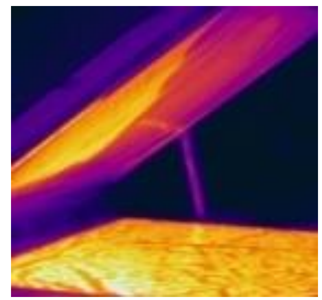
Residential retrofits at scale: opportunity identification, saving estimation and personalized messaging based on communicating thermostat data



ACEEE Summer Study on Energy Efficiency in Buildings

Panel 12: Smart Buildings, Smart Grid, and the Internet of Things

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August 16, 2018

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Motivation

- Utilities: Energy saving opportunities?
  - Space heating is the largest end use for homes in cold/very-cold climates
    - Which buildings to select?
    - How to save energy?

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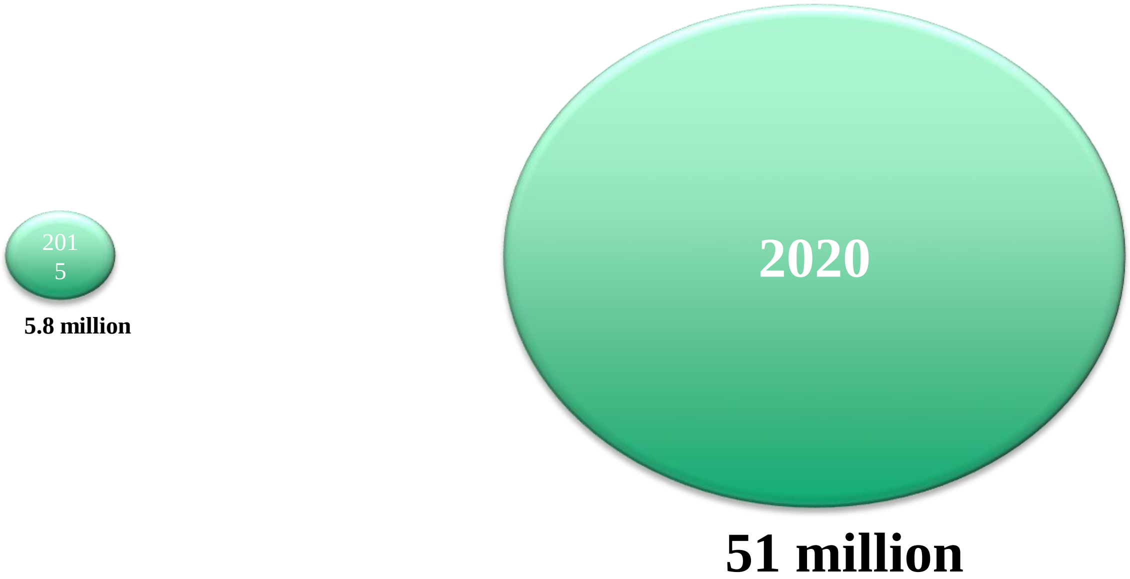
Contours of Solution

- Let's do building retrofits
  - No need to change people's behavior
  - Envelope insulation (walls, attic)
  - Air sealing
- Cannot retrofit all homes
  - Need to remotely ID homes with largest retrofit saving opportunities
  - Need to "sell" to the home owner (ROI)

Sources: DeMark Home Ontario, DOE/PNNL, Mass RASS, DOE/EIA.

Source of data: communicating thermostats (CTs)



- Ubiquitous
- Utility rebates → utility gets CT data
- Data: Indoor temperature and RH, HVAC on/off, …,

Sources: www.achrnews.com/articles/132710-number-of-homes-with-smart-thermostats-grew-rapidly-in-2015.

