U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Sensors and Controls (S&C) R&D Overview

Marina Sofos, Ph.D.

BTO Peer Review

April 16, 2019

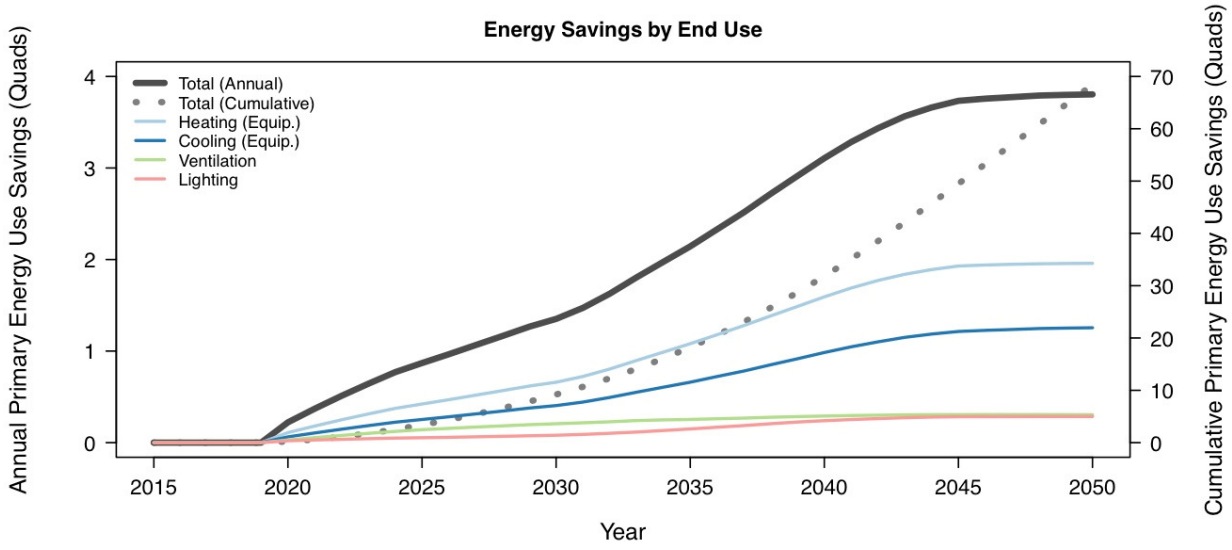
Motivation: Role of S&C Technologies in Buildings

- **Current state-of-the-art:**

  In the commercial sector, an aggregated annual energy savings of 29% is estimated through implementation of efficiency measures to optimize programmable settings based on occupant comfort requirements and to detect and diagnose operation and installation problems.

- **Future technological development:**

  Savings of 1.7 quads in 2030 and 3.7 quads in 2050 are targeted in both the residential and commercial sectors through advancements in the sophistication and scalability of emerging control strategies that can incorporate learning and adaptive capabilities based on changes in operating conditions.



Fernandez, N., Katipamala, S. et al., (2017). PNNL-25985.
Sofos, M., Langevin, J.T. (2018). ACEEE Summer Study on Energy Efficiency in Buildings.

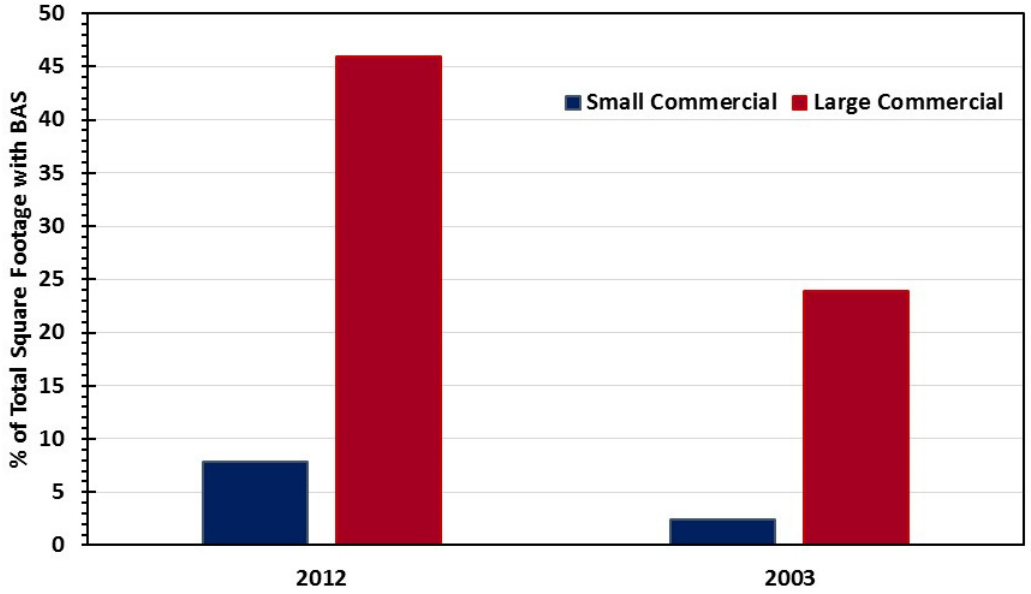
Existing Building Controls Landscape

While growing, adoption still not widespread –

- 46% of large commercial floor space (> 50,000 sq ft) have a centralized BAS, but only 8% of small commercial floor space (< 50,000 sq ft)
- 41% of homes have a programmable thermostat, but only 12% used the functionality and only 3% use a smart thermostat that learns behavior over time

