Field Evaluation of Duct Configuration Impacts on Variable- and Fixed-Capacity Heat Pump Distribution Efficiency

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ABSTRACT

One of the Central Valley Research Homes (CVRH) in Stockton, California provided a controlled yet realistic environment to quantify how duct configuration and leakage affect variable- and fixed-capacity heat pump performance. During the 2025 cooling season, the house alternated between two air-distribution systems - typical "as-found" attic ducts and short buried ducts - and two outdoor units, enabling direct flip/flop comparisons under identical simulated internal gains and thermostat schedules while the building-shell loads varied with outdoor weather.

A comprehensive instrumentation network, including calibrated orifices in both supply and return ducts, measured real-time losses disaggregated into leakage and conduction by duct section. This approach isolates leakage energy loss from conduction and provides minute-level data on distribution efficiency under dynamic operating conditions.

Results show that duct configuration dominates delivered efficiency. Buried compact ducts consistently achieved about 90 percent or better distribution efficiency, an “A-grade” performance, while typical attic ducts averaged 45 to 60 percent, equivalent to a failing grade. Leakage losses rose sharply with fan speed and attic temperature, while conduction losses primarily tracked attic heat and runtime duration. Buried ducts, in contrast, remained largely stable across all operating modes.

This field study provides one of the most detailed real-world characterizations of duct interactions with variable-capacity systems to date. The findings show that advanced heat pump technologies can meet their rated efficiencies only when coupled with high-performing, low-loss duct systems. This is an essential insight for residential retrofit programs and electrification policy design.

Introduction

Residential heat pump efficiency is typically communicated through laboratory ratings such as Seasonal Energy Efficiency Ratio 2 (SEER2) and Energy Efficiency Ratio 2 (EER2), which characterize equipment performance under steady-state conditions and assume idealized distribution systems. In practice, delivered cooling performance depends on the interaction of equipment controls, duct configuration, attic thermal environment, thermostat strategy, and time-varying loads.

Aggregated field metrics often obscure these interactions by averaging across operating and non-operating periods or reconstructing runtime indirectly from energy data. Minute-resolved field measurements provide an opportunity to directly observe delivered performance, losses, and operating behavior without reliance on duty-cycle assumptions. This study leverages that resolution to evaluate how equipment, distribution, and controls interact under real operating conditions.

This study builds on more than a decade of Central Valley Research Homes (CVRH) research (Proctor, Wilcox, and Chitwood 2018) by retaining the controlled occupancy simulation, dual-system experimental design, and comprehensive monitoring framework used in prior California field studies. It also extends earlier work on ducts in conditioned space and residential heat pump best practices by measuring duct leakage, conductive loss, equipment operation, and time-of-use effects at minute-level resolution (Hoeschele et al. 2015; Conant et al. 2023).

While this study focuses on a single home and climate, the Grange site was intentionally selected as a representative vintage slab-on-grade residence with severe attic thermal exposure, providing a stress test for common retrofit conditions documented in California home performance research (Chitwood and Harriman 2012).

Research Questions and Hypotheses

This study evaluates equipment effects, distribution system effects, thermostat control effects, and their interactions using minute-level operating data. The central hypothesis is that distribution system performance dominates delivered cooling outcomes, with equipment efficiency differences playing a secondary role under real-world conditions.

Specific research questions include:

- How do duct configuration and attic exposure influence delivered sensible efficiency and distribution system loss fraction?
- To what extent do equipment-level efficiency differences persist once distribution losses are accounted for?
- How does thermostat strategy alter runtime patterns and distribution system loss dynamics?
- How do combined equipment, distribution, and control choices affect peak-period energy use and cost?
- Does longer peak-period runtime imply higher operating intensity, or are runtime and intensity decoupled under variable-capacity control?

Experimental Design and Test Matrix

The study was conducted at the CVRH Grange site using two heat pump systems operated sequentially under controlled permutations of duct configuration and thermostat strategy across the June–September 2025 cooling season.

Systems were rotated on a fixed schedule (48-hour intervals) to ensure comparable weather exposure. The 48-hour rotation interval was selected as a practical balance between ensuring comparable weather exposure across configurations and allowing each system sufficient time to experience a representative range of indoor, attic, and outdoor thermal conditions. Shorter rotations risk over-weighting transient behavior, while longer rotations increase sensitivity to synoptic weather shifts. The chosen interval minimizes systematic bias while preserving operational realism.

Each system was evaluated under:

- Long / Leaky attic duct configuration
- Short / Buried duct configuration

Thermostat strategies included constant setpoint operation and scheduled cooling setup. The constant schedule maintained a 74 °F cooling setpoint during the constant test periods. The scheduled setup case used an 82 °F setup from 7:00 AM to 4:00 PM during the setup/schedule test periods, followed by recovery to the occupied setpoint. All configurations were operated over sufficient durations to capture a wide range of outdoor and attic thermal conditions, including hot afternoon and peak-period operation.

In this study, "short / buried" ducts refer to a minimized-length attic distribution system routed with reduced surface area and covered by attic insulation to limit thermal exposure; this configuration represents a practical improvement over conventional suspended attic ducts.

Instrumentation and Measurement Context

The instrumentation deployed at the CVRH Grange site provides unusually high temporal resolution and system visibility for a residential field study. Direct measurement of electrical input, controlled imposition and measurement of duct leakage, and distributed, precise air-side temperature and relative humidity sensing allow losses to be quantified in a manner rarely available outside laboratory environments. This enables system-level performance characterization that bridges the gap between lab ratings and real-world operation.

A network of precision calibrated prototype flow-measurement devices (FMDs) was installed throughout the distribution system, including the supply plenum, supply boots, and a dedicated attic-to-return leakage path. Each FMD is computer-controlled, allowing leakage to be precisely set and continuously measured. Thermocouples at each FMD location monitor air temperature continuously, enabling calculation and disaggregation of conductive and leakage-related heat losses.

The same sensors, calibration methods, and signal processing were applied identically across all system configurations. This enables robust relative comparisons between configurations. Differences reported in sensible efficiency, distribution losses, runtime, and cost reflect true operational contrasts rather than measurement artifacts.