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Project Objectives

- Develop a tool for targeted customer outreach in utility EE programs that analyzes CT data to automatically
  - identify homes with largest retrofit opportunities
  - quantify expected savings
- Customer and Utility Benefits:
  - Increase uptake of insulation and air sealing retrofits
  - Decrease the cost of EE programs via targeting
  - Reduce retrofit performance risks using remote EM&V
  - Increase customer engagement
- Ultimate Vision: CTs deployed in most homes identify high-impact opportunities to reduce HVAC energy consumption and ensure retrofit performance

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Technical Approach

- Estimate physical parameters in grey-box model by fitting to CT data:

$$C_r \frac{dT_r}{dt} = Q_{HVAC} + q_{int} + A_w/(R_w/2)(T_w - T_r) + q_{inf} \quad \text{(indoor energy balance)}$$

$$C_w \frac{dT_w}{dt} = A_w/(R_w/2)(T_r - T_w) + A_w/(R_w/2)(T_a - T_w) + q_{ext} \quad \text{(enclosure energy balance)}$$

$$q_{inf} = -\rho_{air} c_{p,air} (C_1 W^{2.6} + C_2 |T_a - T_r|^{1.3})^{0.5} (T_r - T_a) \quad \text{(from I. Walker)}$$

  - *= known, = prediction needed for home assessment*
  - T_r, T_w, T_a = indoor, wall and outdoor temperatures
  - R_w and A_w = overall R-value and area of building envelope
  - C_w and C_r = overall heat capacitance of the walls/internal space (=external/internal thermal mass)
  - Q_{HVAC} = HVAC heat supply
  - q_{int}/q_{ext}/q_{inf} = internal/external heat gains /infiltration heat loss
  - W = wind speed, C_1, C_2 coefficients
- Outputs: R_w, ACH_{50}
  - R-value: “the capacity of an insulating material to resist heat flow. The higher the R-value, the greater the insulating power.”
  - ACH_{50}: “number of time the air volume in a building changes per hour at 50 pascals of pressure”

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We fit CT data to a model for each home's thermal response – this can be challenging!

???

- Ill-posed problem, i.e., different physical parameters can create similar building thermal responses
  - Need for "excitation"
  - Separating conduction and infiltration
- Zip-code based weather
- Different HVAC systems have different response times and characteristics
- Many homes have multiple CTs
- Thermal response "noise" from internal heat gains
- Varying CT data among vendors