Fragmented systems –

- Most centralized systems exclusively manage HVAC
- HVAC separated from control of other building systems (e.g., lighting, plug loads)



**U.S. Energy Information Administration Data*

Challenges Being Explored

Existing Barriers to Implementation of Optimized, Intelligent Operations:

- **Existing controls not designed for energy efficiency –**
  Simple, reactive controls for meeting short-term thermal & ventilation needs
- **Labor intensive –**
  Manual, hand-crafted installation & maintenance
- **High cost –**
  Customized, not integrated into the building design process
- **Limited budgets for energy management–**
  Not considered an "operationally critical" application
- **Limited interoperability –**
  Across systems/vendors
- **Confusion in product offerings –**
  Diversity of system configurations & lack of established performance baselines & testing

BTO S&C R&D Sub-Program Overview

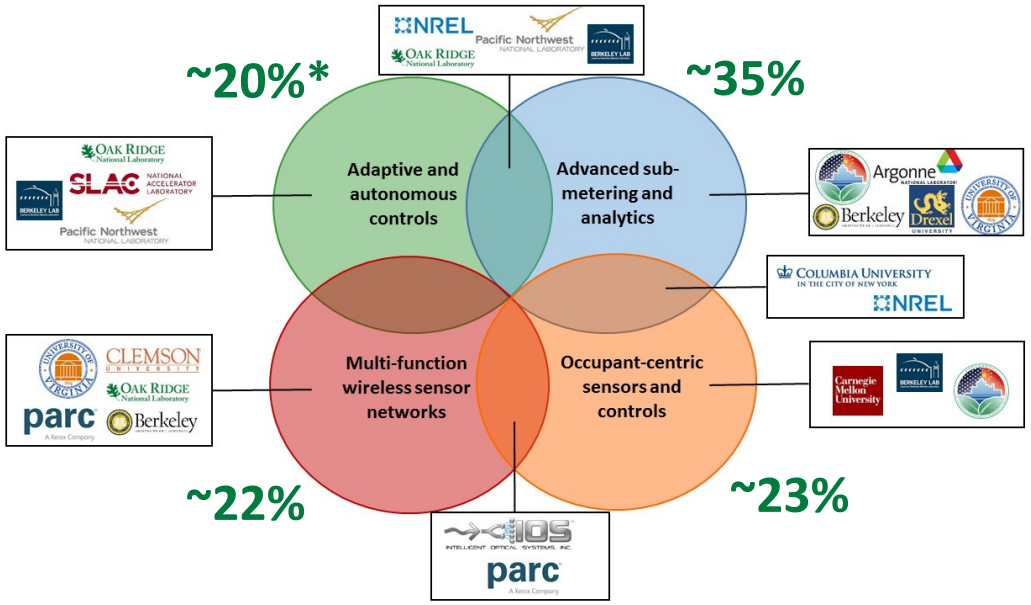
Sub-Program Objective:

Accelerate transition from simple, reactive controls to optimized, whole building controls that can meet both energy and occupant comfort objectives

R&D Approach:

– Sensors/sub-meters: reduce installed costs via automation, develop new sensing modalities

– Controls: develop and optimize model-based and data-driven approaches over longer time scales and multiple spatial scales that can incorporate additional input variables



For more information:

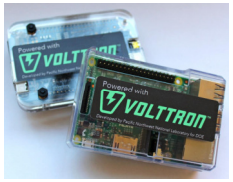
– https://www.energy.gov/eere/buildings/about-sensors-and-controls

**portions of analytics and OCC supporting controls focus area*

BTO-Wide S&C Portfolio Approach

SIMULATION

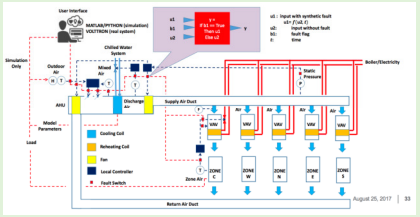
Collaborate with Building Energy Modeling (BEM) sub-program to support controls development and execution through long-term software engine improvements