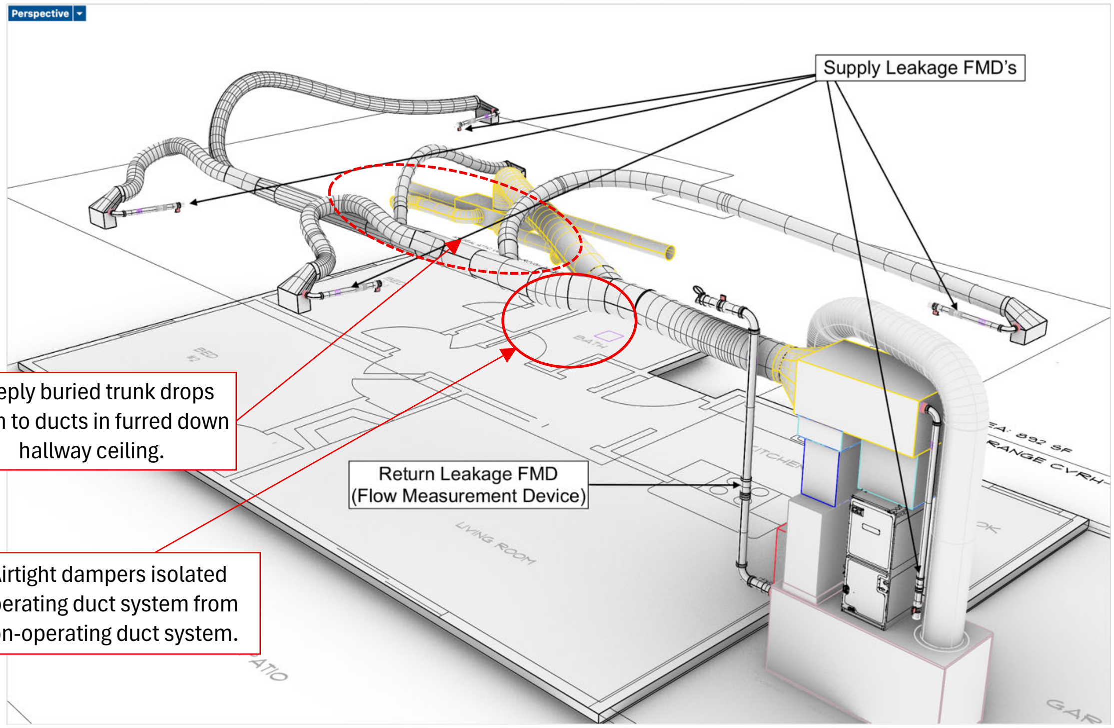

Figure 1. Attic duct system used in experiment, showing location of flow measurement devices.

Definitions, Filters, and Calculations

All performance metrics are derived exclusively from minute-level operating data. Restricting all comparisons to identical operating minutes ensures that observed performance differences reflect system behavior rather than differences in weather exposure, runtime reconstruction, or duty-cycle assumptions.

- **Operating minute:** A one-minute interval during which the system is actively cooling and all required measurements are valid.
- **Coil sensible cooling:** Calculated sensible cooling output at the coil.
- **Delivered sensible cooling:** Coil sensible cooling minus equivalent distribution losses.
- **Coil sensible EER:** Coil sensible cooling divided by electrical energy input.
- **Delivered sensible EER:** Delivered sensible cooling divided by electrical energy input.
- **Equivalent distribution loss energy:** Electrical energy required to produce cooling lost to the distribution system.
- **Time-of-use (TOU) cost:** Minute-level electrical energy multiplied by the applicable Pacific Gas and Electric Company (PG&E) E-TOU-C summer rate.

Peak-period analyses evaluate daily 4:00–9:00 PM windows. A day is included only if the system exhibits at least one cycle with five consecutive minutes of cooling operation during that window. This criterion, used for percentage runtime calculations, ensures elapsed time is reconstructed only where system participation is verified.

Results

Across June-September 2025, the dataset includes 43,220 valid cooling operating minutes, equivalent to approximately 720 hours of compressor operation. Total electrical input during these minutes was 621.4 kWh, with a total electricity cost of $308 under California E-TOU-C summer pricing. Coil-level sensible cooling totaled 6.77 million Btu. Distribution losses represented a substantial fraction of this energy, particularly in the long-duct configuration.

The reported dollar value is intentionally narrow: it is the E-TOU-C energy charge for screened cooling operating minutes only, not a whole-house summer utility bill. It excludes non-cooling household loads, periods without valid compressor operation, customer charges, demand charges, and any costs outside the measured cooling intervals. This makes the cost metric useful for comparing duct configurations under identical measurement rules, but it should not be interpreted as the full seasonal bill impact for an occupied home.

That context also matters: the Grange CVRH is a very small two-bedroom, 848 ft^2 test house with a low design cooling load, and the installed equipment is near the small end of available residential heat-pump capacity. The resulting cooling cost is therefore lower than would be expected for an average California home and should be read as a controlled configuration-comparison metric rather than a whole-home billing estimate.

Summary Performance by Configuration

Energy-weighted sensible efficiency was calculated using identical minute-level operating data across all configurations. Energy-weighted means that each operating minute contributes in proportion to its cooling energy, so high-output minutes have more influence than low-output minutes. Coil sensible EER values ranged from approximately 9.7 to 11.4 Btu/Wh. Delivered sensible EER values ranged more widely because duct losses varied strongly by configuration.

Figure 2 shows the energy-weighted sensible efficiency at the coil and delivered to the conditioned space by system, duct configuration, and thermostat strategy. The constant bars represent the constant-setpoint operation, while the setup bars represent the scheduled setup/recovery operation. Solid bars represent coil-level sensible EER, while hatched bars represent delivered sensible EER after accounting for equivalent distribution losses. The annotated Δ values are the reduction in sensible EER due to distribution losses. Results demonstrate that distribution system performance exerts a dominant influence on delivered cooling efficiency, substantially reducing delivered EER in long/leaky duct configurations, while differences between equipment systems are comparatively modest.