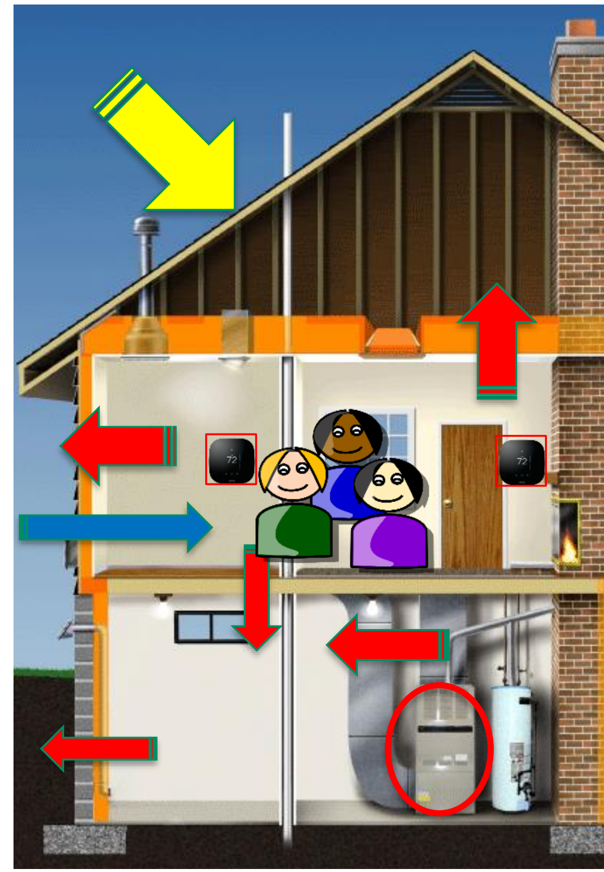
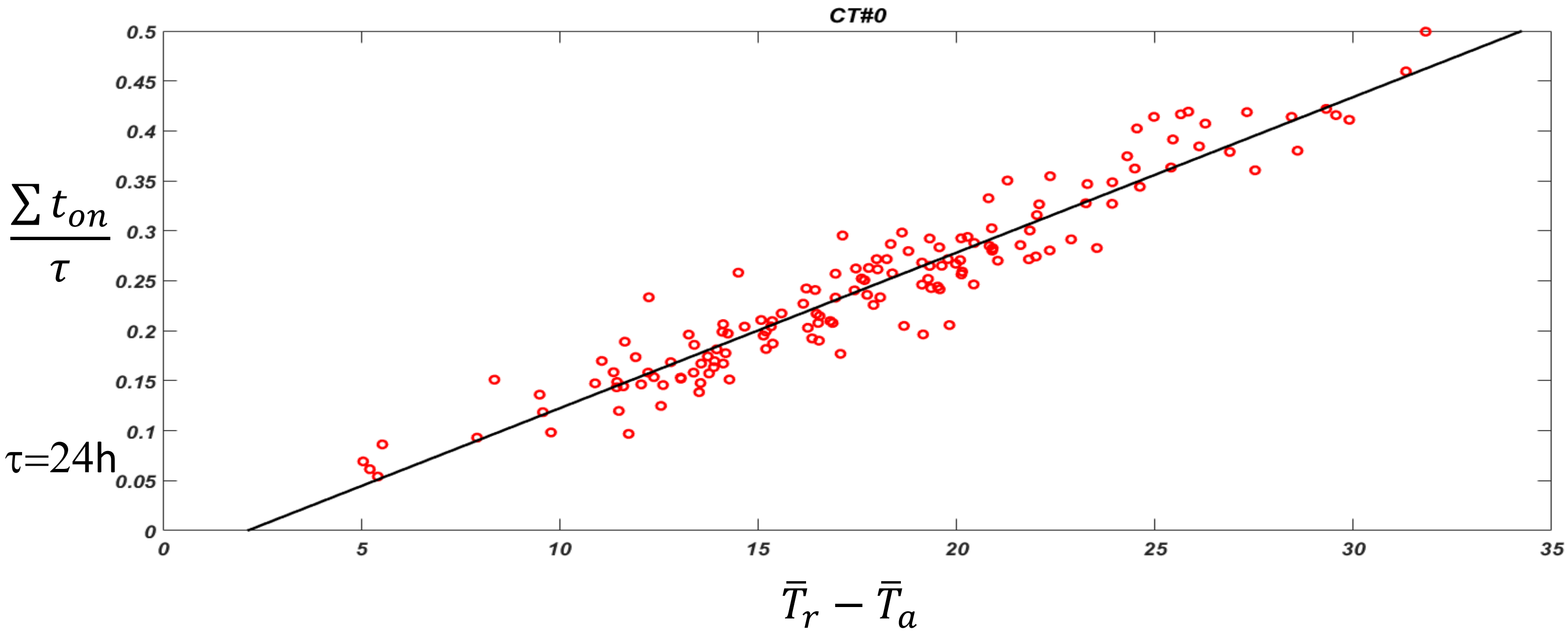


Image Source: DOE, ecobee.

Solution: overall correlations (PRISM on steroids)



- Fels, M. (1986): (fuel billed) $\times \eta = (\overline{conduction} + \overline{infiltration}) \times (\bar{T}_r - \bar{T}_a) - \overline{heat\ gains})$
- $$\frac{\sum t_{on}}{\tau} = \left[\frac{A_w}{R_w Q_{hvac}} + \sqrt{\left(\frac{\rho c_p}{Q_{hvac}}\right)^2 C_1 \bar{W}^{2.6} + \left(\frac{\rho c_p}{Q_{hvac}}\right)^2 C_2 |\bar{T}_r - \bar{T}_a|^{1.3}} \right] (\bar{T}_r - \bar{T}_a) - \frac{q}{Q_{hvac}}$$
- Sacrifice: η (assume ~80%)

Field Data Collection

- Received complete data sets for >600 homes (~150 with 1 CT)
  - Model Inputs:
    - CT data for at least one winter season
    - Gas bill data for 1+ year (coincident with CT data)
    - Envelop area (~Home floorspace and number of stories)
    - ZIP code (for weather)
  - Ground Truth:
    - Home energy assessment (HEA) data (walls, attic, windows)
    - Blowerdoor test data (few homes)
    - Measures implemented (if any)
- Vendors
  - 3 CT Vendors (1: every 5 min, 2-3: event-based)
  - 1 HEA vendor

