U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Physics-based Interval Data Models to Automate and Scale Home Energy Performance Evaluations

Fraunhofer USA
Co-PIs: Kurt Roth, Ph.D. and Michael Zeifman, Ph.D.
(617) 353-1895 kroth@Fraunhofer.org

Project Summary

Timeline:

Start date: 8/1/2016

Planned end date: 1/31/2020

Key Milestones

1. Homes with one communicating thermostat (CT) and furnace or boiler: classify insulation or air-sealing opportunity with 75%+ accuracy, predict runtime with ±25% accuracy (met June 2018)
2. Same, for homes with 2 CTs (met Feb. 2019)

Budget:

Total Project $ to Date (through 2/28/19):

- DOE: $766,963.
- Cost Share: $336,487

Total Project $:

- DOE: $1,050,158.
- Cost Share: $492,061.
- *Total Project: $1,542,219.*

Key Partners:

Eversource
National Grid
Holyoke Gas & Electric (HG&E)

Project Outcome:

Validated algorithms that automatically analyze communicating thermostat (CT) data to accurately identify homes with a major attic and/or wall insulation or Air sealing retrofit opportunity and accurately estimate the retrofit energy savings.

This will enable targeted and customized outreach by utility energy efficiency programs to improve their effectiveness:

1. Double the uptake of energy audits
2. Double the uptake of target energy conservation measures (ECMs)
3. Provide remote EM&V of those retrofits

Team

Fraunhofer USA

Applied R&D Expertise in:
- Building Physics
- Applied Mathematics
- Energy Modeling

Kurt Roth, Ph.D.

Michael Zeifman, Ph.D.

Amine Lazrak, Ph.D.

The largest electric and gas utilities in New England
- Run the EE programs ranked #1 by ACEEE
- Contribute anonymized customer data
  - Communicating thermostat (CT) time series
  - Monthly gas bills
  - Home dimensions
- Implement a randomized-controlled trial (RCT)
- Provide feedback on EE program integration

EVERSOURCE ENERGY

nationalgrid

Sources: CEE.

Challenge

Utility Energy Efficiency Program Challenges:

- **Large Unrealized Savings Opportunities**
  - 20-25% of homes with poor/no insulation
  - Slow market uptake of home insulation and air-sealing measures

    → <1% of households/year in Massachusetts (top U.S. EE programs)
- **Home Retrofit Program Cost-effectiveness**
  - Home energy assessments (HEAs) are costly ($250-400) and inconvenient
  - Only about 1/3rd of HEAs result in a major retrofit

    → Customer acquisition cost of ~$1,000, threatening program cost effectiveness
  - *Claimable* low-cost lighting savings that support other retrofits are projected to be greatly diminished circa 2020 ("LED cliff")
- **Systematic field problems with retrofits often not identified for years**

Sources: ACEEE (2018), DOE/BTO (2012), DOE/EIA (2019).

Approach: Project Technical Objectives

- Develop and validate a tool for targeted customer outreach in utility EE programs that analyzes communicating thermostat (CT) data to automatically and accurately:
  - Identify homes with largest retrofit opportunities
    - Insulation upgrade (overall R-value)
    - Air sealing upgrade (ACH_{50})
  - Quantify expected savings from retrofits
  - Perform post-retrofit performance evaluation, measurement and verification (EM&V) for individual customers

- Leverage the rapidly growing installed base of CTs
  - Approximately 30 million in U.S. homes circa 2019
  - Utility access to CT data through incentives

Sources: E-Source, Miziolek (2019)