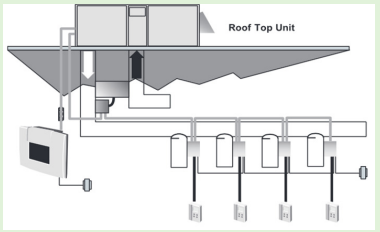


EnergyPlus

BENCHMARKING

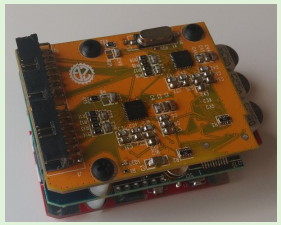
Development of testing frameworks/ methods & curated datasets to spur innovation by establishing expected performance





RESEARCH & DEVELOPMENT

Innovations in performance of sensor and control technologies to optimize building operations and achieve energy savings goals



VALIDATION

Collaborate with integration programs (RBI and CBI) to verify and increase confidence in implementing new technologies and strategies

R&D Funding Mechanisms

1. Directed National Laboratory Efforts – Annual Operating Plan (AOP) - ~40%

a) 1-3 Year Merit-Reviewed Lab Call Awards: FY17-19

b) Consortia: DOE Grid Modernization Lab Consortium (GMLC)

c) Industry Partnerships: CRADAs* and Small Business Voucher (SBV)

2. Awarded by Funding Opportunity Announcements (FOA) to Industry, Academia or National Labs- ~60%

a) FOAs: BENEFIT, BUILD *

b) Consortia: US-China Clean Energy Research Center (CERC)*

c) Small Business Innovation Research (SBIR)

* ***Cost-share required:*** *50% for CRADAs and CERC; 10-20% for FOAs*

Sub-program Evolution: Relevant Solicitations & Activities

2012

Scoping

Small- and Medium-Sized Commercial Building Monitoring and Controls Needs: A Scoping Study, PNNL-22169 (October 2012)

2013

FOA

Building Technologies "Turn Key" Open Source Software Solutions for Energy Management of Small to Medium Sized Buildings-2013,
DE-FOA-0000822 (March 28, 2013)

- Develop "turn key" BAS software solution for small commercial buildings that includes an open source architecture developed and tested initially at lab scale and in field with three plug and play devices, user-interface, and at least three software tools (i.e. "apps") for: control system set-up, system status display, and control system point auto-mapping

2014

FOA

Buildings Energy Efficiency Frontiers & Innovation Technologies (BENEFIT) – 2014,
DE-FOA-0001027 (Feb 4, 2014)

- Innovative Sensors and Sensor Systems

2015

FOA

Building University Innovators and Leaders Development (BUILD)-2015,
DE-FOA-0001167 (Nov 11, 2014)

- University-based teams (both undergraduate and graduate students led by faculty sponsor) with a minimum 50% direct project costs supporting undergraduates in innovative building energy efficiency technologies

Scoping

BTO Sensors and Controls R&D Workshop (April 2015)

Sub-program Evolution: Relevant Solicitations & Activities

2016

FOA

Small Business Innovation Research (SBIR)- 2016 Phase 1 Release 2, DE-FOA-00011417 (Nov 30, 2015)

- Technologies for Sensing and Managing Indoor Air Quality in Buildings – Accurate, stable humidity sensors

FOA

Building Energy Efficiency Frontiers and Innovation Technologies (BENEFIT)-2016, DE-FOA-0001383 (Dec 15, 2015)

- Open Topic for Energy Efficiency Solutions for Residential & Commercial Buildings
- Human-in-the-Loop Sensor & Control Systems
- Plug-and-Play Sensor Systems

2017

AOP

Building Technologies Offices FY2017 National Laboratory Call for Proposals & Merit Review, BTO-LMR-0001719 (Feb 3, 2016)

- Building Equipment Sub-metering
- Adaptive and Fault Tolerant Building Controls

FOA

Buildings Energy Efficiency Frontiers & Innovation Technologies (BENEFIT) – 2017, DE-FOA-0001632 (Nov 30, 2016)

- Open Topic for Energy Efficiency Solutions for Residential & Commercial Buildings
- Miscellaneous Electric Loads Research and Development (R&D)

2018

FOA

Buildings Energy Efficiency Frontiers & Innovation Technologies (BENEFIT) – 2018, DE-FOA-0001825 (Apr 27, 2018)