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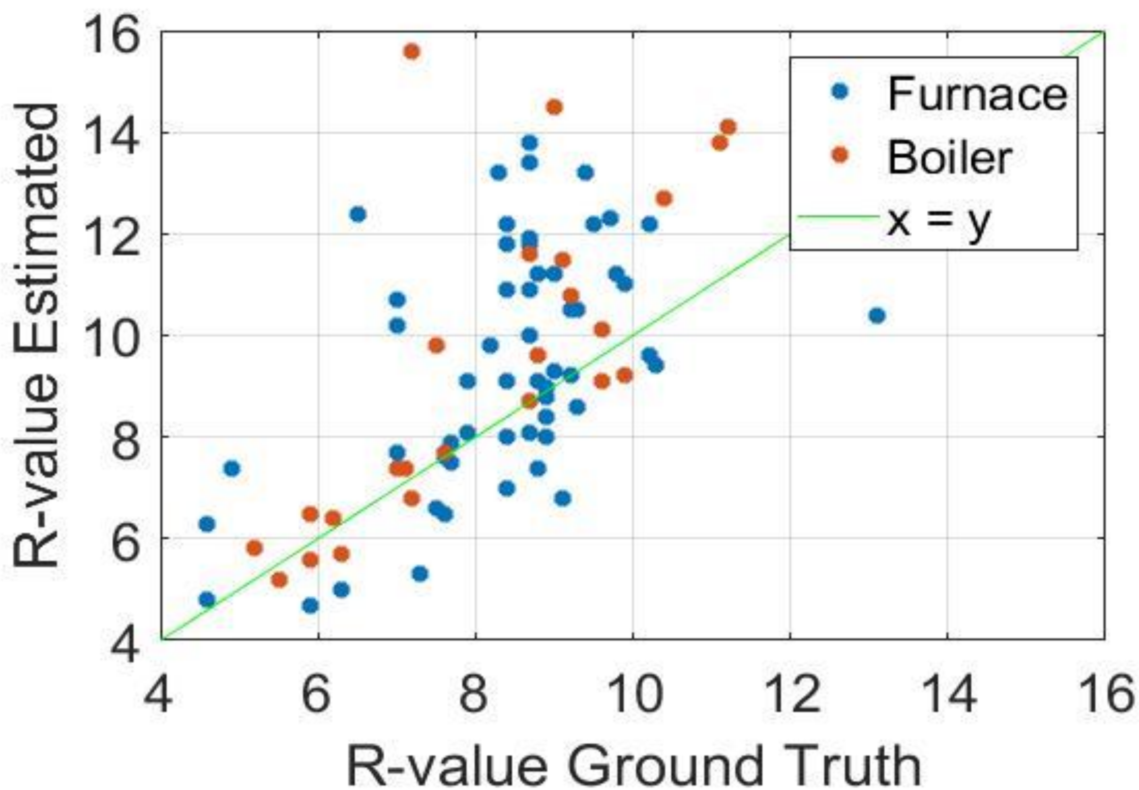
The algorithms effectively identify homes with insulation retrofit opportunities, for both furnaces and boilers.



