

Advanced HVAC Control in Real Buildings

State of the Art, Protocols, and Deployment

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Advanced HVAC control plans ahead

- Conventional control:

- still the industry standard
- e.g. bang-bang, PID, and RBC
- mainly reacts to current conditions

- Advanced control:

- also predicts or learns
- shifts HVAC operation across time
- e.g. optimal control, MPC, DDPC, RL, and LLMs

- 1) MPC: optimizes future actions using a model
- 2) DDPC: keeps predictive-control benefits with less modeling
- 3) RL: learns a control policy from data or simulation
- 4) LLMs: reason over data and text to support decisions

RBC: rule-based control

PID: proportional-integral-derivative

MPC¹: model predictive control

DDPC²: data-driven predictive control

RL¹: reinforcement learning

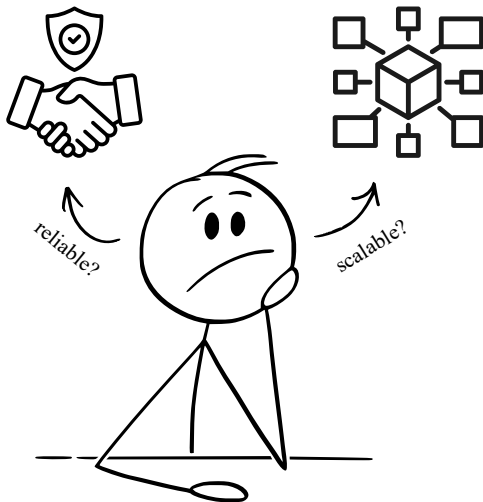
LLM: large language model

¹ **A.J. Khabbazi**, E.N. Pergantis, L.D. Reyes Premer, P. Papageorgiou, A.H. Lee, J.E. Braun, G.P. Henze, and K.J. Kircher, "Lessons learned from field demonstrations of model predictive control and reinforcement learning for residential and commercial HVAC: A review," *Applied Energy*, 2025.

² L.D. Reyes Premer, **A.J. Khabbazi**, and K.J. Kircher, "Indirect data-driven predictive control and the state-space predictor," *Pending*, 2026.

What is the main challenge?

*Can they work **reliably** at **scale** in real buildings?*



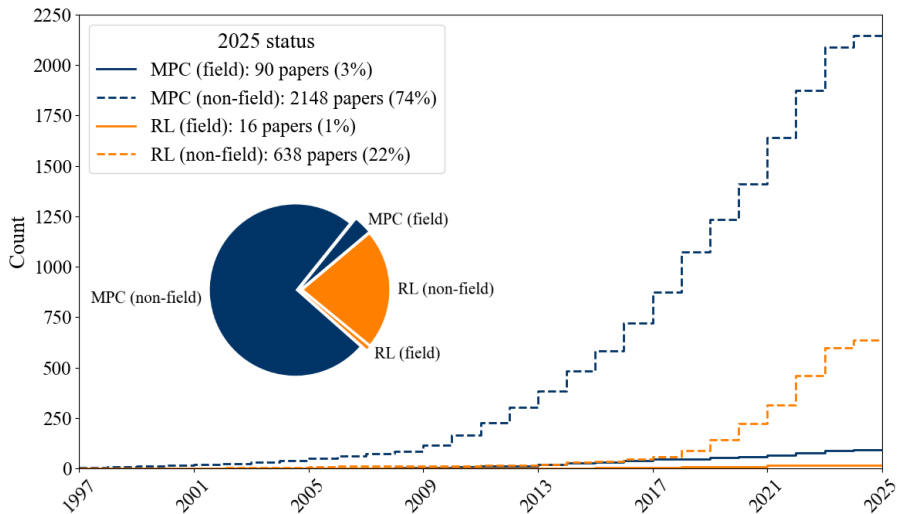
Field demonstrations matter because simulation is not enough^{3,4}

- Simulation can show potential
- But field deployment must work in real buildings
- Field demonstrations can:
 - ✓ show practical value to decision makers
 - ✓ reveal implementation challenges
 - ✓ test performance under real-world uncertainty

³ **A.J. Khabbazi**, E.N. Pergantis, L.D. Reyes Premer, A.H. Lee, J. Ma, H. Liu, G.P. Henze, and K.J. Kircher, "What Have We Learned From Field Demonstrations of Advanced Commercial HVAC Control?", *International High Performance Buildings Conference*, 2024.