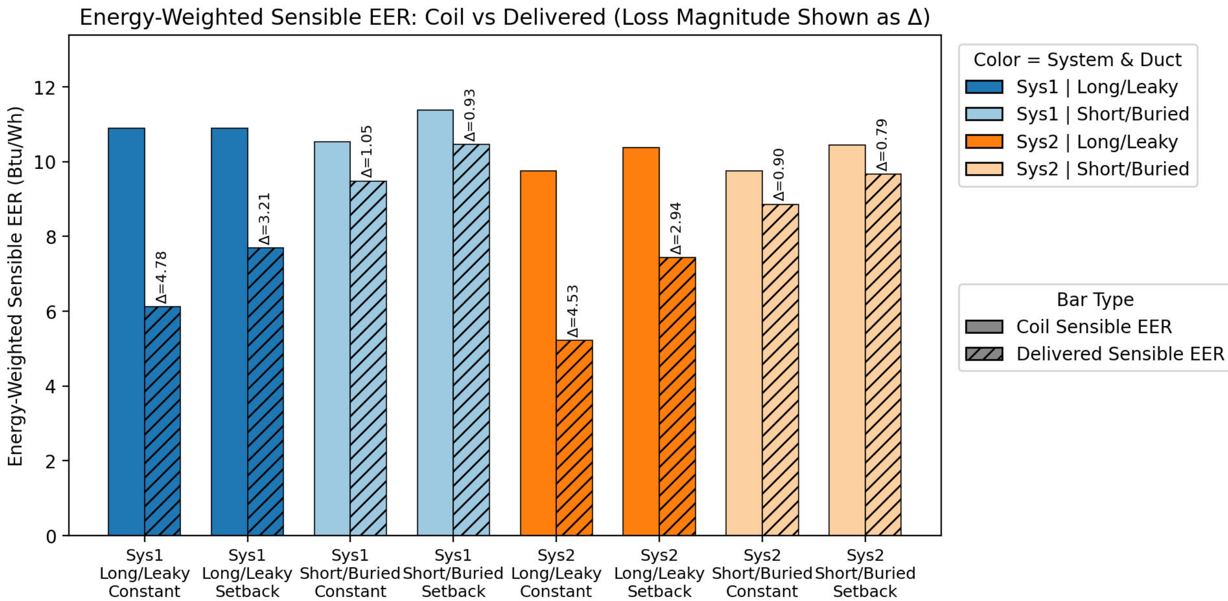

Figure 2. Energy-weighted sensible efficiency at the coil and delivered to the conditioned space by system, duct configuration, and thermostat strategy.

While variable-capacity equipment exhibited higher coil-level sensible efficiency under many operating conditions, distribution losses dominated delivered performance outcomes. The close agreement between coil and delivered sensible EER in the short / buried duct configuration highlights the importance of distribution quality in translating equipment efficiency into delivered cooling.

Figure 3 presents delivered sensible cooling rate as a function of instantaneous system electrical input using minute-level operating data. Each point represents a single cooling minute, and both heat pump systems are pooled within each duct-configuration trend rather than differentiated by system. This presentation emphasizes the distribution pathway because the duct-configuration separation is larger and more persistent than the equipment-to-equipment separation.

For a given electrical input, delivered sensible cooling is strongly dependent on duct configuration. Short, buried duct systems consistently deliver substantially more sensible cooling per minute than long, attic-exposed, leaky duct systems across the full range of operating power. The vertical separation between the aggregated trendlines is large and persistent, reinforcing that distribution losses dominate delivered performance outcomes.

Because delivered efficiency collapses in the presence of distribution losses even when coil-level efficiency remains high, the following section isolates the effect of duct configuration directly.

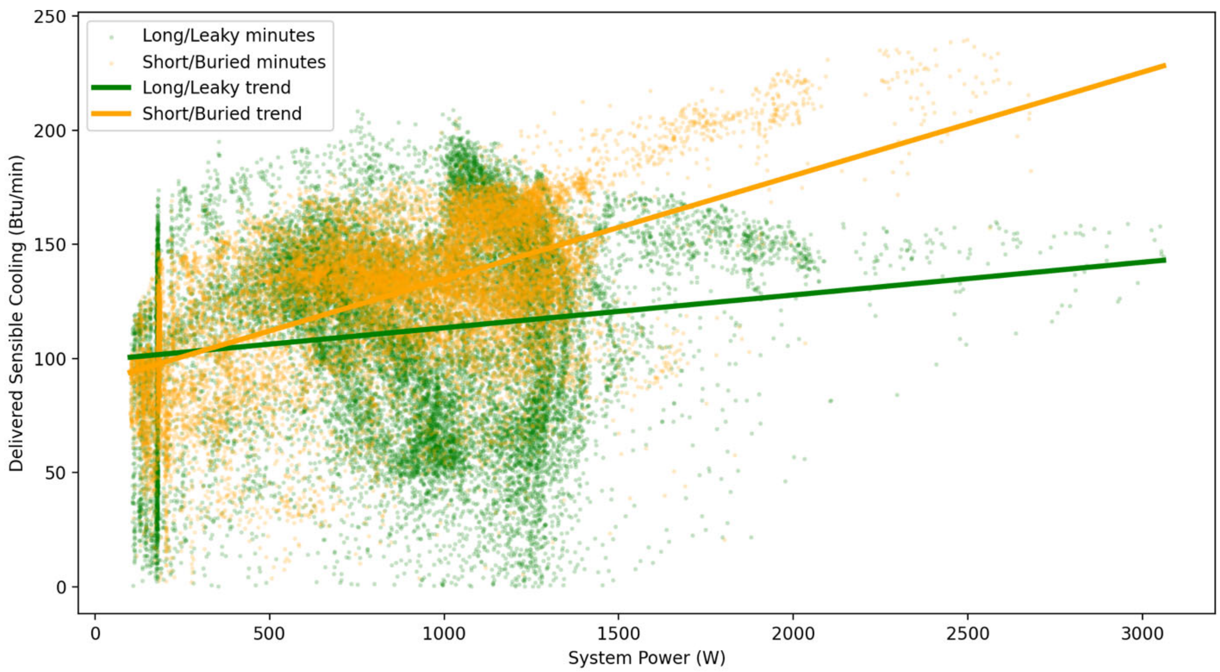

Figure 3. Delivered sensible cooling versus instantaneous system electrical input for all cooling operating minutes.

Distribution System Effects

Across the full summer dataset (June–September), the long / leaky duct configuration produced approximately 418 kWh of equivalent distribution loss energy, compared to approximately 75 kWh for the short / buried configuration. The long / leaky configuration represents an increase in distribution system losses of roughly 457 percent from the short / buried configuration, attributable to duct configuration alone, independent of equipment type or control strategy.

Loss behavior differed markedly with attic temperature. For long ducts, the loss fraction increased sharply as attic temperatures rose, frequently exceeding 90 percent at attic temperatures above approximately 130 °F, indicating that most of the coil-generated sensible cooling failed to reach the conditioned space during the hottest conditions. In contrast, short / buried duct losses remained comparatively low, generally below about 10 percent across comparable attic temperature ranges, demonstrating substantially improved delivery efficiency.

Figure 4 shows the loss fraction as attic temperature increases, calculated as the difference between coil-level and delivered sensible cooling divided by delivered cooling. Under this delivered-normalized formulation, values greater than 1.0 indicate that more cooling is lost in the distribution system than is delivered to the conditioned space. The metric is intentionally unbounded and highlights how distribution penalties accelerate under high attic temperatures, especially for long, attic-exposed ducts.