Classification Accuracy (R>8 or ≤ 8) = 88%

n = 88

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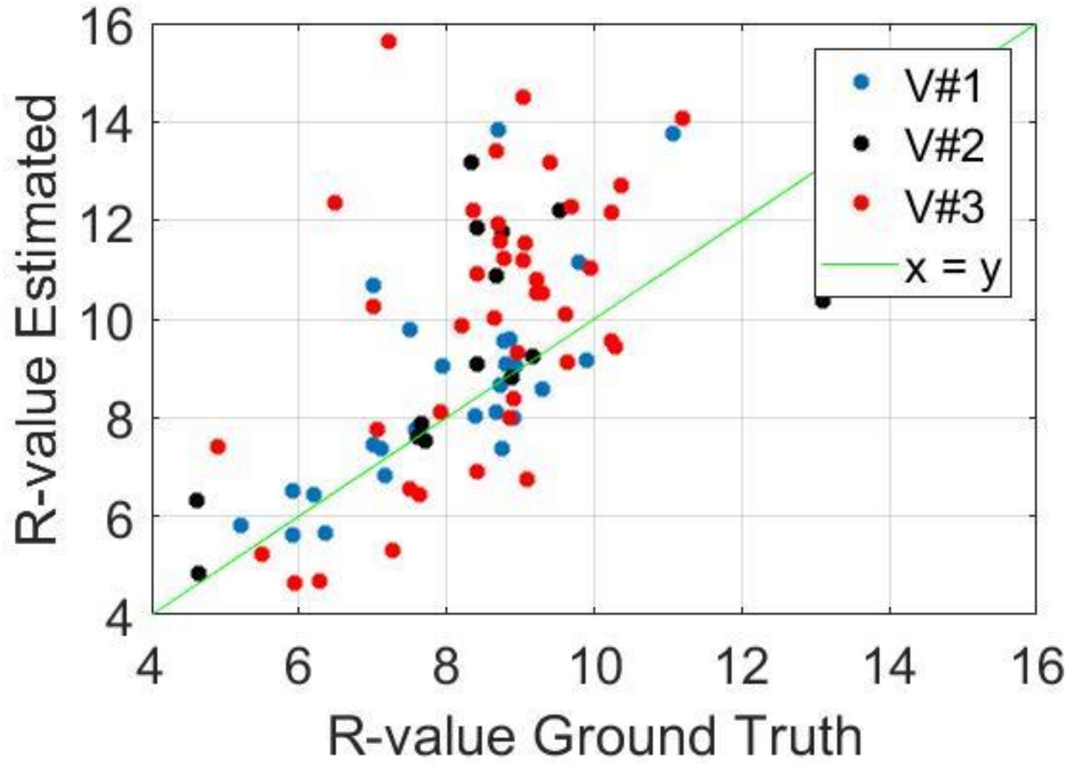
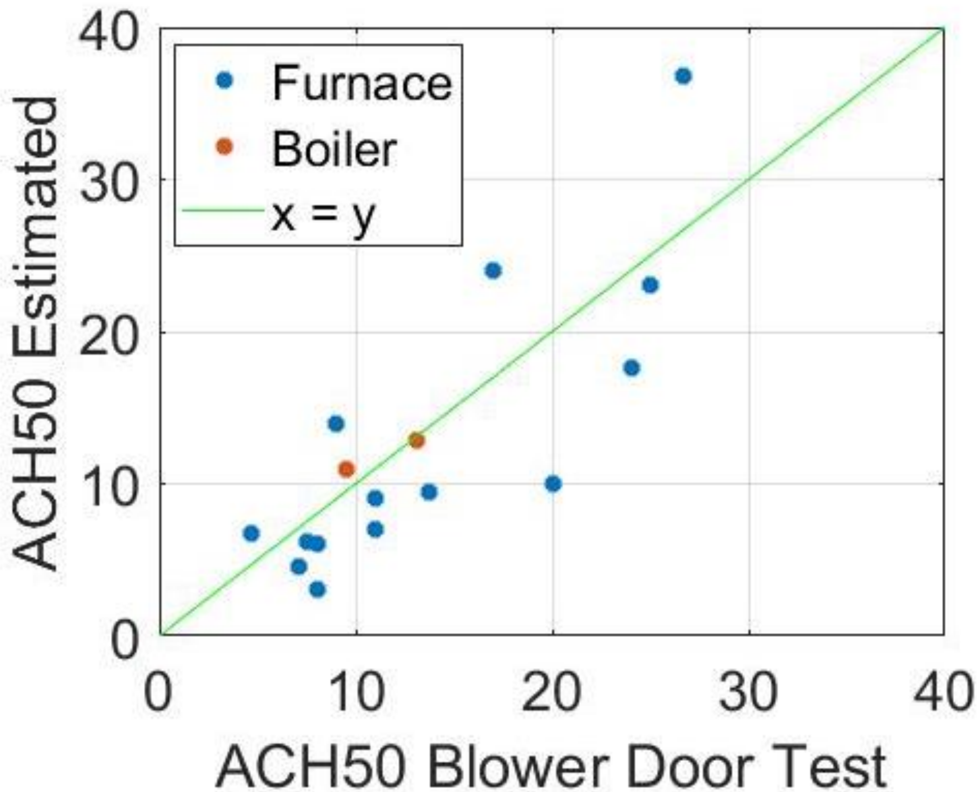
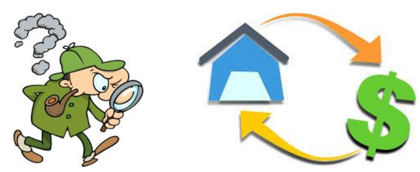
Classification accuracy does not appear to vary with CT vendor.