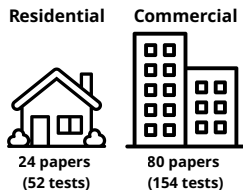
⁴ G.P. Henze, K.J. Kircher, and J.E. Braun, "Why has advanced commercial HVAC control not yet achieved its promise?", *Journal of Building Performance Simulation*, 2025.

Field studies remain a small share of the MPC and RL literature



Scope and dataset

- Peer-reviewed field demonstrations of advanced HVAC control in real buildings
- Focus on **model predictive control (MPC)** and **reinforcement learning (RL)**
- Final dataset: **104 papers (206 tests)** since the first MPC field demo in 2005⁵

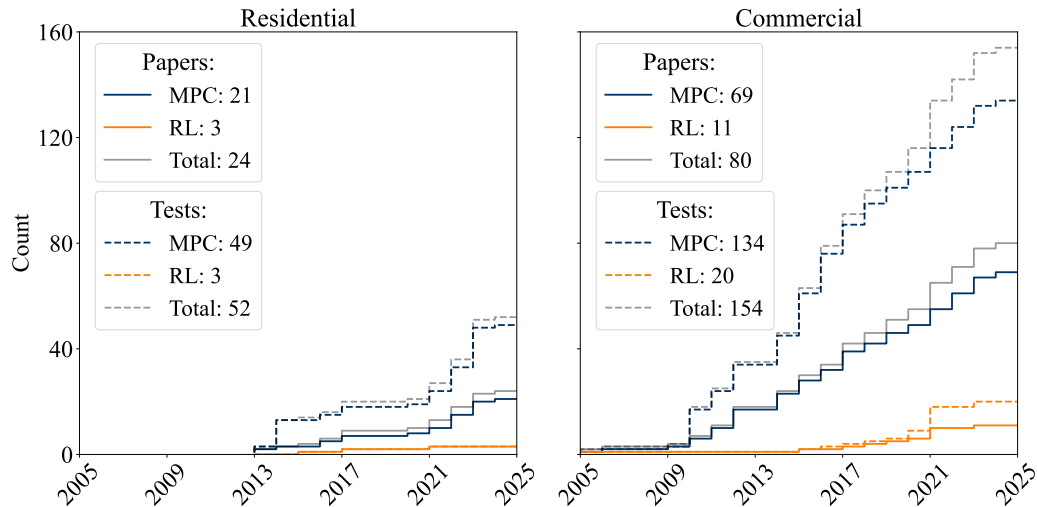


$\Rightarrow^{\text{Goal}}$ What field work shows?

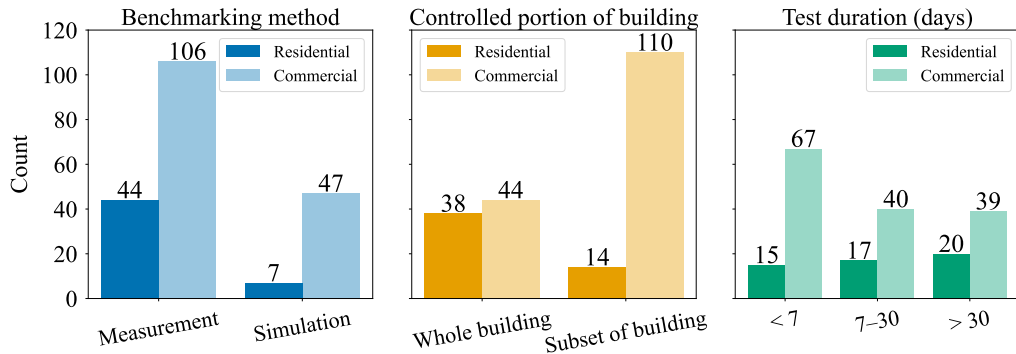
$\Rightarrow^{\text{Goal}}$ What reporting still misses?

