be amortized across production volumes in a factory-built product (Helmns et al. 2021b). The workforce dimension further amplifies costs: the CCC project documented "120 refrigerant leaks out of 124 apartments" with conventional mini-split installations, underscoring the need to "design for the labor force that is going to install it" (TRC/LBNL 2024). In addition to actual costs, any capital or operational savings must be sufficiently large to overcome resistance to change in a conservative industry. For developers, customer discovery interviews performed during the CCC project found that "2 to 3% project first cost savings is the minimum to get a developer to do something new." (TRC/LBNL 2024)

Representative Metrics, Testing, and Valuation Gap

Unlike HPs rated by SEER, HSPF, and COP under representative test conditions, TES has no equivalent performance metric. This was identified this as a top-level barrier by industry representatives (Gluesenkamp et al. 2025), and additional stakeholder interviews confirmed that manufacturers specifically need a new metric to represent TES benefits (Jayaprabha et al. 2024). Like many new and emerging technologies TES components lack recognition and classification in ways that are acceptable to the industry and building inspection professionals. There is no universally accepted test method for variable-speed AWHPs, meaning performance data relies on unvalidated manufacturer claims. Finally, a recent study found that utility valuation methods underpredict TES grid benefits by 38 to 57%, meaning TES is credited for only about half its actual load flexibility contribution (WCEC 2024).

Market and Rate Structure Barriers

HP+PCM TES "does not provide energy cost reductions with current winter residential TOU tariffs" (Helmns et al. 2022), limiting cost savings despite significant demand reduction capability.

Summer commercial TOU rates with large on/off-peak swings and demand charges are more favorable, explaining why cold PCM (ice) for cooling load shifting is far more common. The full economic value of TES is realized only when demand reduction incentives, deferred capacity costs, or wholesale market participation is included (Li et al. 2021). Customer awareness is a fundamental gap: 67% of multifamily decision-makers said nobody had spoken with them about HPs (Guidehouse/Cadeo 2022). Another recent study found awareness is the largest barrier in the commercial sector (Slipstream 2024). The split-incentive problem (owners pay for equipment, tenants benefit from savings) suppresses investment in multifamily buildings, compounded by emergency replacement dynamics that favor lowest first-cost options and limited contractor familiarity with HP+TES technology.

Opportunities

The challenges described in the previous section are not insurmountable. This section outlines three opportunities that form a pathway from custom-engineered prototypes to mass-deployable products. Each directly addresses one or more of the identified challenges.

Validated Testing and Characterization

Industry assessment metrics and procedures for PCM TES are emerging. Shete et al. (2025) developed dimensionless performance curves for latent heat TES that enable standardized comparison across geometries and PCM materials by normalizing to dimensionless parameters, building on earlier frameworks by (Helmns and Carey 2018). These curves represent a first step toward TES evaluation methods analogous to other HVAC components. Kumar et al. (2020) established that combined T-History and X-ray diffraction methods are necessary for proper PCM characterization, noting that previous literature attributed performance loss to phase segregation "without any scientific validation." We are now conducting laboratory work to address specific needs identified through field experience: long-duration cycling to detect degradation, temperature-controlled environments to isolate PCM behavior, and instrumentation for state-of-charge estimation in sealed products. Concurrently, we are conducting the first known experimental evaluation of R290 residential AWHPs, generating performance data that fills a critical gap for validating manufacturer specifications and calibrating simulation models.

Supervisory Controls

Rule-based control (RBC) serves as a practical near-term solution. However, even with dynamic rules, RBC struggles under the complexity and variability of real-world microgrid operation, where diverse weather and load scenarios quickly exceed the capacity of heuristic logic.