- Novel Approaches for Cyber-physical Systems in Buildings – S&C/BEM Nexus

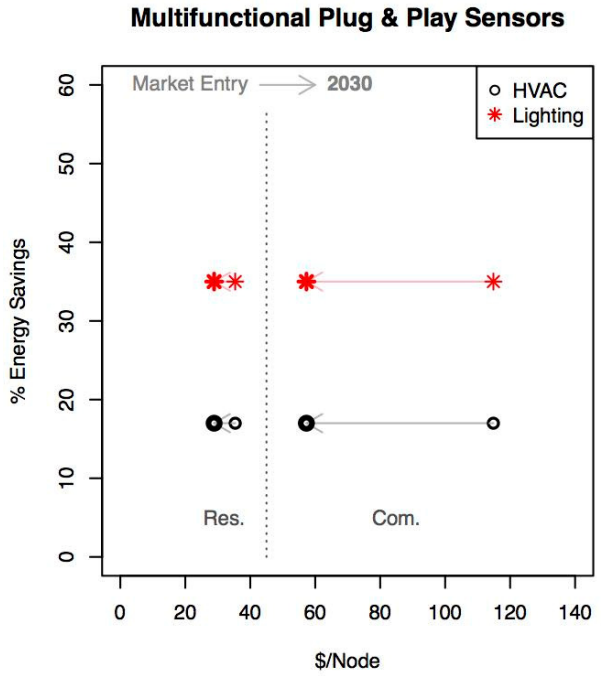
2019

Multi-Functional, Plug-and-Play Wireless Sensor Networks

Focus Area	Relevant ECM	Sector	Installed Cost		Energy Performance (HVAC, Lighting)		2030 Energy Savings Technical Potential
			Market Entry	2030 Target	Market Entry	2030 Goal	
Wireless Sensor Networks	Plug-and-play sensors	Residential	$35/ node	$29/ node	17%, 35%		1.14 quads
		Commercial	$115/ node	$57/ node			0.99 quads

Areas of Research:

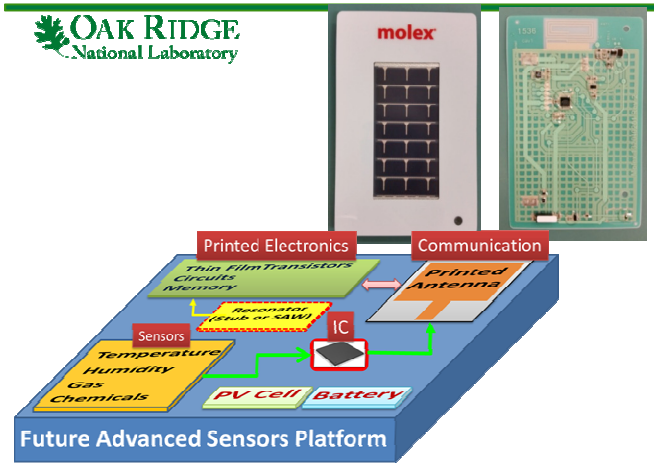
- Enhanced wireless communications
- Operational power lifetime
- Accuracy and reliability,
- Modular design and materials cost reduction,
- IT system expansion,
- Automated calibration, recognition and configuration,
- Flexible placement methods



Relevant Solicitations: BENEFIT FY14 (exploratory); BENEFIT FY16 Plug-and-Play Sensor Systems

BENEFIT FY2016 FOA - $4.7 million, 4 awards

OAK RIDGE National Laboratory



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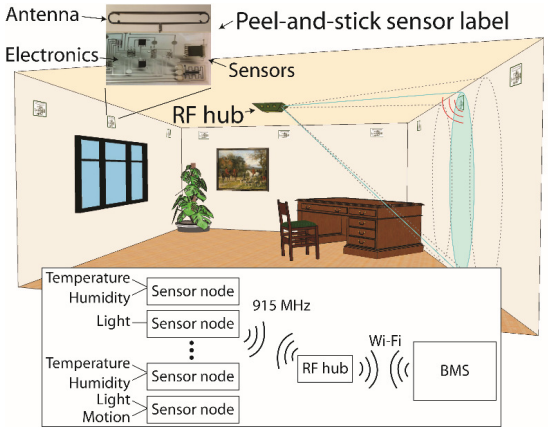
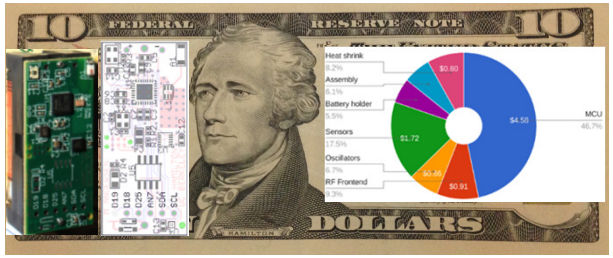


