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

New 2016 Project

2017 Building Technologies Office Peer Review

Fraunhofer USA

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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Project Summary

Timeline:

Start date: 9/21/2016 (contract received)

Planned end date: 7/31/2019

Key Milestones

1. Homes with one CT + furnace: classification accuracy 75%+ for target ECMs, predict runtime with ±25% accuracy (June, 2017)
2. Homes with multiple CTs + furnace: 75%+ classification accuracy for target ECMs, predict runtime ±25% accuracy (July, 2018)

Budget:

Total Project $ to Date:

- DOE: $71,893 (as of 2/22/2017)
- Cost Share: $33,683 (estimated, 32%)
- *Total Project: $99,836*

Contracted Project $:

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

Key Partners:

Eversource Energy
Holyoke Gas & Electric
National Grid

Project Outcome:

Validate algorithms that automatically analyze communicating thermostat (CT) data to identify homes with at least one target energy conservation measure (ECM):

- Attic and/or wall insulation; air sealing, and heating system upgrade.

Enable targeted and customized outreach by utility energy efficiency programs to:

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

Project Motivation

Problem Statement:

- Space heating is the largest end use for homes in cold/very-cold climates
- Homes with poor/no insulation or inefficient heating systems have higher heating energy consumption
  - ~20-25 percent of homes
- Wall and/or attic insulation, air sealing, and HVAC system upgrades can significantly reduce space heating energy consumption
- Programs face high customer acquisition costs
- Slow market uptake of these proven measures
  - <1% of households/year in Massachusetts

Sources: DeMark Home Ontario. S. Edwards-Musa, Eversource Energy.

Project Objectives and Benefits

Project Objective: Develop a tool for utility energy efficiency (EE) programs that **analyzes communicating thermostat (CT) data** to **automatically identify** and **quantify the benefit** of **targeted and customized retrofit opportunities**

Customer and Utility Benefits:

- Double the deployment rate of the target energy conservation measures (ECMs)
- 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**

Sources: DOE BTO (2012), Massachusetts TRM (2013).

Project Impact

Project Impact:

- *Basic* ECMs identified have a technical heating savings potential ~0.5 quad/year
  - *Consumer savings of **$4-5 billion per year***
    - *Potential* annual *ROI on DOE investment of 3-4,000+*
  - Further savings from space cooling savings, deeper retrofits

BTO Building America Goals Addressed:

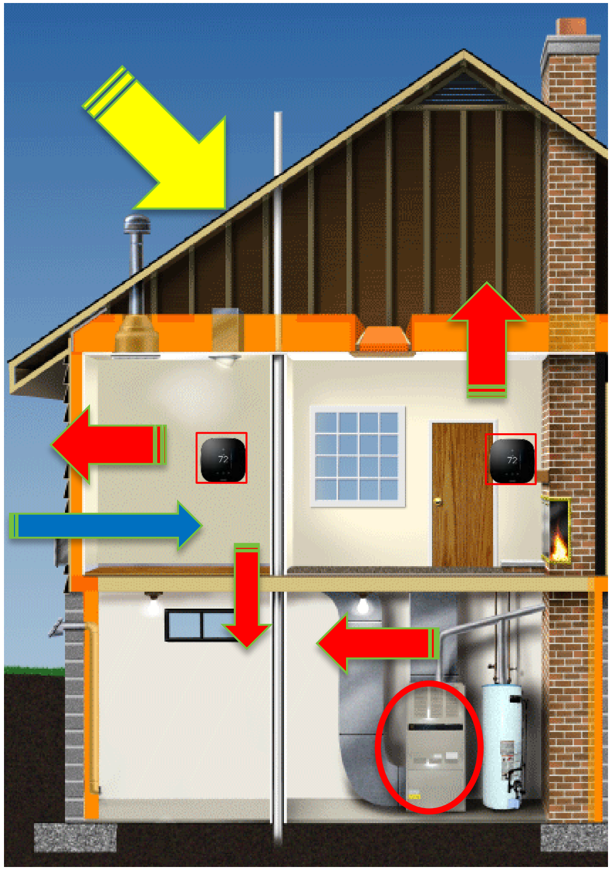
Affordably achieve 40% EUI reduction for existing homes

- Increase market demand for high-impact, high-performance home retrofits
  - Addresses two largest end uses: Space heating and cooling
- Reduce risk: Ensure retrofits *achieve and maintain* high performance
- Leverage dramatic growth in CT installed base = very low incremental cost