Approach: Data Used

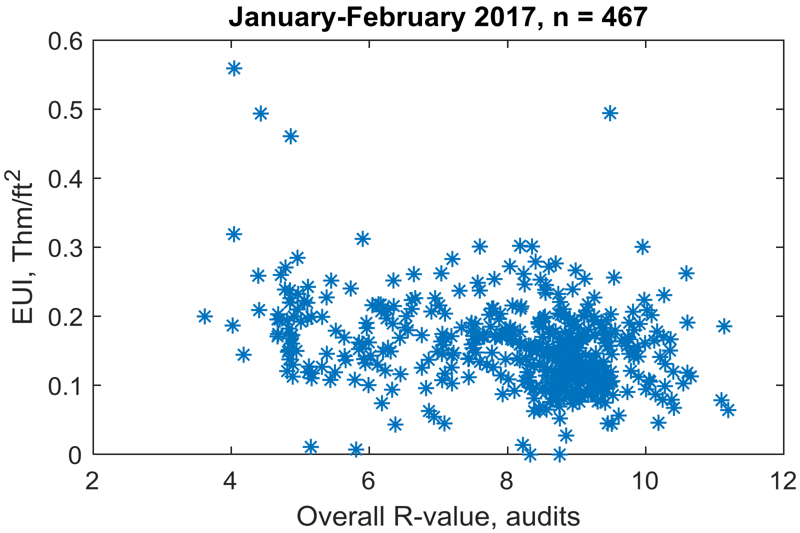
We received data for 2,000+ homes for algorithm development and validation

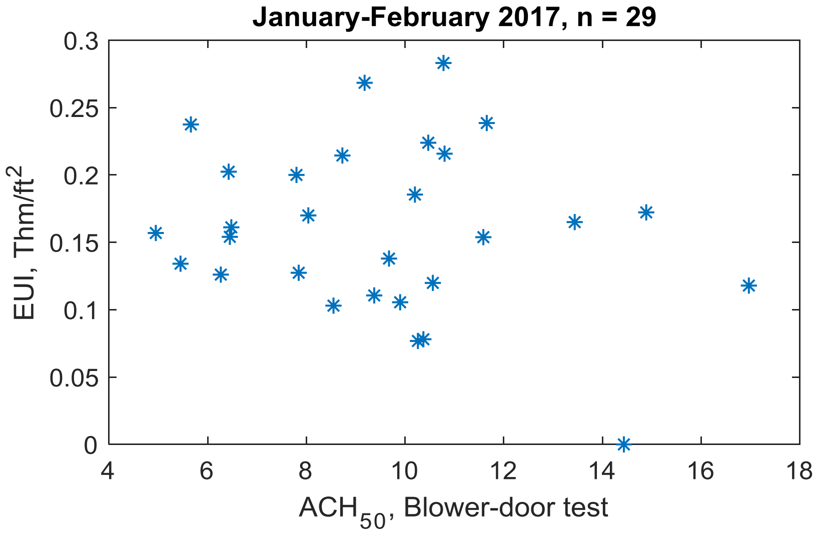
- *Complete* data sets includes: CT data for a heating season, coincident gas bills for 12 months, HEA data (conditioned area, volume, # of floors, R-values for envelope, ZIP Code, HVAC type – furnace or boiler)
- For some homes: Blower-door test results, ECM implementation data available
- Missing runtime is a persistent problem (50%+ of homes)

CT Vendor & Valid Data Sets	Data field				
	Heating System Status	Room Temp	Outdoor Temp	Wind Speed	Time Stamp
#1: 41 complete data sets (27 furnaces, 10 boilers)	Total runtime over 5-min interval Resolution=1s	5-minute average, Resolution=1°F	Hourly average from weather station Resolution=1°F	Hourly average from weather station Resolution =1km/h	Every 5 minutes
#2: 211 homes with complete sets (133/43) CT #3: 366 homes with complete sets (125/192)	On/Off status reported when any data field changes	Reported when any data field changes (not clear if average) Resolution=1°F	Hourly average from weather station Resolution=1°F	Not reported	Reported when any data field changes, Resolution=1s

Approach: Comparison with State of the Art

Utility State-of-the-Art – Space Heating Energy Usage Intensity (EUI, therm/ft^2): We found no significant correlation between EUI and whole-home R-value or ACH_{50}.





Other Approaches	Predict R-value	Predict ACH_{50}	Saving Prediction	EM&V	Validated	Scalable	Data Quality
PRISM[a]	✓	X	?	?	X	✓	✓
Cooling Curves[b]	X	X	X	?	X	✓	X
EnergyPlus Autotune"[c]	?	?	?	?	?	?	X

[a]Hallinan, K.P. et al. 2011. *ASHRAE Trans.* 117. [b]Goldman, E., *et al.* 2014. "Are Thermostats the New Energy Audits?" ; [c]J.R. New et al. 2016. *Appl. Energy* 182.