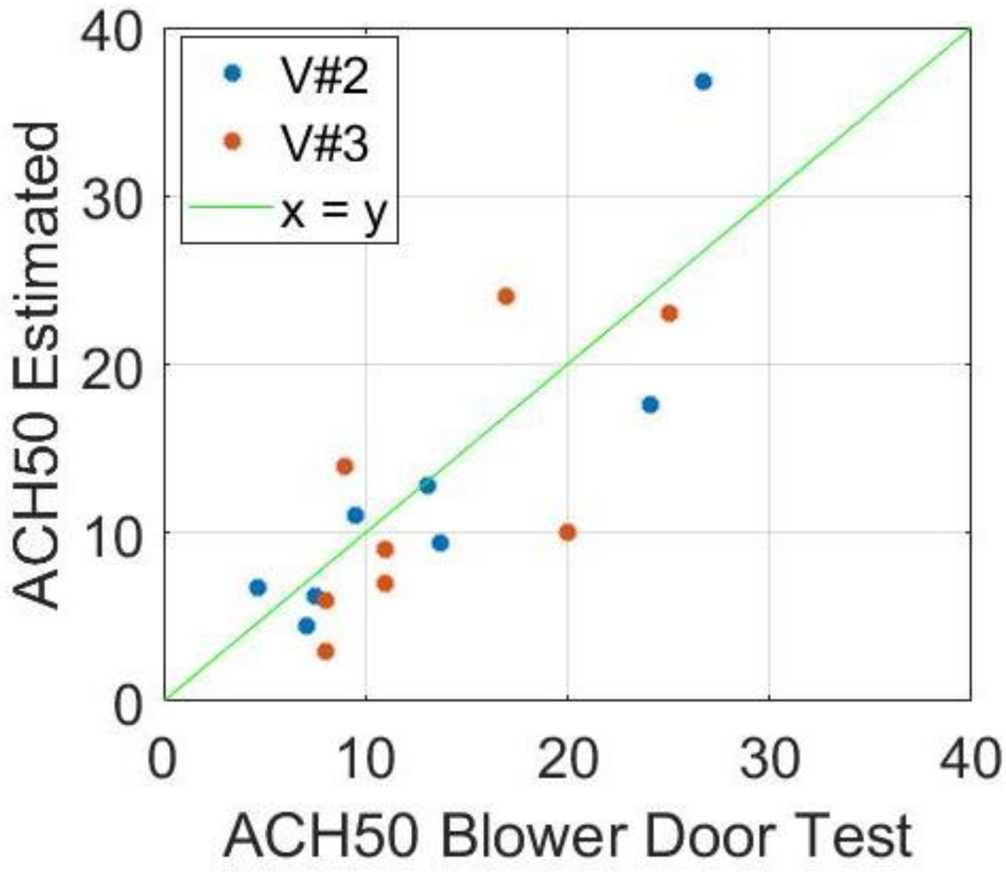
The algorithm accurately classifies ACH_{50}.



n = 16



ACH_{50} accuracy does not appear to vary with CT vendor.