Approach: Technical Challenges

What the thermostat reports:

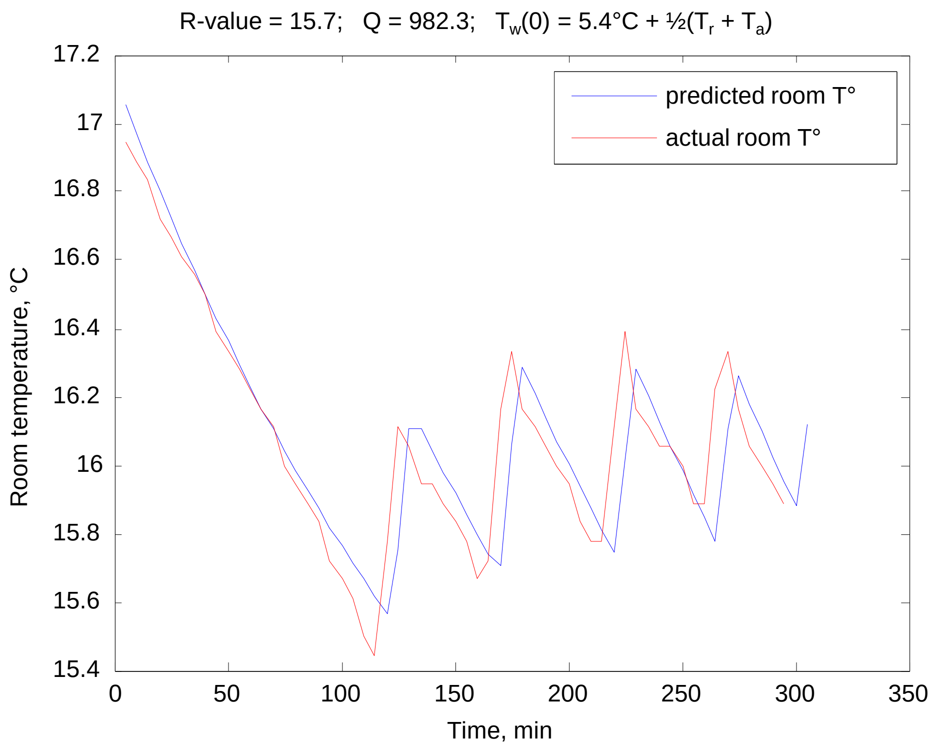
Date	Time	System Setting	System Mode	Calendar Event	Program Mode	Cool Set Temp (F)	Heat Set Temp (F)	Current Temp (F)	Current Humidity (%RH)	Outdoor Temp (F)	Wind Speed (km/h)	Cool Stage 1 (sec)	Heat Stage 1 (sec)	Fan (sec)
3/29/2016	0:00:00	auto	heatOff		Sleep	82	63	70	39	43.8	16	0	0	0
3/29/2016	0:05:00	auto	heatOff		Sleep	82	63	69.9	39	43.8	16	0	0	0
3/29/2016	0:10:00	auto	heatOff		Sleep	82	63	69.8	40	43.8	16	0	0	0
3/29/2016	0:15:00	auto	heatOff		Sleep	82	63	69.8	40	43.8	16	0	0	0
3/29/2016	0:20:00	auto	heatOff		Sleep	82	63	69.8	40	43.8	16	0	0	0
3/29/2016	0:25:00	auto	heatOff		Sleep	82	63	69.7	40	43.8	16	0	0	0
3/29/2016	0:30:00	auto	heatOff		Sleep	82	63	69.6	40	42.7	22	0	0	0
3/29/2016	0:35:00	auto	heatOff		Sleep	82	63	69.4	40	42.7	22	0	0	0
3/29/2016	0:40:00	auto	heatOff		Sleep	82	63	69.3	40	42.7	22	0	0	0
3/29/2016	0:45:00	auto	heatOff		Sleep	82	63	69.1	40	42.7	22	0	0	0
3/29/2016	0:50:00	auto	heatOff		Sleep	82	63	69	40	42.7	22	0	0	0
3/29/2016	0:55:00	auto	heatOff		Sleep	82	63	68.9	40	42.7	22	0	0	0
3/29/2016	1:00:00	auto	heatOff		Sleep	82	63	68.9	40	42.7	22	0	0	0
3/29/2016	1:05:00	auto	heatOff		Sleep	82	63	68.8	40	42.7	22	0	0	0
3/29/2016	1:10:00	auto	heatOff		Sleep	82	63	68.7	40	42.7	22	0	0	0
3/29/2016	1:15:00	auto	heatOff		Sleep	82	63	68.6	40	42.7	22	0	0	0
3/29/2016	1:20:00	auto	heatOff		Sleep	82	63	68.6	40	42.7	22	0	0	0
3/29/2016	1:25:00	auto	heatOff		Sleep	82	63	68.5	40	42.7	22	0	0	0
3/29/2016	1:30:00	auto	heatOff		Sleep	82	63	68.5	40	42.6	19	0	0	0
3/29/2016	1:35:00	auto	heatOff		Sleep	82	63	68.4	40	42.6	19	0	0	0
3/29/2016	1:40:00	auto	heatOff		Sleep	82	63	68.4	40	42.6	19	0	0	0
3/29/2016	1:45:00	auto	heatOff		Sleep	82	63	68.3	40	42.6	19	0	0	0
3/29/2016	1:50:00	auto	heatOff		Sleep	82	63	68.2	40	42.6	19	0	0	0
3/29/2016	1:55:00	auto	heatOff		Sleep	82	63	68.2	41	42.6	19	0	0	0
3/29/2016	2:00:00	auto	heatOff		Sleep	82	63	68.1	41	42.6	19	0	0	0