⁵ G.P. Henze, D.E. Kalz, S. Liu, and C. Felsmann, "Experimental Analysis of Model-Based Predictive Optimal Control for Active and Passive Building Thermal Storage Inventory," *HVAC&R Research*, 2005.

Field demonstrations have grown, but unevenly

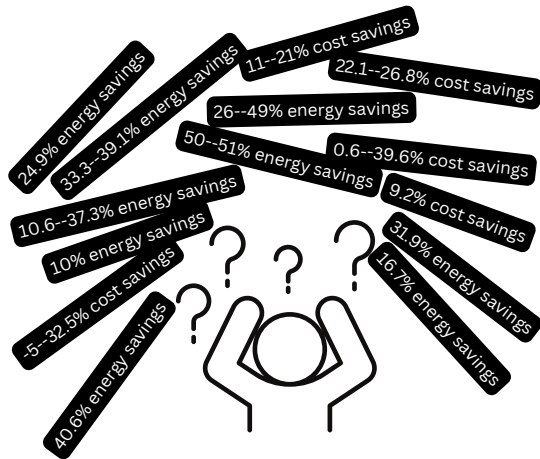


Three protocol choices matter most



⇒ **WHY?** These strongly affect how reported savings should be interpreted.

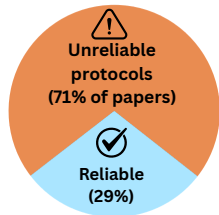
Unreliable M&V can make savings hard to interpret



After filtering for reliable protocols, the results remain promising

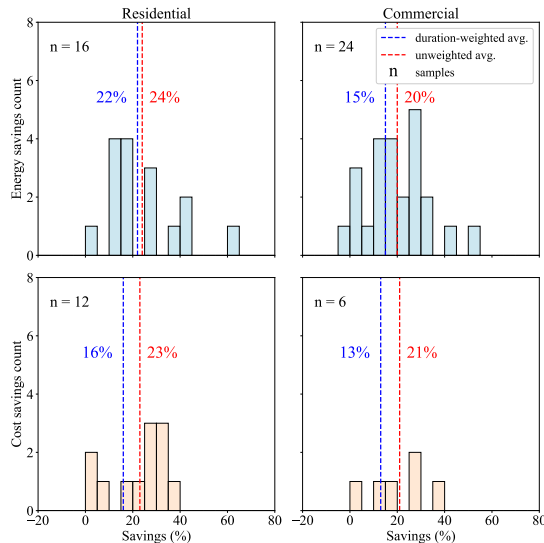
- Kept only tests that:

- ◇ used measured benchmarks
- ◇ controlled whole building or large subset
- ◇ lasted at least 7 days



- Reported both averages

- ◇ **unweighted**: all tests count equally
- ◇ **duration-weighted**: longer tests count more
- ◇ weighted reflects stronger evidence