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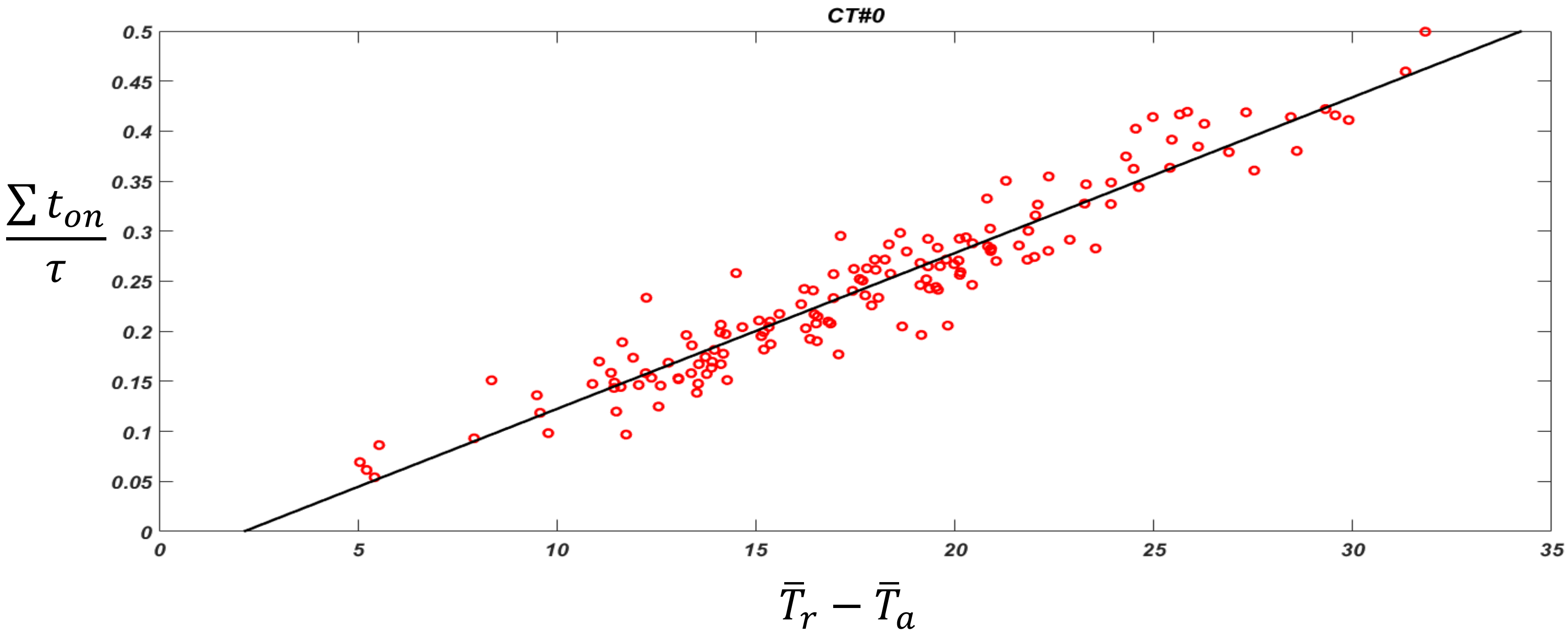
Significance of results: The blowerdoor test

Source: Holtkamp Heating & A/C, Inc.

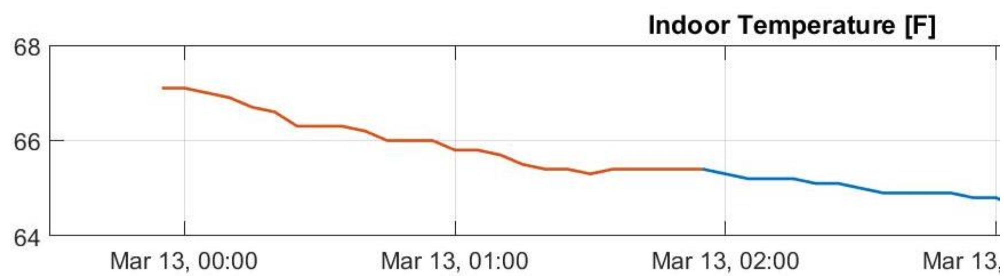
Saving estimations



- Retrofits → new R_w and/or air leakage coefficients
- Predict how correlations will change
- Calculate savings
- Easy to incorporate: thermal comfort, different weather

“Time Constant” Approach

- Simple exponential decay with rate $\frac{1}{\tau} \cong \frac{A_w}{C_r R_w}$ when $Q_{HVAC} = 0$, assuming:
  - 1st order model (no building envelope): $C_r \frac{dT_r}{dt} = Q_{HVAC} + q_{int} + A_w/R_w(T_a - T_r) + q_{inf}$
  - Infiltration: neglected totally or only wind effect present (no thermal stack effect)
- Let’s attempt this approach under mild conditions:
  - Calculated from midnight to 2AM time windows
  - No heating for 1+hour before midnight and during time window
  - T_a varies by <2°C
  - T_r does not increase by >0.2°F
  - Mean T_a <40°F



***T_a* = 14-16°F**

References: Chong and George (2016), Goldman et al. (2014)