Approach: Modified Grey-box Model

Estimate physical parameters in 2nd order grey-box model by fitting to CT data:

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

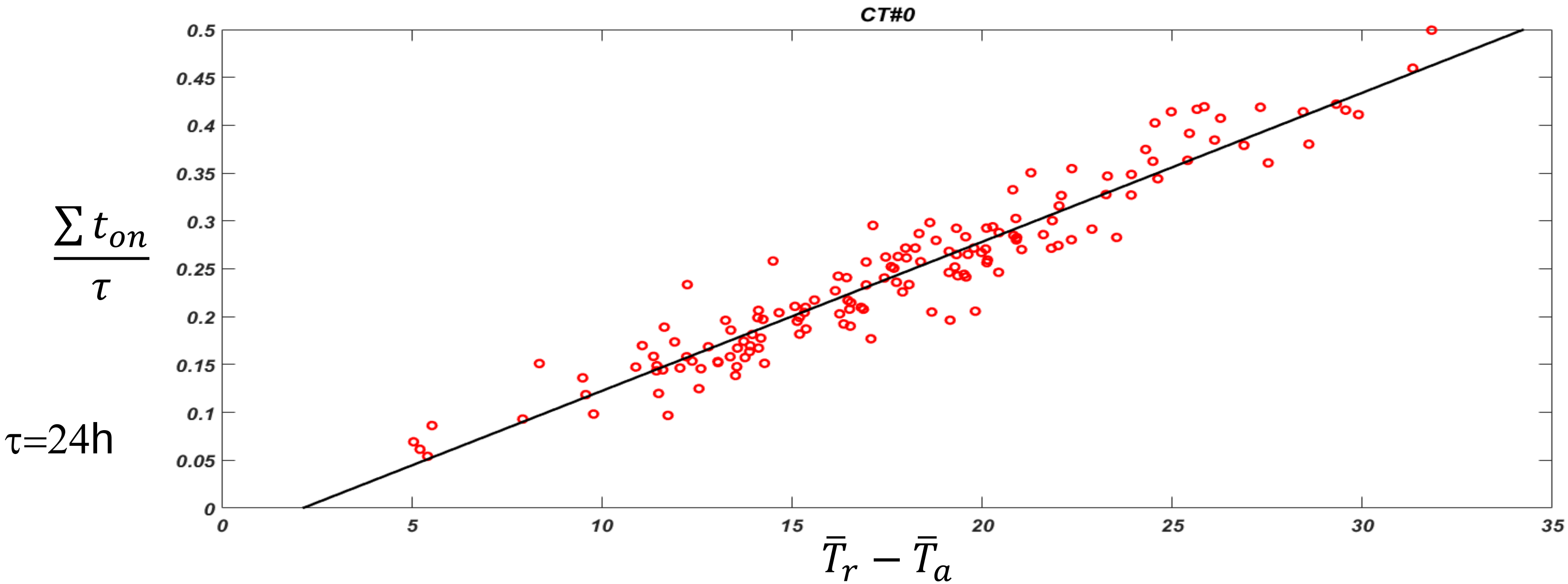
$$C_w \frac{dT_w}{dt} = A_w/(R_w/2)(T_r - T_w) + A_w/(R_w/2)(T_a - T_w) + q_{ext}$$ (enclosure energy balance)

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

- [green] = *known*, [red] = *prediction needed for home assessment*
- T_r, T_w, T_a = indoor, enclosure (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

- Innovations:
  - Isolate infiltration from R-value assessment by comparing runtime during periods with similar outdoor temperatures and high- and low-wind speeds (2018 patent application)
  - Use "global" correlations (e.g., time integrals of the equations) to address zone- and data-quality challenges (patent applications, 2017-2018)
- Three Peer-Reviewed Publications: *Proc. BuildSys 2017; Proc. ACEEE Summer Study (2018); Energy Efficiency* (2019).