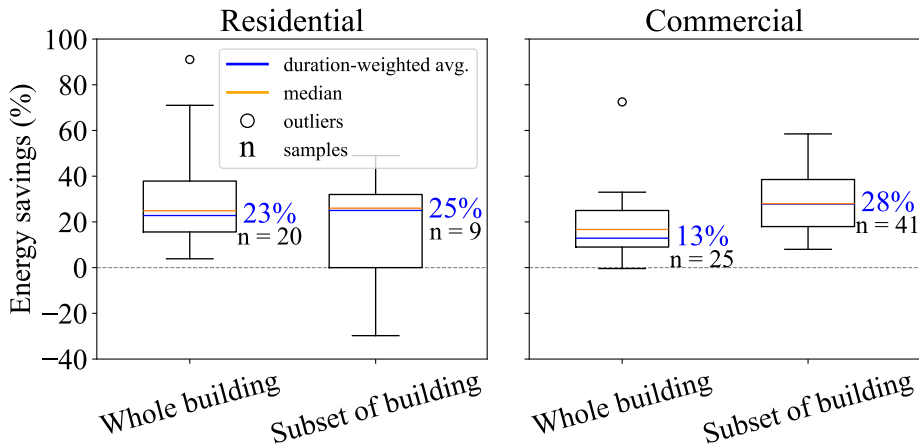
Open-access dataset and checklist

- Open-access dataset for the reviewed field demonstrations
- Supports:
 - ◇ future literature reviews
 - ◇ more standardized reporting
 - ◇ easier comparison across studies
- Includes a reporting checklist for future field work



GitHub repo:
dataset and checklist

Subset-of-building control tends to report higher energy savings



Longer tests receive more weight

$$\overline{\% \text{ savings}} = \frac{\sum_i (\% \text{ savings})_i \cdot (\text{duration})_i}{\sum_i (\text{duration})_i}$$

* Filtered for measurement-based benchmarking.

Subset-of-building control can overestimate savings⁶

- Advanced control applied to only **a few** zones
- Savings reported only for the **controlled** zones
- Heat transfer with adjacent zones **ignored**

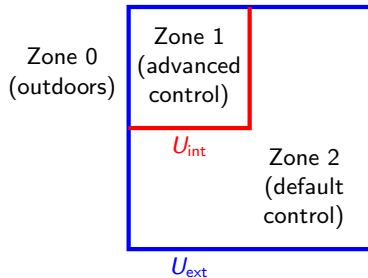
Suppose:

Advanced control lowers one zone's temperature

⇒ heat is drawn from adjacent zones

⇒ adjacent zones need more heat

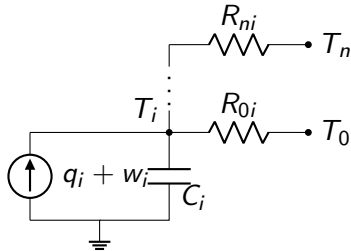
⇒ the **controlled**-zone savings are overstated



^{Goal}
⇒ A more reliable M&V method for multi-zone buildings

⁶ **A.J. Khabbazi** and K.J. Kircher, "Small HVAC Control Demonstrations in Larger Buildings Often Overestimate Savings," *American Control Conference (ACC)*, 2026.

Thermal circuit, baseline dynamics, and experiment dynamics



Baseline dynamics:

$$C_i \frac{dT_i(t)}{dt} = \sum_{j=0}^n \alpha_{ij} (T_j(t) - T_i(t)) + q_i(t) + w_i(t)$$

Experiment dynamics:

$$C_i \frac{d\tilde{T}_i(t)}{dt} = \sum_{j=0}^n \alpha_{ij} (\tilde{T}_j(t) - \tilde{T}_i(t)) + \tilde{q}_i(t) + w_i(t)$$

T_i : temperature of zone i

T_0 : outdoor temperature

T_n : temperature of adjacent zone n

C_i : thermal capacitance of zone i

R_{0i} : thermal resistance between outdoors and zone i

R_{ni} : thermal resistance between zones n and i

q_i : heating input to zone i

w_i : exogenous heat gain in zone i

$T_i(t)$: baseline temperature of zone i

$q_i(t)$: baseline heating input to zone i

α_{ij} : thermal conductance between zones i and j

$j = 0$: outdoors; $j = 1, \dots, n$: other zones

$\tilde{T}_i(t)$: experiment temperature of zone i

$\tilde{q}_i(t)$: experiment heating input to zone i

same building $\Rightarrow$ same C_i and α_{ij}

same time period $\Rightarrow$ same $w_i(t)$

Controlled-zone savings can exceed whole-building savings

Whole-building cumulative savings:

$$S_{\text{whole}} := \sum_{i=1}^n \int_0^{\tau} a_i(t) (q_i(t) - \tilde{q}_i(t)) \, dt$$

n : all zones $a_i(t)$: thermal price in zone i

Controlled-zone cumulative savings:

$$S_{\text{controlled}} := \sum_{i=1}^m \int_0^{\tau} a_i(t) (q_i(t) - \tilde{q}_i(t)) \, dt$$

m : controlled zones

In general, $S_{\text{controlled}} > S_{\text{whole}}$.