Sources: DOE, Ecobee, Fraunhofer CSE.

Approach: Technical Challenges

Example of parameter estimation by curve fitting using CT data from a single night.



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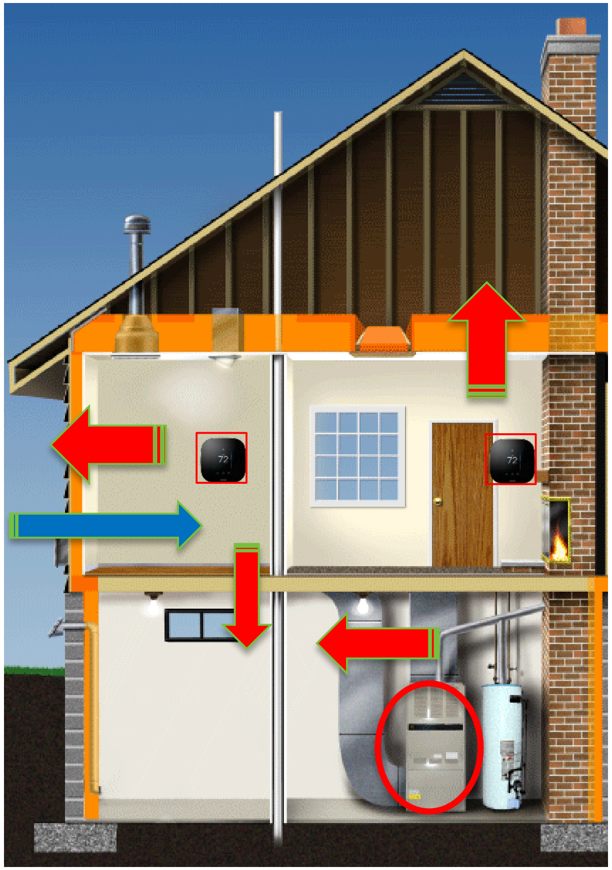

Sources: DOE, Ecobee, Fraunhofer CSE.

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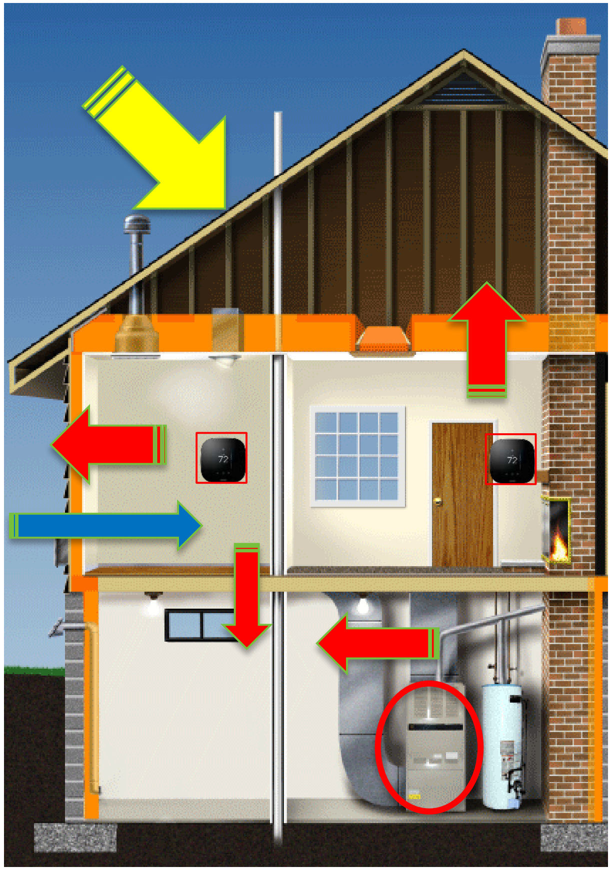
Approach: Technical Challenges and Approach