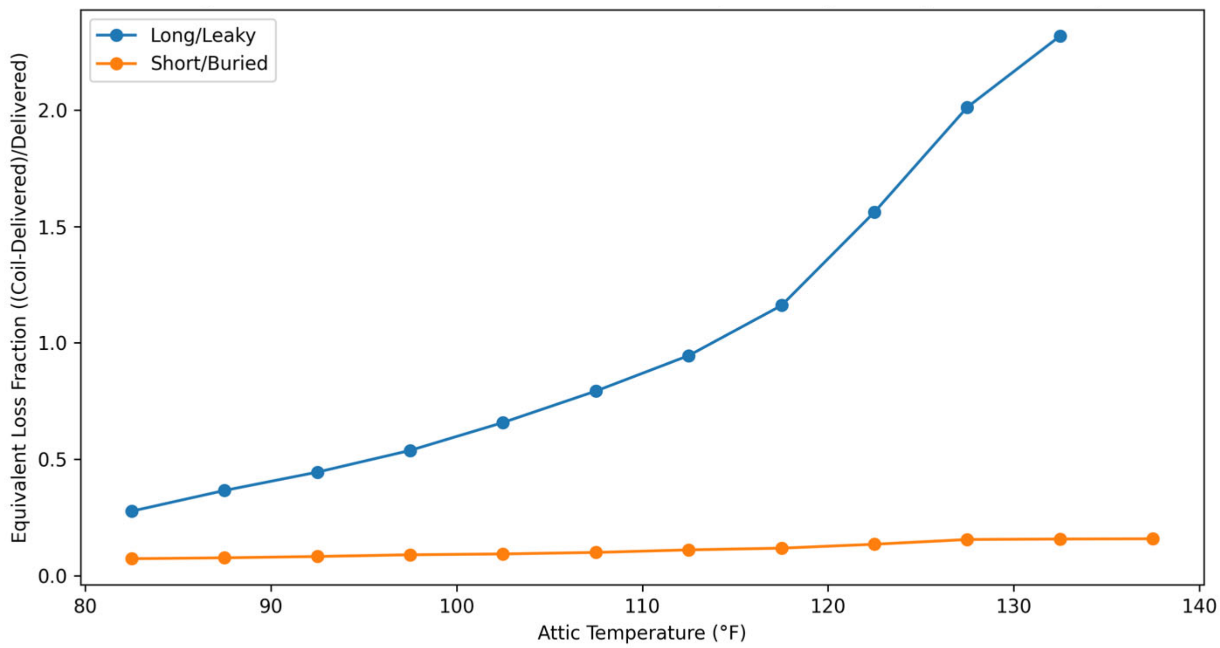

Figure 4. Delivered-normalized loss fraction vs. Attic temperature (5 °F bins; ≥120 minutes/bin).

Peak Operating Conditions

Cooling system performance during peak outdoor and attic temperature conditions is governed not only by equipment capacity and efficiency, but by the magnitude and distribution of losses occurring within the air distribution system. To illustrate how these losses arise under real operating conditions, Figure 5 decomposes coil sensible cooling output into delivered cooling and individual loss components for representative peak cooling operation. This figure illustrates the physical mechanisms underlying the elevated runtime, reduced delivered efficiency, and increased time-of-use cost observed for long duct configurations throughout the cooling season.

As shown, short, buried ducts experience relatively small losses that are dominated by conductive heat transfer, allowing the majority of coil output to reach the conditioned space. In contrast, long, attic-exposed duct configurations exhibit large and multi-path losses, including both supply and return leakage to the attic as well as elevated conductive gains driven by high attic temperatures. These loss pathways reduce delivered cooling efficiency and impose a direct operational penalty, requiring additional runtime to achieve comparable space conditioning during peak periods.

Distribution losses measured in the long-duct configuration arise from two coupled mechanisms: (1) air leakage, in which conditioned supply air or return air is exchanged with the unconditioned attic, and (2) thermal losses associated with duct geometry and attic exposure, including conductive heat transfer through duct surfaces and residence-time effects that occur as air travels through long duct runs. Since the short / buried duct system is tightly sealed, leakage-loss calculations apply to the long-duct configuration only, where both supply- and return-side leakage flows are directly measured using the CVRH flow-measurement device (FMD) network.

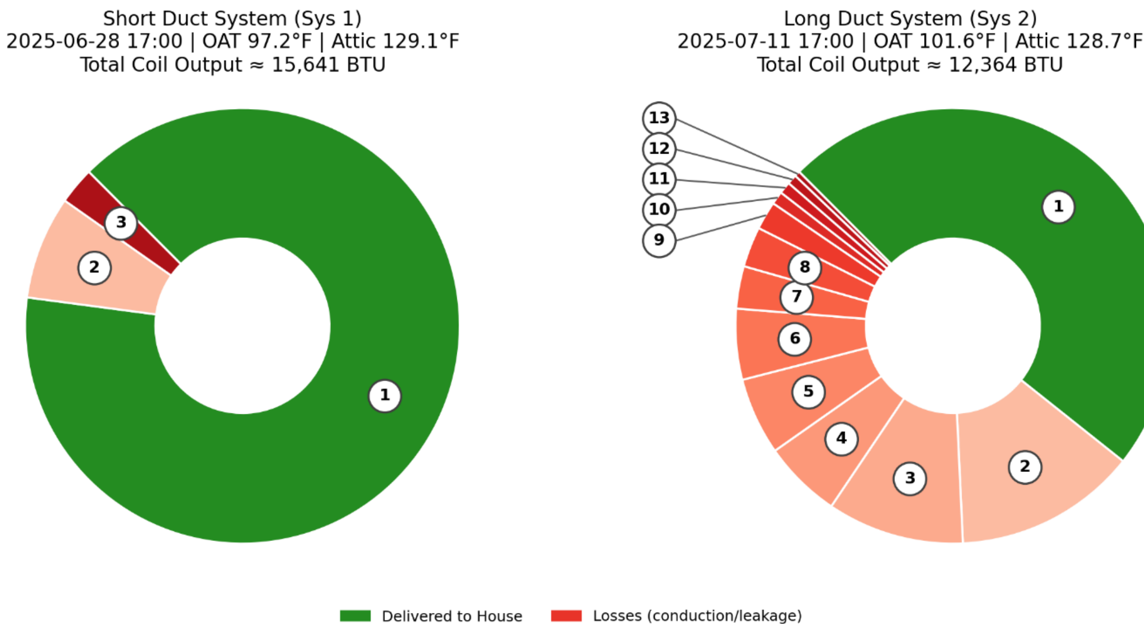

Figure 5. Decomposition of coil sensible cooling output into delivered cooling and equivalent distribution loss components during representative peak cooling operation for short, buried ducts (left) and long, attic-exposed, leaky ducts (right). ID markers refer to Table 1.