Model predictive control (MPC) addresses these limitations by solving real-time optimization using forecasts of weather, loads, and prices, applying only the first control action before receding and recomputing. Shi et al. demonstrated 36.9% energy savings over RBC (2022), and the first field validation of MPC for grid-interactive HP+TES (Qiao et al. 2024) confirmed these benefits translate to real-world performance. We developed an MPC mixed integer linear programming (MILP) algorithm for the ARC microgrid that uses a hierarchical approach: the upper layer allocates energy across battery, thermal storage, and direct load supply, while the lower layer enforces physical constraints and outputs optimized mode integers. Key tradeoffs include model accuracy versus computational efficiency (linear models are fast but oversimplify phase transition dynamics). The mismatch between continuous power flow optimization and discrete mode control also undermines the full effectiveness of MPC. MPC also requires accurate system parameters (power flows, storage capacity, heat losses, PCM properties), for which no calibration method exists.

Reinforcement learning (RL) offers a complementary model-free alternative. An RL agent learns optimal control policies, including discrete mode selections and continuous setpoint adjustments, through iterative interaction with a high-fidelity digital twin, circumventing MPC's parameter estimation challenge. The RL controller is under development, being trained in simulation before deployment to replace RBC at the ARC site.

System Design Improvements

The most consequential opportunity is the transition from custom-engineered, field-assembled HP+TES systems to factory-built, integrated products. Factory production enables scaled design, quality control, and volume pricing while reducing field labor and installation complexity.

Lower Cost System Components

R&D is ongoing to reduce the costs of PCM TES. A key innovation under development is a polymer-based PCM heat exchanger targeting approximately 40% cost reduction compared to copper-based products, using a cross-flow design enabling simultaneous charging and discharging (LBNL/ORNL 2024). The 40% is the CCC program's project-level cost-reduction goal rather than a value derived from a detailed cost analysis.

Modular Factory-Assembled TES Nodes

The modular TES node concept developed for the CCC project demonstrates how factory assembly addresses integration complexity. Each node is a factory-assembled unit containing buffer tanks, thermal storage (water-based, with provisions for PCM when validated), electric resistance backup, circulators, control valves, and an industrial control panel with internal breakers. A single electrical feeder per unit reduces field wiring to a simple connection, and Class II (low voltage) internal wiring minimizes the code compliance burden.

System Design Innovation for Commercial and Multifamily Applications

In larger buildings, modular configurations combining TES and HPs offer significant consolidation. LBNL and Aris Hydronics won a recent DOE Prize for a modular hydronic HP system providing heating, cooling, and hot water without individual in-unit electrical upgrades. This multiplexing architecture uses a small number of centralized HPs serving multiple dwelling units via hydronic distribution, dramatically reducing refrigerant connections and leak risk, outdoor unit count, within-unit electrical circuits, and skilled labor burden. Factory-charged HPs eliminate field refrigerant handling entirely, enabling installation by plumbers and general contractors, which is significant given the documented HVAC technician shortage and installation quality problems.

Toward a Packaged HP+TES Product

The ultimate goal is a fully packaged HP+TES product for mass manufacturing. Analogous to a rooftop unit (RTU) or vertical packaged unit (VPU), it integrates HP, PCM TES, hydronic distribution, and supervisory controls into a single factory-assembled enclosure. Key characteristics include:

- Integrated packaging: all components assembled and tested in a factory, arriving on-site as a single unit sized to local climate and tariff conditions.

- Grid-interactive controls: an integrated platform communicating with dynamic pricing servers and weather forecasts to optimize charge/discharge scheduling using MPC or RL strategies without custom per-site programming.
- Simplified installation: field work reduces to connecting ductwork (or hydronic piping) and electrical power, comparable to installing a conventional RTU.
- Serviceability: modular internal construction allows subcomponents to be removed for off-site maintenance or factory refurbishment.