Key Challenges:

- Different physical parameters can create similar building thermal responses
- Different HVAC systems have different response times and characteristics
- Many homes have multiple CTs
- Thermal response “noise” from internal heat gains



Project Approach:

Analyze *real-world CT, interval, and home energy audit data* to successively refine home thermal response models to *accurately estimate home physical parameter*s that correspond to the target ECMs *in increasingly complex situations*.

Sources: DOE, Ecobee.

Approach: Technical Approach

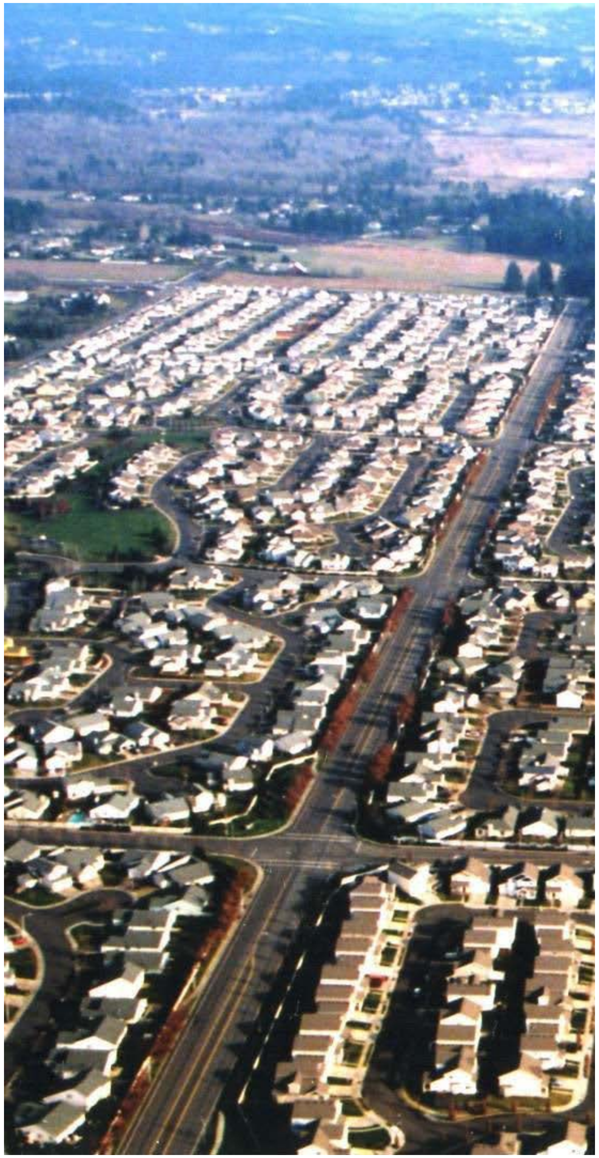
Basic Approach:

1. Energy balances on the enclosure and indoor air
2. Fit real-world CT data sets to gray-box thermal models to determine the physical parameters
3. Compare physical parameters to thresholds indicative of retrofit opportunity

Approach to Overcoming the Technical Challenges: Data, Data, and More Data

Superior data quality and quantity enables a ***hybrid gray-box thermal modeling and machine-learning approach*** to develop and train algorithms

- CT and Home Energy Audit data for several hundred + homes
- Deep "ground truth" data from 80 homes with CTs
  - Home energy audit with blower door testing
  - Interval gas (hourly) and electric (5-minute) data



Source: Clearmeadows Community Association, DOE.