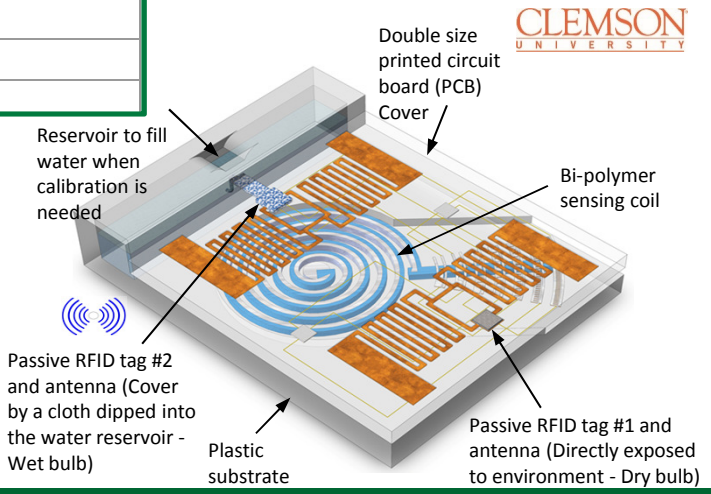
Table 4.1. Technical Targets

ID	Category	Value
4.1.1	Operational lifetime of power source	
	(a) Mean time to replacement (for batteries)	≥ 10 years
	(b) Mean time between charging (for energy harvesters)	≥ 72 hours
4.1.2	Calibration (lifetime duration of accurate sensor operation)	≥ 5 years
4.1.3	Positional Accuracy (distance from true node location)	≤ 2 feet
4.1.4	Nodes Correctly Located	≥ 90 %
4.1.5	# of Sensed Variables/Node	≥ 1

Berkeley
UNIVERSITY OF CALIFORNIA



CLEMSON UNIVERSITY



Success story – ORNL CRADA

- **Fall 2013:** Seedling effort initiated
- **Spring 2015:** CRADA with Molex, electronics manufacturer, established to manufacture prototypes and investigate scaling of the initial processing conditions – 2 prototypes developed

- **Fall 2016:** BENEFIT award made to research approaches to extend the lifetime of the on-board power source improving the efficiency of the energy harvester and extending battery lifetime between charges, as well as optimizing the calibration process
- **Summer 2017:** Field testing for 3 months during at the Flexible Research Platforms (FRP) based on application-specific requirements developed with interested OEM partners; Collected data compared to building instrumentation to validate the accuracy of the measurements made.
- **Fall 2017:** Field testing at 2 OEM partner facilities (i.e., occupied buildings) conducted (SkyCentrics and Pilot Flying J)
- **Summer 2018:** CRADA established with SkyCentrics, OEM partner, to incorporate into their product lines; CRADA manufacturing partner, Molex, investigating commercialization pathways
- **Spring 2019:** Molex licensed initial ORNL patent

Advanced Monitoring and Data Analytics

Focus Area	Relevant ECM	Sector	Installed Cost		Energy Performance (HVAC, Lighting)		2030 Energy Savings Technical Potential
			Market Entry	2030 Target	Market Entry	2030 Goal	
Advanced Monitoring and Data Analytics	AFDD and sub-metering	Commercial	$0.14/ ft^2 floor		25%, N/A	30%, N/A	1.18 quads

Areas of Research:

- Lower-cost, higher accuracy sub-metering
- Non-invasive, high accuracy load disaggregation techniques
- Whole-building AFDD approaches for small and large commercial (model-based, hybrid, data-driven)
- AFDD testing and evaluation framework

Relevant Solicitations: BUILD FY15; BENEFIT FY16 Open; National Lab Call FY17-19; BENEFIT FY17 MELs

Success story – ANL Low-cost Sub-meter

Low cost sensing methods needed that can easily be incorporated into low power microcontrollers and interface circuits.

Approach:

- Coreless differential flux gate magnetometer (DFGM) current sensor and matched compact signal conditioning solution for closed loop current measurements.
- Minimize component count and connectivity by combining several required measurement and control features into a single compact chip to reduce required chip count and board size.

Timeline:

- **Fall 2016:** National Lab Call seedling initiated
- **Fall 2018:** DOE-TCF award to support CRADA with manufacturing partner, BTCPower, to build up meter hardware/accessory product manufacturing and distribution supply chain for commercialization

Goal:

±0.2% accuracy, $10/ phase

Argonne NATIONAL LABORATORY

AFDD Performance Testing, Benchmark Datasets

Challenge:

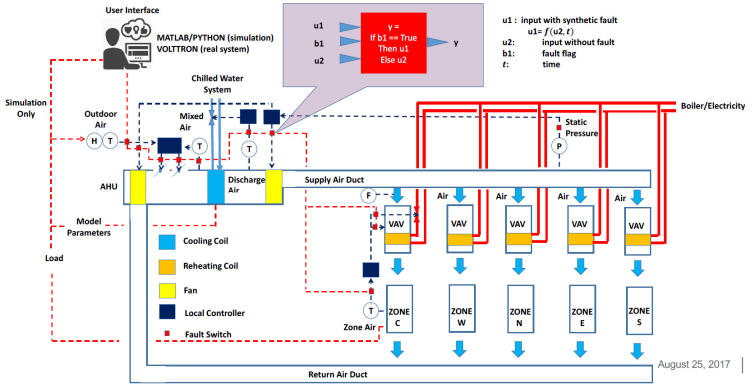
New algorithms continuously created, yet no way to compare, contrast, benchmark their performance