Table 1. Loss component key for Figure 5.

Short Duct System (Sys 1)		
ID	Component	% output
1	Delivered to House	89.6
2	**Thermal Loss: Supply Duct**	**7.6**
3	**Thermal Loss: Return Duct**	**2.7**

Long Duct System (Sys 2)						
ID	Component	% output		ID	Component	% output
1	Delivered to House	48.2		8	Leakage: Supply Plenum	3.0
2	Leakage: Return Plenum	13.6		**9**	**Thermal Loss: Bath**	**2.1**
3	**Thermal Loss: Living**	**10.2**		10	Leakage: Bed 1	1.0
4	**Thermal Loss: Dining**	**5.8**		11	Leakage: Bed 2	0.9
5	**Thermal Loss: Bed 2**	**5.7**		12	Leakage: Dining	0.8
6	**Thermal Loss: Bed1**	**5.2**		13	Leakage: Living Room	0.4
7	**Thermal Loss: Return Duct**	**3.2**				

Note: Btu/hr values represent the component breakdown of total coil sensible cooling output at the selected peak-cooling snapshots. Percentages may not sum to exactly 100% due to rounding.

Across the long-duct cases, energy-weighted leakage averaged approximately 79-86 CFM, or about 12-13% of coil airflow. Leakage occurred on both the supply and return sides, but the minute-resolved loss-component analysis indicates that leakage accounted for only about 30-32% of total distribution losses. The remaining 68-70% was associated with thermal mechanisms tied to duct surface area, residence time, and attic exposure. This distinction matters for retrofit strategy: duct tightening can recover a meaningful portion of lost performance, but most of the observed penalty persists unless duct exposure or duct extent is reduced through burial, encapsulation, relocation into conditioned space, or distribution redesign.

Electrical energy values presented in this analysis are directly measured. Air-side quantities and Btu-derived loss components are calculated from field sensors and are intended for comparative system-level attribution rather than laboratory-grade absolute heat-transfer precision. Loss-component shares are therefore interpreted as approximate but robust indicators of the relative importance of leakage versus geometry and exposure effects.

Equipment Effects

Although variable-capacity equipment expands the operating envelope and enables lower average power operation during part-load conditions, these advantages do not compensate for large distribution losses. Once delivered cooling is considered, differences attributable to equipment type are consistently smaller than those driven by duct configuration. This finding does not diminish the value of high-efficiency equipment, but it demonstrates that equipment performance is constrained by the system into which it is installed.

Variable-capacity equipment demonstrated higher coil-level sensible efficiency under many operating conditions; however, differences between systems were modest compared to the magnitude of distribution losses. Figure 6 shows that daily delivered sensible EER separates primarily by duct configuration, with long/leaky duct days shifted to lower delivered EER and short/buried duct days clustered at higher delivered EER. This demonstrates that equipment performance gains can be masked or overwhelmed when the distribution path is inefficient.

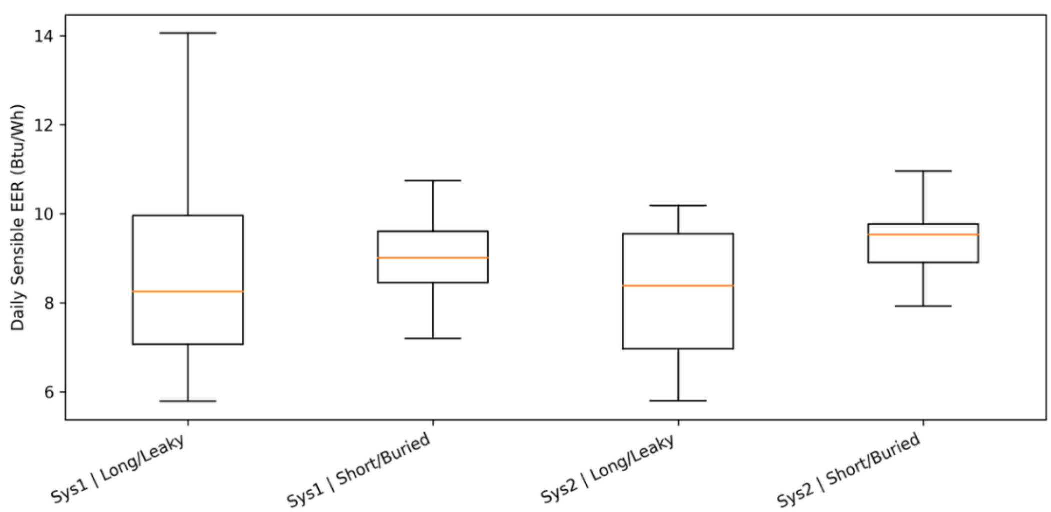

Figure 6. Distribution of daily delivered sensible EER.

Weather-Normalized Performance

Coil sensible EER declined with increasing outdoor air temperature as expected. Energy-weighted EER values ranged from approximately 14–17 Btu/Wh at 65 °F outdoor temperature to approximately 7–9 Btu/Wh at 95 °F, depending on configuration, as shown in Figure 7.