This factory-built approach directly addresses the three cost drivers identified in the challenge section: it eliminates bespoke engineering by standardizing the product, reduces installation labor and skill requirements, and enables volume pricing through manufacturing scale. Figure 8 shows a conceptual design developed by LBNL. LBNL is currently engaging with potential industry partners to continue commercial development of this concept (Figure 8). The unit integrates an air-source HP (upper section with intake louvers), modular PCM thermal energy storage, hydronic distribution, and grid-interactive controls in a single outdoor enclosure

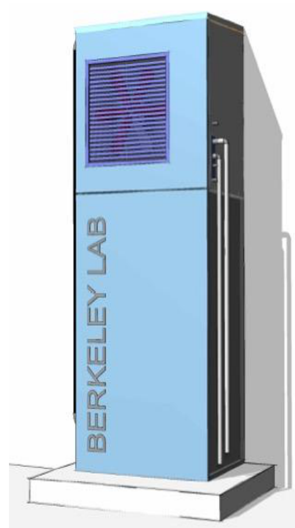

Figure 8: Conceptual design of a factory-built packaged HP+TES unit for small commercial buildings.

Conclusions and Recommendations

Summary

This paper examined five challenges and three opportunities for HVAC + PCM TES systems in buildings, drawing on two field deployment projects and supporting laboratory and simulation research.

The five challenges are:

1. Controls misalignment between HPs and TES: proprietary HP controls are unaware of TES state and grid signals, costing up to 37% in energy savings relative to optimized control.
2. PCM integration and heat exchanger reliability: custom-built systems experienced material degradation from air exposure and push-to-connect fitting failures, underscoring the need for factory-controlled manufacturing.
3. High integration and deployment costs: bespoke design and installation, with viability contingent on project-specific conditions and developer thresholds as low as 2 to 3% first cost savings.
4. Absence of metrics, testing protocols, and valuation methods: utility methods undercount TES benefits by 38 to 57%.
5. Market and rate structure barriers: winter TOU rates that do not reward load shifting, a 67% customer awareness gap, and split incentives in multifamily buildings.

The three opportunities are:

1. Validated testing and characterization methods, including dimensionless performance curves (Shete et al. 2025), T-History/XRD protocols (Kumar et al. 2020), and systematic experimental test plans bridging the gap between specifications and field performance.
2. Model-based supervisory controls, from practical rule-based approaches to MPC demonstrating 36.9% energy savings in field validation study (Shi et al. 2022), enabled by digital twin simulation frameworks.
3. Factory-built integrated products, including modular TES nodes with single-feeder electrical connections, polymer heat exchangers targeting 40% cost reduction, multiplexing architectures, and factory-charged HPs eliminating field refrigerant handling.

Thermal resilience is an additional benefit: a demonstration project in Maine showed a house with AWHP+TES maintained comfortable temperatures for 5 hours on the coldest day of winter with no grid electricity (GridWorks 2024b).

Recommendations

Based on these findings, we offer three key recommendations:

1. **For manufacturers**: invest in factory-integrated HP+TES products with open control interfaces, moving beyond component-level sales toward system-level solutions. PCM suppliers should deliver materials in hermetically sealed containers with cycle-life data from new test methods (T-History, XRD). The gap between manufacturer specifications and field performance requires the development of new testing protocols.
2. **For builders, designers and utilities**: develop classifications for TES that ease adoption and establish reliable performance maps for variable-speed AWHPs. Revise TES valuation methodologies to capture the full grid benefits currently undercounted by 38 to 57%. Develop winter TOU rates and demand response programs that compensate building-integrated TES for load flexibility.
3. **For researchers**: prioritize field validation of MPC for HP+TES systems, as the gap between simulation and field-demonstrated benefits remains a credibility barrier. Develop new performance metrics for TES (building on (Shete et al. 2025)). Investigate low-cost supervisory control architectures (ESP32 microcontrollers with cloud optimization) as alternatives to PLC-based systems.

Next Steps

Phase 3 testing at the ARC site will involve deployment of the RL-based supervisory control and the evaluation of its performance against the RBC baseline in a real microgrid environment. The Massachusetts pilot will continue generating operational data for combi HP+TES performance and controls optimization in a cold climate context, and work towards addressing the operational challenges. HP characterization will generate the first independently validated performance data and performance maps for variable-speed AWHPs modeling.

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