Project Outcome: Test procedures and public datasets to evaluate AFDD algorithm performance

Approach:

Develop test procedure → Curate dataset → Demonstrate on AFDD algorithms → Open dataset to public, expand

Initial Dataset: Most common AHU-VAV faults, simulated and experimental data, single and multi-zone, diversity of operational conditions and fault intensities



Laboratory Consortium Leads:

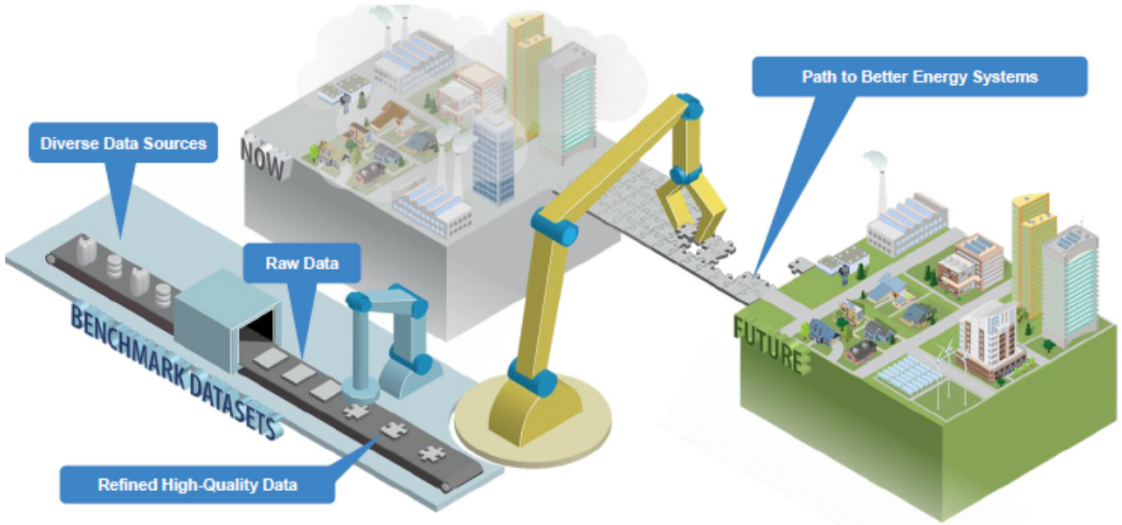
NREL National Renewable Energy Laboratory; Pacific Northwest; Berkeley Lab; Oak Ridge National Laboratory

External Advisory Group:

Drexel University; SkyFoundry; Carrier; KGS Buildings; Siemens; The University of Alabama; United Technologies Research Center; New York State of Opportunity. NYSERDA; Hydro Québec; Southern Company; University of Nebraska Lincoln; NIST; neea; Tridium; BC Hydro; Walmart

Benchmark Dataset of Building Conditions

How do we get the most out of datasets generated and collected by buildings?
How do we create our own that can have maximum impact?



What kinds of data?

- Temperature
- Humidity
- Occupancy
- Air quality
- Irradiance
- Submetered end uses
- Weather
- Supply air characteristics
- and more…

Laboratory Consortium Leads:

NREL National Renewable Energy Laboratory
Oak Ridge National Laboratory
Pacific Northwest
Berkeley Lab

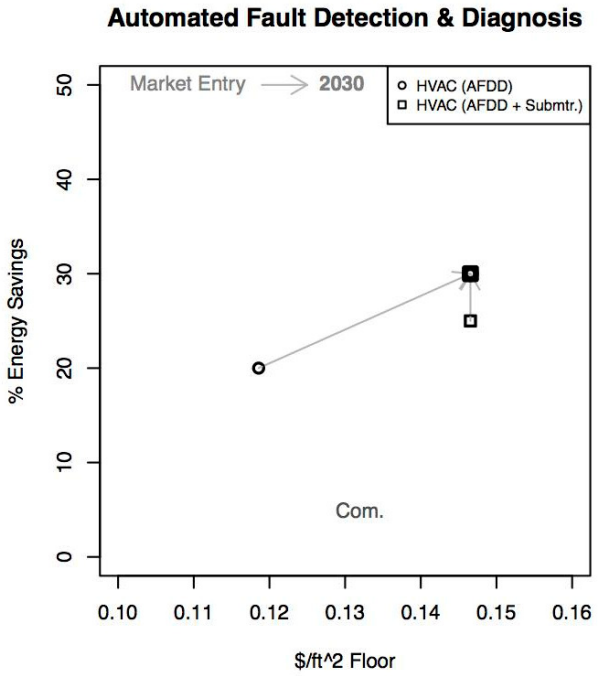
- Characterize potential use cases for buildings datasets
- Define an appropriate data infrastructure
- Inventory existing buildings datasets to identify resources that can be used/shared
- Develop an experimental plan for a subsequent multi-year effort to collect and curate high-quality, well-calibrated datasets of building operations through robust instrumentation.