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Approach: Scaling for Impact

1. Project Team: Two leading IOUs and innovative muni
   – Leverages data from existing CT programs
2. Project integrates randomized controlled trial (RCT) to validate key hypothesis of project:

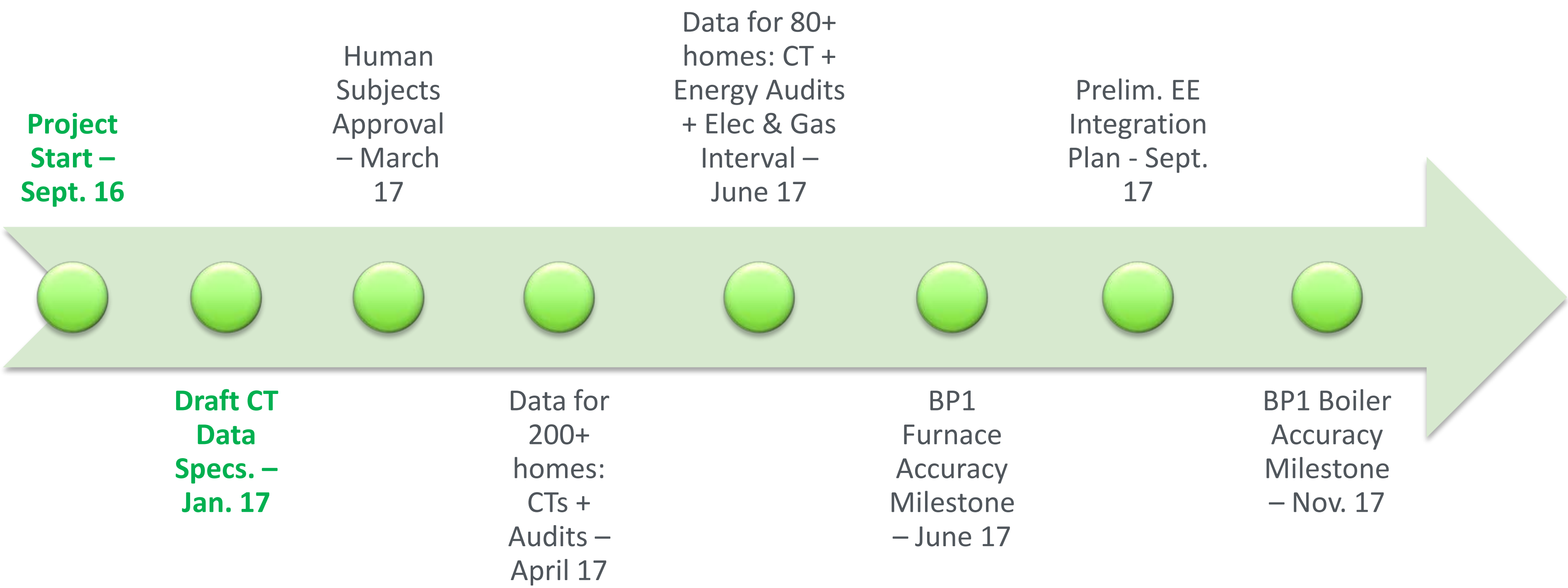
   Do targeted outreach and customized EE offers double the uptake of home energy audits and targeted ECMs?
3. Project Deliverables to Scale Impact
   – CT Data Specification
   – Best Practices Guide for EE Program Integration
4. Near-term outcome: Integrate with Eversource and National Grid EE programs
5. Target Future Outcomes:
   – Leverage growth in CTs – projected ~25MM in 2019
   – CT data specification adopted by other utilities, EE programs, and EnergyStar
   – CT analytics used by other EE programs

Source: ACHRNews (2015).

Progress and Accomplishments – *Note: New Project*

- Reviewed literature on lumped parameter/gray box modeling and identification
  - Second-order model should be sufficient (considered higher-order)
  - Curve-fitting-based approach
- Derived closed-form solution to 2nd-order gray-box differential equations
- Developed a program for parameter estimation in MATLAB
  - Fitting the closed-form solution for room T° to observed T° (from CT data)
  - Estimates R-value and heat flux using single or multiple nights of data
  - Can also estimate air leakage parameter with data from multiple nights
  - Preliminary testing with existing, proprietary CT data
- Developed a program for fuel consumption estimation in MATLAB
  - Based on PRISM (PRInceton Scorekeeping Method)
  - Calculates heating energy consumption rate
  - Given the estimated heat flux, calculates HVAC efficiency

Progress and Accomplishments – *Note: New Project*



BP1 Accuracy Milestones are for homes with *one CT and heating system*:

a) ±25% accuracy in HVAC runtime

b) 75%+ classification accuracy

BP2: Extend accuracy to homes with *multiple* CTs, energy savings estimates for ECMs.