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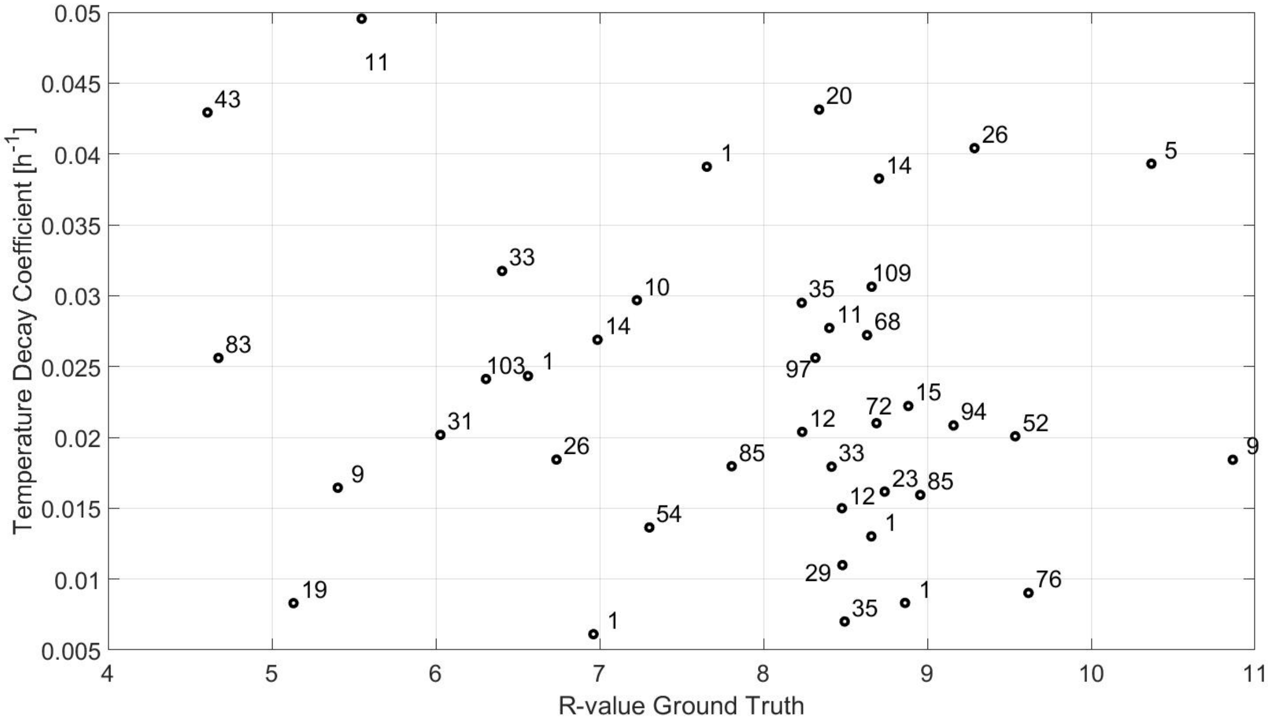
Time Constant Approach: correlation 1/τ vs. R-value?

$$\frac{1}{\tau} \cong \frac{A_w}{C_r R_w}$$

under the time-constant assumptions

Number of time windows used to calculate α value shown



2nd-order model with wind and stack effects:

$$C_r \frac{dT_r}{dt} = Q_{HVAC} + q_{int} + A_w/(R_w/2)(T_w - T_r) + q_{inf}$$

$$q_{inf} = -\rho_{air} c_{p,air} (C_1 W^{2.6} + C_2 |T_a - T_r|^{1.3})^{0.5} (T_r - T_a)$$

Conclusions and Looking Forward

- For homes with 1 CT, we can accurately:
  - Estimate ACH_{50}
  - Classify whole-home R-value
  - Separate insulation from air sealing opportunities

- Next:
  - Extend algorithms to homes with multiple CTs
  - Evaluate ability to predict energy savings from target retrofits
  - Perform Randomized Controlled Trial (RCT) to test hypothesis: Does targeted, customized outreach increase rate of HEAs conducted *and* ECM implementation?
  - Finalize recommendations for scale-up: CT Data Specification, Best Practices Guide for Utility Program Integration

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