Approach: High-resolution PRISM



- PRISM: (fuel billed) $\times \eta = (\overline{conduction} + \overline{infiltration}) \times (\overline{T_r} - \overline{T_a}) - \overline{heat\ gains})$

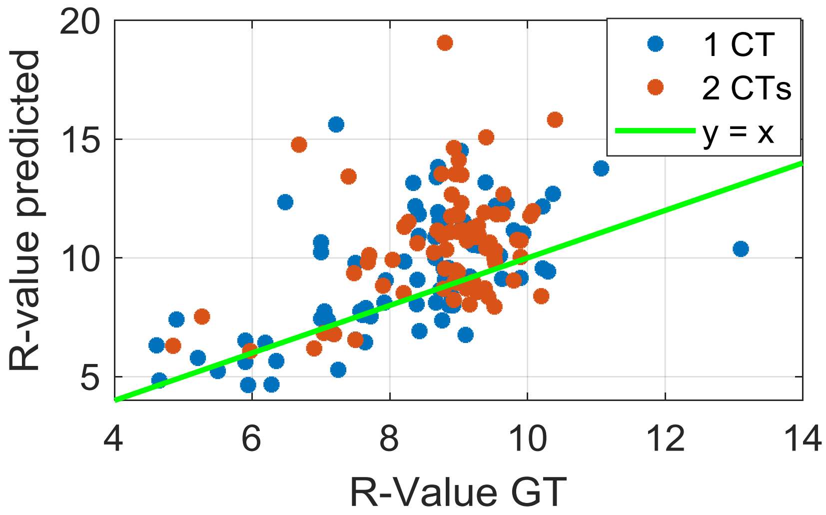
$$\frac{\sum t_{on}}{\tau} = \left[\frac{A_w}{R_w Q_{hvac}} + \sqrt{\left(\frac{\rho c_p}{Q_{hvac}}\right)^2 C_1 \bar{W}^{2.6} + \left(\frac{\rho c_p}{Q_{hvac}}\right)^2 C_2 |\bar{T}_r - \bar{T}_a|^{1.3}} \right] (\bar{T}_r - \bar{T}_a) - \frac{q}{Q_{hvac}}$$

- Sacrifice: η (assume ~80%)
- Can predict runtime and future savings from retrofits, and perform EM&V

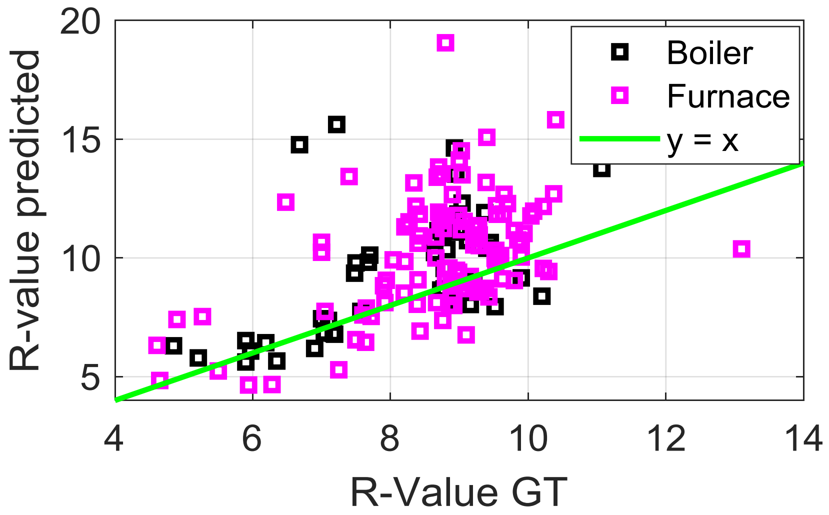
Sources: Fels (1986).

Results: Overall R-value

We classified whole-home R-value with a 89% accuracy as compared to ground-truth values derived from the home energy assessments (n = 154).