Lessons Learned to Date:

- CT data access and resolution varies greatly among CT providers
- Energy audit information vs. data

Project Integration and Collaboration

Project Integration: Team comprises utility residential and evaluation teams
- Discussions with leading CT manufacturers about data resolution and sharing
- CPUC, NYSERDA, and PG&E have expressed interest in the project
- *Future:* Share and scale the project outcomes through leading utility EE forums

Partners, Subcontractors, and Collaborators: Core team has three utility members
- Data sharing: CT and home energy audit data, interval data
- Planning and execution of the RCT pilot to evaluate effectiveness
- Development of Best Practices Guide for integration of the algorithms with EE programs (for both increasing EE deployment and EM&V)

Communications:
- "Communicating Thermostats as a Tool for Home Energy Performance Assessment" – *Proc. 2017 IEEE Intl. Conf. on Consumer Electronics (ICCE).* Jan.
- 2017 Better Buildings Summit – Accepted invitation to present

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Conclusions, Next Steps, and Future Plans

Conclusions:

- Systematic data-driven approach to develop algorithms
- Identifies high-impact retrofits for largest residential end use
- Increases market demand for impactful retrofits and validates performance
- Clear path to commercialization and scale through leading utility EE programs

Next Steps and Future Plans:

- Further refine algorithms for single-family homes with furnace + 1CT
- Secure Human Subjects approval
- Start working with larger Eversource and National Grid data sets
- Recruit 80 HG&E homes for project – deploy CTs, complete energy audits

Potential Project Extensions to Increase Project Impact:

- Validate effectiveness in more moderate climates
- Expand to space heating with heat pumps
- Expand to space cooling applications
    - Deeper integration of electric interval data

REFERENCE SLIDES

Project Budget

Project Budget: DOE Funds: $1,050,158, Team Cost Share: $492,061;
Total $1,542,219

Variances: None to date.

Federal Cost to Date: $71,893 as of Feb. 22, 2017; (7% of total federal funds)
Cost Share to Date: $33,683 estimated (32%)

Additional Funding: $492K in cost share from utility partners and Fraunhofer.

Budget History & Projections					
9/21/16– FY 2016 (past)		FY 2017 (current & planned)		FY 2018 – 7/31/19 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$18,398	$11,058	$331,760	$153,012	$700,000	$327,991
38% cost share		32% cost share		32% cost share	

Project Plan and Schedule

Project Start: 9/21/2016 (contract received, backdated to 8/1/2016)
Projected End: 7/31/2019

Completed work — **M** Expected Milestone
Active Task — **M** Updated Milestone
Future Task — **GNG** Go/No-Go Decision Point

	FY 2016	FY 2017				FY 2018				FY 2019			
	Q4 (July-Sept)	Q1 (Oct-Dec)	Q2 (Jan-March)	Q3 (Apr-June)	Q4 (July-Sept)	Q1 (Oct-Dec)	Q2 (Jan-March)	Q3 (Apr-June)	Q4 (July-Sept)	Q1 (Oct-Dec)	Q2 (Jan-March)	Q3 (Apr-June)	Q4 (July-Sept)
Past Work													
Q1 Milestone: Draft CT Data Specification		M	M										
Current/Future Work													
Q2 Milestone: Data from 80+ homes			M	M									
Q3 Milestone: Data from 200+ homes				M									
Q3 Milestone: Furnace + 1CT Algorithm Accuracy				M									
Q4 Milestone: Draft EE Program Integration Plan					M								
Q5 Milestone: Boiler + 1CT Algorithm Accuracy						M							
BP1 Go/No-Go Decision Point: 1CT Accuracy						GNG							
Q6 Milestone: 2CT Models Demonstrated							M						
Q7 Milestone: 2CT Model Accuracy									M				
Q8 Milestone: Retrofit Energy Savings Accuracy									M				
Q8 Milestone: Field RCT Test Plan Completed									M				
Q8 Miletstone: Final EE Program Integration Plan									M				
Q9 Milestone: Final CT Data Specification											M		
BP2 Go/No-Go Decision: 2CT Model Accuracy									GNG				
BP2 Go/No-Go Decision: Retrofit Energy Savings Accuracy									GNG				
Q10 Milestone: Field RCT Implemented											M		
Q11 Milestone: RCT Evaluation Completed												M	
Final Reporting: Final Project Report													FR
Final Reporting: Best Practices Guide for Scale Up													FR