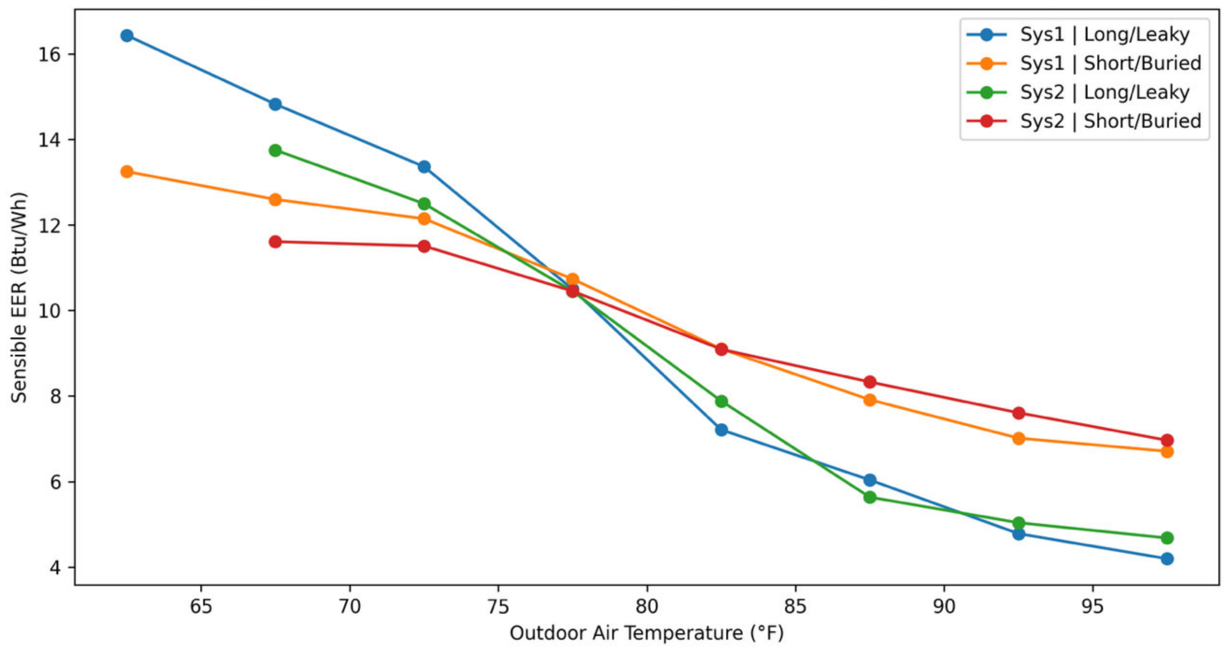

Figure 7. Sensible EER vs outdoor temperature (5 °F bins; ≥120 minutes/bin).

Thermostat Strategy Effects

The charts in Figure 8 show the average runtime, cooling energy, and delivered sensible EER for active days, defined as days with more than 2 minutes of cooling runtime.

Thermostat setup strategies reduced total runtime but altered the timing and magnitude of distribution losses. Recovery periods often coincided with elevated attic temperatures, increasing instantaneous duct losses and reducing delivered efficiency. The setup strategy appears to save less energy for Sys 1 because the variable-capacity system can operate at lower power for longer periods under constant control; reducing runtime does not reduce energy as strongly when much of the operation is already low-intensity. Sys 2, with more conventional cycling behavior, showed a larger energy reduction under setup because avoided runtime more directly reduced compressor operation.

Peak period hours showed a pronounced collapse in distribution efficiency during recovery periods under high fan operation, with distribution efficiencies clustering well below 0.4 in the long-duct configuration. This indicates that thermostat strategies intended to reduce runtime or shift load may inadvertently increase distribution losses when recovery coincides with elevated attic temperatures. Control strategies therefore cannot be evaluated independently of distribution system characteristics.

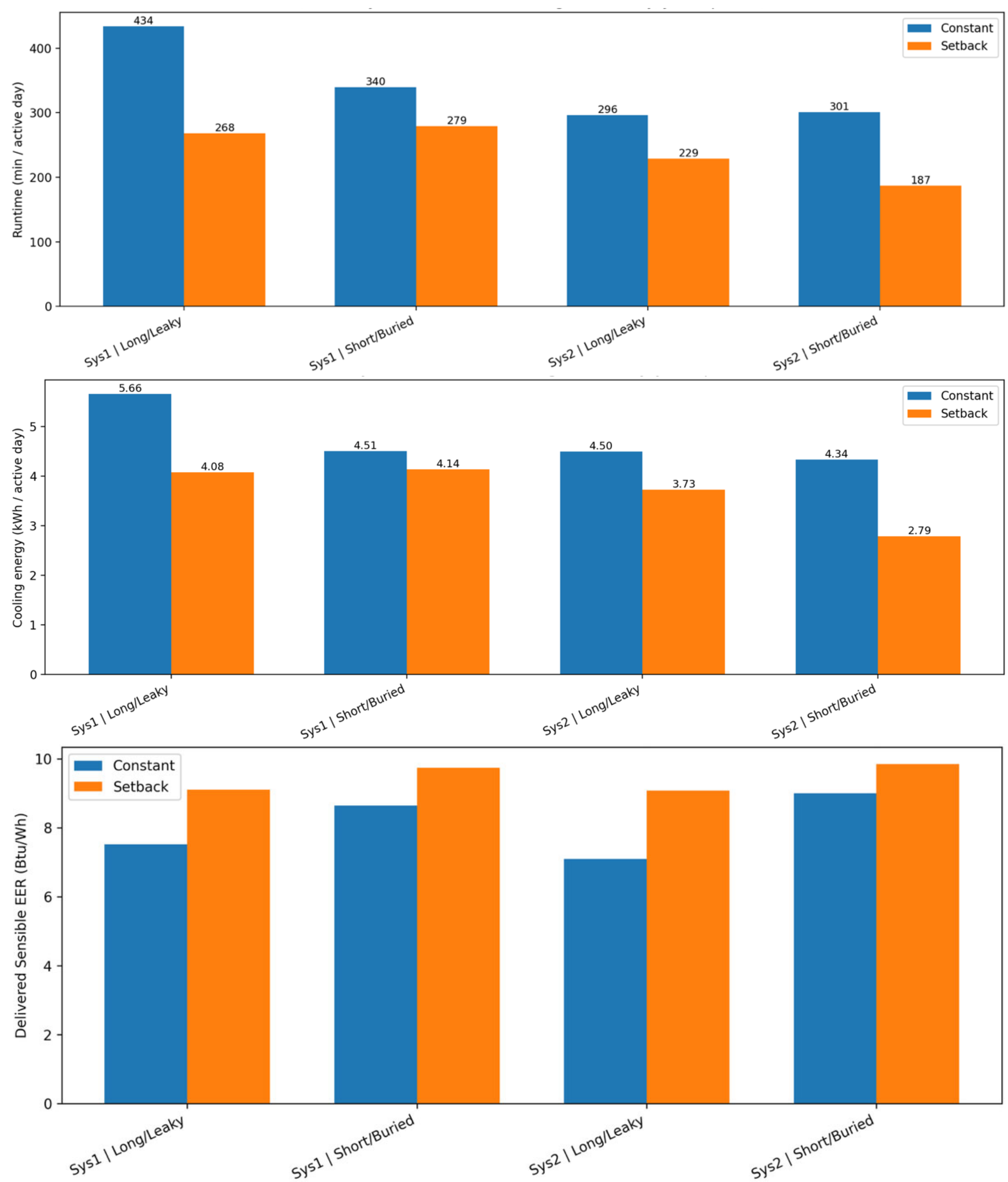

Figure 8. (top to bottom) (a) Average runtime by thermostat strategy, (b) average cooling energy by thermostat strategy, and (c) delivered sensible EER by thermostat strategy.