⇒ How large is the overestimation, and how can we correct it?

Theorem gives the exact savings overestimation error

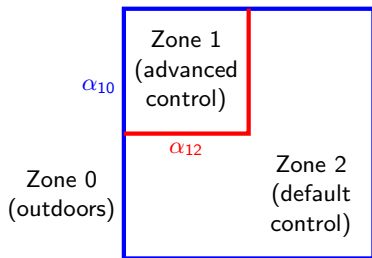
Overestimation error:

$$S_{\text{controlled}} - S_{\text{whole}} = \sum_{i=1}^m \sum_{j=m+1}^n \alpha_{ij} \int_0^{\tau} a_j(t) (T_i(t) - \tilde{T}_i(t)) dt$$

- The error depends on:
 - ◇ α_{ij} : coupling between controlled and uncontrolled zones
 - ◇ $T_i(t) - \tilde{T}_i(t)$: temperature changes caused by advanced control
 - ◇ $a_j(t)$: thermal price in adjacent uncontrolled zones
- $\alpha_{ij} = 0 \Rightarrow$ zero error
- Larger $\alpha_{ij} \Rightarrow$ larger error
- The same theorem gives the true whole-building savings with no baseline energy model

In a two-zone case ($n = 2$, $m = 1$), the bias scales as α_{12}/α_{10}

$$e := \frac{S_{\text{controlled}} - S_{\text{whole}}}{S_{\text{whole}}} = \frac{\text{overestimation error}}{\text{true savings}} = \frac{\alpha_{12}}{\alpha_{10}} \xrightarrow{\alpha=UA} \frac{U_{12}A_{12}}{U_{10}A_{10}}$$

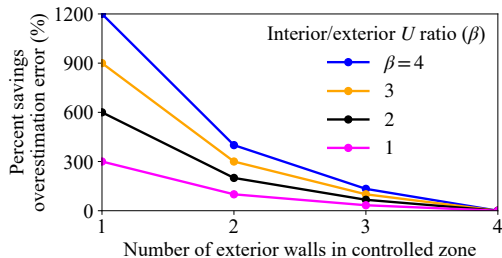


U_{ij} : overall heat transfer coefficient between zones i and j

A_{ij} : heat-transfer area between zones i and j

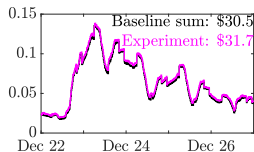
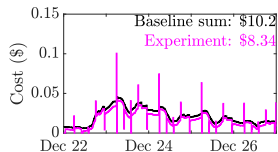
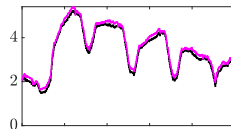
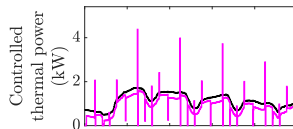
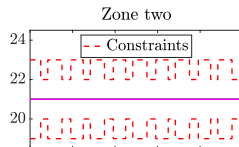
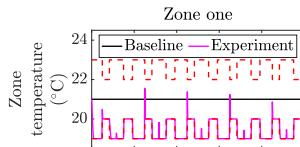
$\Rightarrow$ Depends on insulation and zone geometry

- Higher U_{12} or $A_{12} \Rightarrow$ larger bias
- Lower U_{10} or $A_{10} \Rightarrow$ larger bias



Numerical example closely matches theory

- Zone 1 savings: \$1.83
- Zone 2 penalty: \$1.21
- True whole-building savings: \$0.62
- Zone-level overestimation: $\approx 195\%$
- Theory: 200%



Next
 $\Rightarrow$

Does the same hold experimentally?

Thank you

Questions?

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