Advanced Controls

Focus Area	Relevant ECM	Sector	Installed Cost		Energy Performance (HVAC, Lighting)		2030 Energy Savings Technical Potential
			Market Entry	2030 Target	Market Entry	2030 Goal	
Advanced Controls	AFDD	Commercial	$0.12/ ft^2 floor	$0.14/ ft^2 floor	20%, N/A	30%, N/A	1.18 quads

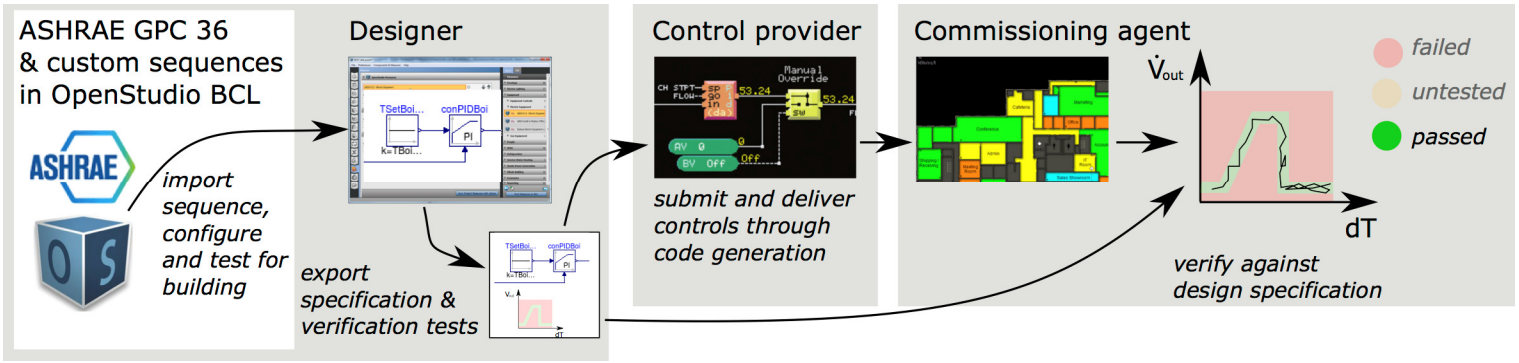
Areas of Research:

- Reduce complexity, improve accuracy, and automate tuning of adaptive control approaches
- Automate controls design, testing, and implementation (end-to-end-quality control)
- Establish baseline performance, testing of new algorithms



Relevant Solicitations: BENEFIT FY16 Open; National Lab Call FY17-19; BENEFIT FY17 S&C/BEM Nexus

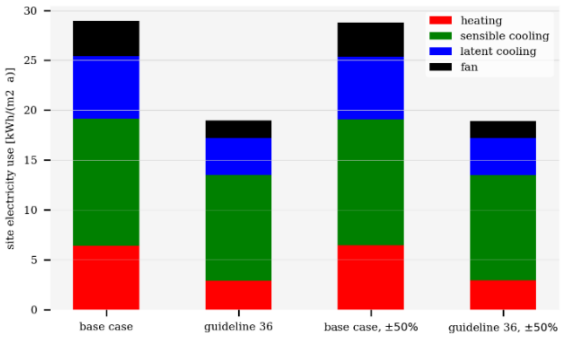
OpenBuildingControl



Codify best practice | Design | Implement | Verify against original design

BACnet standardizes communication, **OpenBuildingControl** will standardize control sequences & verification tests:

- basic functional building blocks
- composition rules for control sequences, and for bidding and automatic implementation
- declaration of functional verification tests criteria.



Key Innovations

Digital, executable control specification, CDL, enabling:

- Sharing of best-practice, e.g., ASHRAE Guideline 36
- Error-free implementation of the specified control sequence
- Formal process that connects design to operation
- Formal verification of design intent
- Integration with Spawn: next-gen BEM engine that also supports control workflows

www.obc.lbl.gov

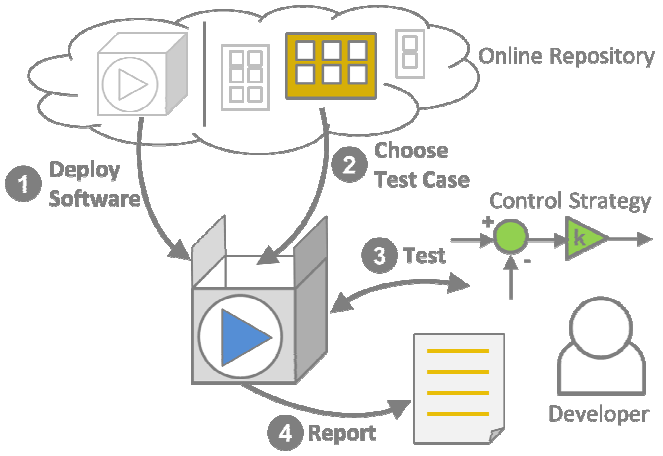
Testing of Advanced Controls

Challenge:

While many advanced control strategies show promise in R&D phase, adoption at scale requires low implementation costs to reduce payback period and verified performance to gain the trust of building owners and operators.