Results by number of CTs

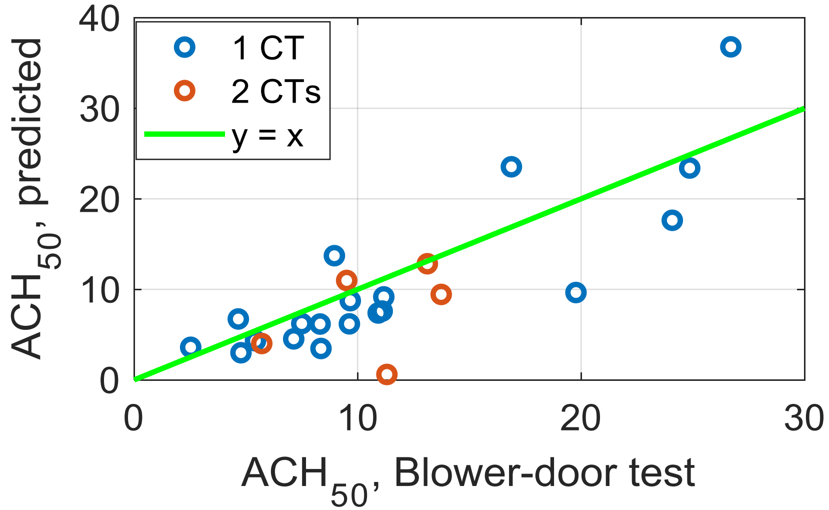


Results by heating system type

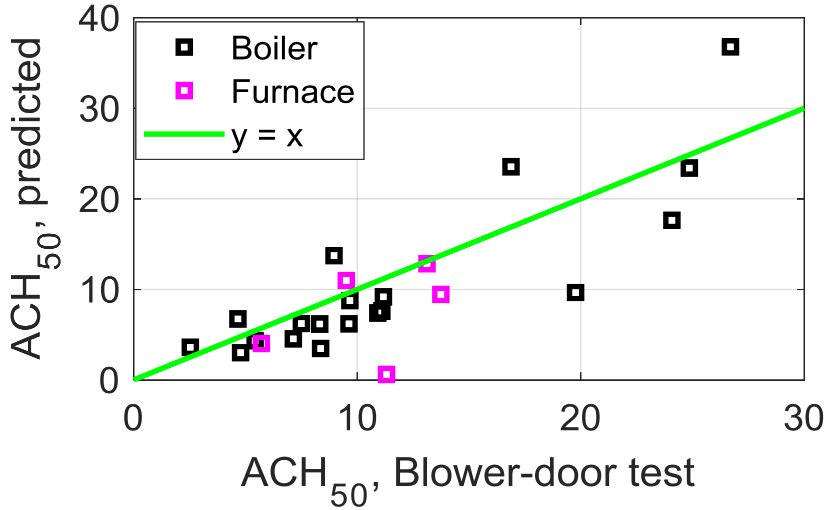
Classification Accuracy (R>8 or ≤ 8) = 89%

Results: ACH_{50}

We classified ACH_{50} with a 96% accuracy as compared to ground-truth values from blower-door tests (n= 24).



Results by number of CTs



Results by heating system type

Classification Accuracy (ACH_{50} > 15 or ≤ 15) = 96%

Impact

Market Opportunity:

- **Space heating is the largest residential end use (~6 quad/~30% of total energy)**
- **Roofs, walls and air leakage account for ~12, 19, and 28% of load, respectively**
- **20-25% of homes with poor/no insulation consume more space heating energy**
- **Wall and/or attic insulation and air sealing can significantly reduce space heating and cooling energy consumption**

  → *Basic* retrofits could save consumers approximately ***$4-5 billion per year***

  → Major contribution to achieving Building America goal of saving 40%+ for existing homes through High-Performance, Moisture-Managed Envelopes at scale

Market Impact: License validated algorithms to enhance utility energy-efficiency (EE) programs by identifying homes with a major insulation or air-sealing retrofit opportunity to enable targeted and customized outreach:

1. Double the uptake of energy audits
2. Double the uptake of target energy conservation measures (ECMs)
3. Provide remote EM&V of retrofits
4. Increase program cost effectiveness

Stakeholder Engagement

The two largest utilities in New England are integral team members

- Shared comprehensive anonymized data sets for >4,000 customers
- Planning and implementing randomized-controlled trial (RCT) using algorithms
- Shaping program integration strategy
- Working with leading home energy services provider (CLEAResult)

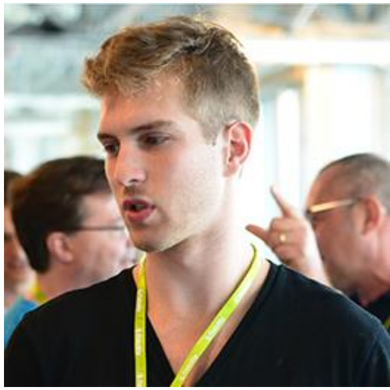
Presentations to utility EE program administrators

- Consortium for Energy Efficiency (CEE) Winter Program Meeting (2019)
  - CEE members = ~79% of utility EE funds
- ACEEE Summer Study (2018)
- EPRI Smart Thermostats and Customer Connected Devices Workshop (2019)

EVERSOURCE ENERGY

Peter Klint

Brian Greenfield



Brenda Pike

Cassandra Vickers

nationalgrid

Sources: CEE.