Peak-Period Runtime Utilization

Using eligible daily 4:00-9:00 PM windows, Sys 1 occupied a larger fraction of peak windows than Sys 2 across both duct configurations. Eligible windows were days with at least one cycle containing five consecutive valid cooling operating minutes during the 4:00-9:00 PM period; days with no cooling operation in the window or insufficient valid measurement data were excluded. This reflects greater temporal engagement, not necessarily higher energy intensity.

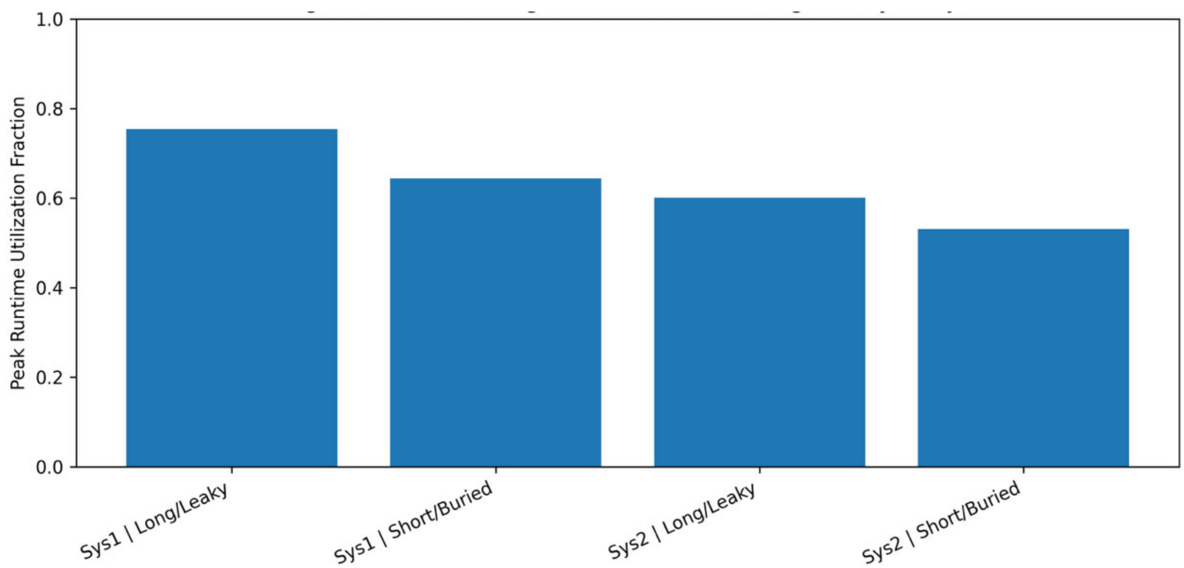

Figure 9. Peak-period runtime utilization (eligible days only).

Peak-Period Energy Intensity

To distinguish runtime duration from operating intensity, electrical energy consumption during eligible peak windows was normalized by actual runtime within those windows. Table 2 summarizes average electricity consumption per hour of active cooling during peak periods.

Table 2. Electrical energy consumption normalized by peak-period runtime.

System	Duct Configuration	Eligible Peak Days	Mean Peak Runtime (min)	Mean Peak kWh	kWh per Peak-Runtime Hour
Sys 1	Long / Leaky	22	226	3.18	0.84
Sys 1	Short / Buried	20	193	2.71	0.84
Sys 2	Long / Leaky	21	181	2.90	0.96
Sys 2	Short / Buried	20	160	2.40	0.90

Although Sys 1 occupied a larger fraction of peak windows, its average electrical energy consumption per hour of active cooling was lower than that of Sys 2. This indicates that longer peak-period runtime does not imply higher operating intensity and is consistent with variable-capacity modulation that extends runtime while reducing average power draw.

Time-of-Use Cost Implications

On average, long, attic-exposed ducts impose roughly five times higher peak-period distribution loss cost per hour of active cooling than short, buried ducts under the same operating conditions.

To translate measured distribution losses into customer-relevant impacts, minute-resolved cooling operation data were evaluated under California E-TOU-C summer pricing, restricted to peak periods (4:00–9:00 PM). Using identical eligible operating minutes across configurations, equivalent distribution loss energy was converted to peak-period electrical cost. Figures 10 and 11 show that long, attic-exposed duct configurations impose substantially higher hourly and daily TOU costs than short, buried ducts, reflecting both increased runtime exposure and elevated loss fractions during the most expensive hours of system operation.

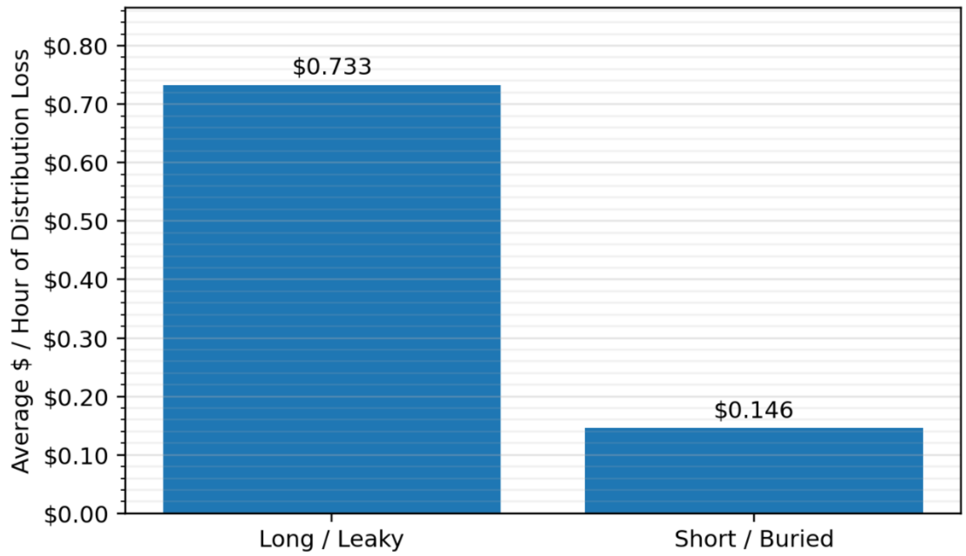

Figure 10. Average hourly electrical cost associated with equivalent distribution losses during TOU peak periods. Results combine both heat pump systems.

Figure 10 summarizes the average hourly peak-period distribution-loss cost, while Figure 11 shows that the penalty recurs across individual weekdays. Together, these results show that long, attic-exposed ducts create both higher average peak-period loss cost and persistent daily cost exposure relative to short, buried ducts.

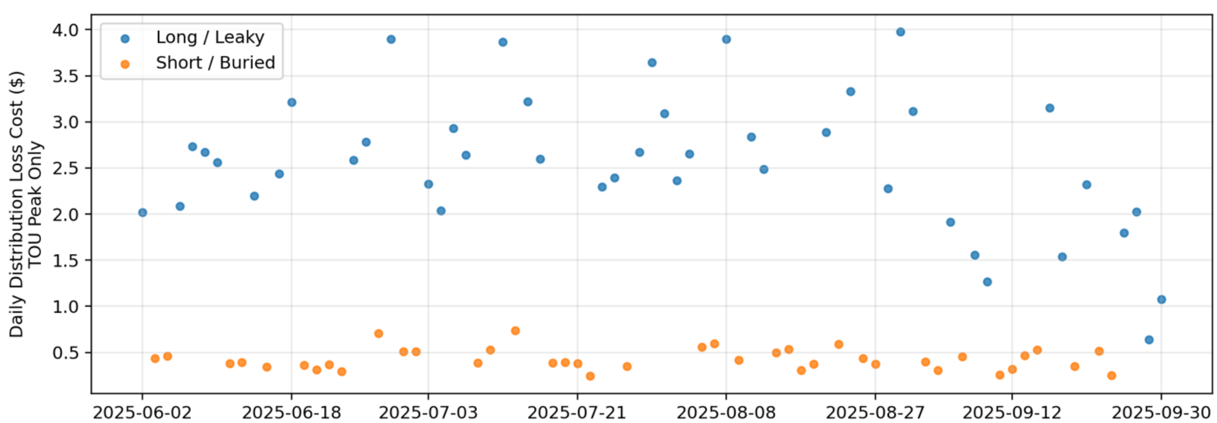

Figure 11. Daily electrical cost attributable to equivalent distribution losses during TOU peak periods. Points represent individual weekdays; systems are combined and grouped by duct configuration.

Discussion

When normalized by active cooling days, long, attic-exposed ducts required about one additional hour of compressor runtime per day relative to short, buried ducts. The long, exposed ducts averaged 399 minutes per active day, compared with 339 minutes for the short, buried ducts. Results collectively demonstrate that cooling performance and peak-period cost are system-level outcomes dominated by distribution configuration, with attic-exposed ducts imposing structural efficiency and time-of-use penalties that persist across operating conditions and accumulate systematically over the cooling season. Equipment efficiency differences, while measurable, are consistently secondary.

Although this study reflects a single site, the dominant mechanisms identified - duct surface area, leakage fraction, attic thermal exposure, and time-structured operation - are common in existing CA housing stock. The long, attic-exposed ducts intentionally represent common suspended attic ducts, imperfect but code-compliant sealing, and high peak attic temperatures. Absolute magnitudes will vary by home, but the relative dominance of distribution performance is relevant across many retrofit and replacement scenarios.

These effects are visible because the experiment used minute resolved data and identical operating minutes across an entire season. More aggregated or duty-cycle-based approaches would have masked the time-structured loss behavior documented here.

Recommendations

Results from this minute-resolved field evaluation show that cooling performance, runtime behavior, and peak-period cost are system-level outcomes dominated by distribution configuration. At this site, most of the penalty associated with long, attic-exposed ducts was structural rather than purely leakage-driven. The following recommendations are offered for programs, practitioners, and future research:

- **Prioritize distribution system geometry and exposure in heat pump programs:** Across all tested configurations, duct configuration has a much larger effect on delivered cooling and TOU cost than equipment efficiency. In long, attic-exposed ducts, measured leakage accounted for only 30–32% of total distribution losses; the remaining 68–70% were thermal losses tied to attic exposure. Therefore, duct sealing leaves most of the problem in place, and heat pump efficiency alone is not sufficient to make up for these losses. Programs should prioritize strategies that reduce duct exposure, including compact layouts, burial, encapsulation, and relocation into conditioned space, especially where attic temperatures routinely exceed 120–130 °F.

- **Evaluate thermostat strategies in conjunction with distribution performance:** Thermostat setup and recovery strategies materially altered both runtime patterns and distribution losses. In long, attic-exposed ducts, recovery during periods of high attic temperature produced disproportionate loss penalties. Contractors can evaluate this risk by documenting duct location, duct surface area, insulation level, leakage, airflow, and return/supply pathway exposure; reviewing thermostat recovery schedules; and testing whether room response yields long recovery and stratification during hot attic conditions. Programs should avoid treating thermostat flexibility as independent of duct condition.

- **Treat distribution upgrades as energy measures, not comfort-only measures:** The observed penalty - equivalent to about one additional hour of cooling runtime per active day for long, attic-exposed ducts – shows distribution improvements can deliver meaningful energy and cost benefits. Because most of the penalty is structural, program frameworks that treat duct upgrades mainly as comfort or durability measures understate their value. Distribution geometry and exposure should be treated as first-order energy variables, alongside equipment selection.

- **Adopt minute-resolved evaluation methods for TOU analysis:** Aggregated or duty-cycle–based metrics obscure critical interactions among equipment modulation, runtime intensity, duct losses, and TOU pricing. Minute-resolved analysis using identical operating minutes across configurations provides cleaner attribution of performance and cost drivers and avoids biases from non-operating periods. This approach is especially useful to evaluate TOU impacts under variable-capacity operation, where longer runtime does not necessarily imply higher operating intensity.

- **Extend this framework to additional climates, housing types, and operating modes:** Future work should apply this minute-resolved framework across additional sites, climates, and housing types, and extend the analysis to heating-season and latent cooling performance. Although these results come from a hot-dry climate and a small vintage slab-on-grade home, the dominance of distribution geometry and exposure suggests that similar effects may appear in other regions and building types. Multi-site studies would help test generalizability and support scalable program and design guidance.

References

Chitwood, Rick, and Lew Harriman. 2012. *Measured Home Performance: A Guide to Best Practices for Home Energy Retrofits in California.* Prepared for the California Energy Commission. https://www.researchgate.net/publication/294617059.

Conant, Abram, Mike MacFarland, Marshall Hunt, David Springer, and James Haile. 2023. "Best Practices Guide: Residential Variable Capacity Heat Pumps." *ETCC-CA website.* July. https://www.etcc-ca.com/reports/best-practices-guide-residential-variable-capacity-heat-pumps.

Hoeschele, Marc, Rick Chitwood, Elizabeth Weitzel, and Alea German. 2015. *Evaluation of Ducts in Conditioned Space in New California Homes.* Pacific Gas and Electric Company. http://www.etcc-ca.com/reports/evaluation-ducts-conditioned-space-new-california-homes.

Proctor, John, Bruce Wilcox, and Rick Chitwood. 2018. *The Central Valley Research Homes Project.* Sacramento: California Energy Commission. https://www.researchgate.net/publication/342135376.