Remaining Project Work: Validation to Scale

BP2 (through May 2019):

- Launch RCT with targeted, customized outreach
- Complete Final CT Data Framework & Specification
- Complete Final Conceptual Plan to Integrate Algorithms in EE Programs

BP3 (June 2019 – January 2020):

- Evaluate the RCT
- Validate CTs for home-level ECM EM&V
- Compose Best Practices Guide for Scale Up

Future Work

- License algorithms to EE programs
- Apply algorithms to CTs used with air conditioners and heat pumps

Remaining Project Work: Validation to Scale

RCT Research Questions: Does reaching out to customers with specific ECMS and predicted savings increase:

1. Home Energy Assessment (HEA) uptake
2. Uptake of energy conservation measures

Randomized Controlled Trial (RCT) Design

Group Type	Description	Additional Outreach?	N (approx.)
Control	1. CT incentive, have CT data	Generic outreach.	700
	2. CT incentive, other CT type	None.	1,000
	3. No CT incentive	None.	1,000
Treatment	1. CT incentive, have CT data	Customized outreach	250

Thank You

Fraunhofer USA

Co-PIs: Kurt Roth, Ph.D. and Michael Zeifman, Ph.D.

Contact: 617 353-1895 – kroth@Fraunhofer.org

REFERENCE SLIDES

Project Budget

Project Budget:

- Approved (BP1+BP2): DOE = $862,480, Cost Share = $384,202
- Additional BP3 Funds (approval pending): DOE=$187,668 ($107,859 CS)

Variances: No appreciable total budget variances; reallocated ~80% of HG&E budget due to nonperformance.

Cost to Date: 72% of $1,542,219 expended (through 2/28/19)

Additional Funding: None beyond Fraunhofer and utility partners' cost share.

Budget History					
8/1/2016 – FY 2018 (past)		FY 2019 (through 2/28/19)		FY 2020 – 1/31/2020 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$600,948	$245,561	$766,963	$336,487	$1,050,158	$492,061

Project Plan and Schedule

- Project Initiation Date: 8/1/16 (received on 9/21/16)
- Original Project Completion Date: 7/31/2019
  - Requested and received six-month project no-cost extension, primarily due to delays in receipt of project, human subjects review, and hiring post-doctoral fellow.

Project Schedule		
Project Start: 8/1/2016		Completed Work
Projected End: 1/31/2020		Active Task (in progress work)
	M	Milestone/Deliverable (Originally Planned)
	M	Milestone/Deliverable (Actual)

	FY2016	FY2017				FY2018				FY2019				FY2020	
Task	Q4 (July-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (July-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (July-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (July-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)
Past Work															
Q1 Milestone: Draft CT Data Specification		M	M												
Q2 Milestone: Data from 80+ homes			M												
Q3 Milestone: Data from 200+ homes				M				M							
Q3 Milestone: Furnace + 1CT Algorithm Accuracy				M				M							
Q4 Milestone: Draft EE Program Integration Plan					M			M							
Q5 Milestone: Boiler + 1CT Algorithm Accuracy						M		M							
BP1 Go/No-Go Decision Point: 1CT Accuracy						GNG		GNG							
Q6 Milestone: 2CT Models Demonstrated										M					
Q7 Milestone: 2CT Model Accuracy										M	M				
Q8 Milestone: Retrofit Energy Savings Accuracy										M	M				
Q8 Milestone: Field RCT Test Plan Completed										M	M				
Current/Future Work															
Q8 Milestone: Final EE Program Integration Plan										M					
Q9 Milestone: Final CT Data Specification											M				
BP2 Go/No-Go Decision Point: 2CT Model Accuracy												GNG			
BP2 Go/No-Go Decision Point: Retrofit Savings Accuracy												GNG			
Q10 Milestone: Field RCT Implemented												M			
Q11 Milestone: RCT Evaluation Completed															M
Final Reporting: Final Project Report															M
Final Reporting: Best Practices Guide for Scale-Up															M