Solution:

- Building emulation can significantly aid in meeting these requirements before the cost and risk of testing new strategies needs to be taken on by building stakeholders
- Made more possible recently by innovations in building performance simulation (i.e. use of the Modelica and Functional Mockup Interface (FMI) standards)



The **Building Operation Testing (BOPTEST)** framework will consist of a series of test procedures, benchmark test cases, and standard emulation environment to validate, compare, and debug advanced control strategies

In collaboration with IBPSA Project 1** (https://ibpsa.github.io/project1) – **2018-2023

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Pacific Northwest

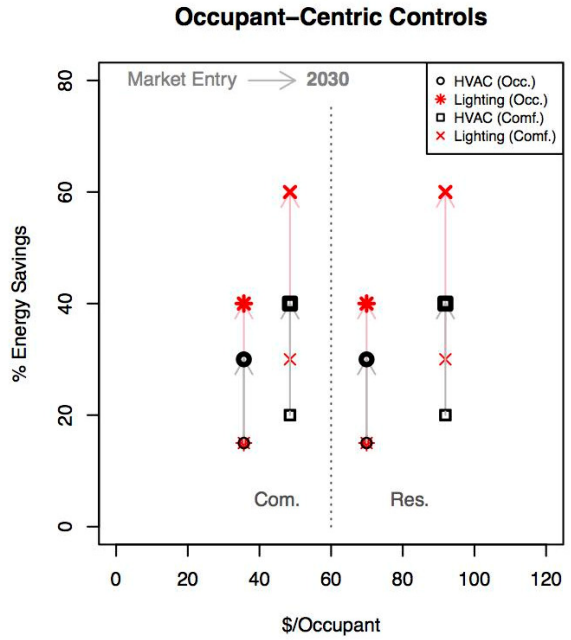
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Occupant-centric Sensing and Controls

Focus Area	Relevant ECM	Sector	Installed Cost		Energy Performance (HVAC, Lighting)		2030 Energy Savings Technical Potential
			Market Entry	2030 Target	Market Entry	2030 Goal	
Occupant-centric Sensors and Controls	Occupancy Counting	Residential	$70/ occupant		15%, 15%	30%, 40%	2.31 quads
		Commercial	$36/ occupant				1.10 quads
	Occupancy Comfort	Residential	$92/ occupant		20%, 30%	40%, 60%	3.14 quads
		Commercial	$49/ occupant				1.49 quads

Areas of Research:

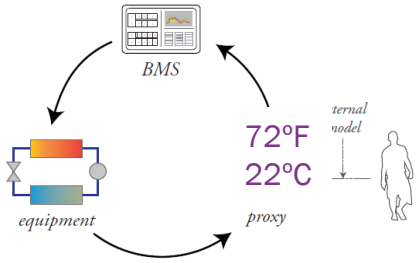
- Human-in-the-Loop MPC approaches (mostly commercial buildings)
- Occupancy sensor development (including long-term accuracy and calibration of CO_2, humidity) to complement ARPA-E SENSOR program
- Incorporation of occupancy parameters (i.e., comfort, behavior) into controls design and operations

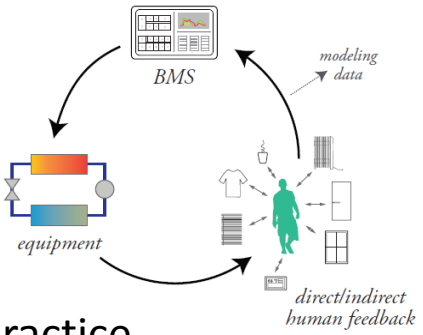


Relevant Solicitations: BENEFIT FY16 Human-in-the-Loop & Open; BENEFIT FY18

Defining Occupant-Centered Measures

- **Improve understanding and quantification of occupant behavior (i.e., comfort preference, presence and movement, and interactions with control systems)**
- **Incorporation occupant behavior models into building design/operation and control strategies**





IEA Annex 79:

- Launched in 2018; follow-on to Annex 66
- Impact of multiple, interdependent parameters on actions
- Affects of building control interfaces and logic on behavior
- Use of BAS and other data streams
- Identify data necessary to apply behavior and models into design practice

ASHRAE MTG:OBB:

- Launched in 2016; Chapter recently accepted into ASHRAE Handbook
- Inform energy and indoor environmental calculations, standards 55, 62.1, 62.2, 90.1, 90.2 and 189.1

Improving Thermal Comfort Measurements

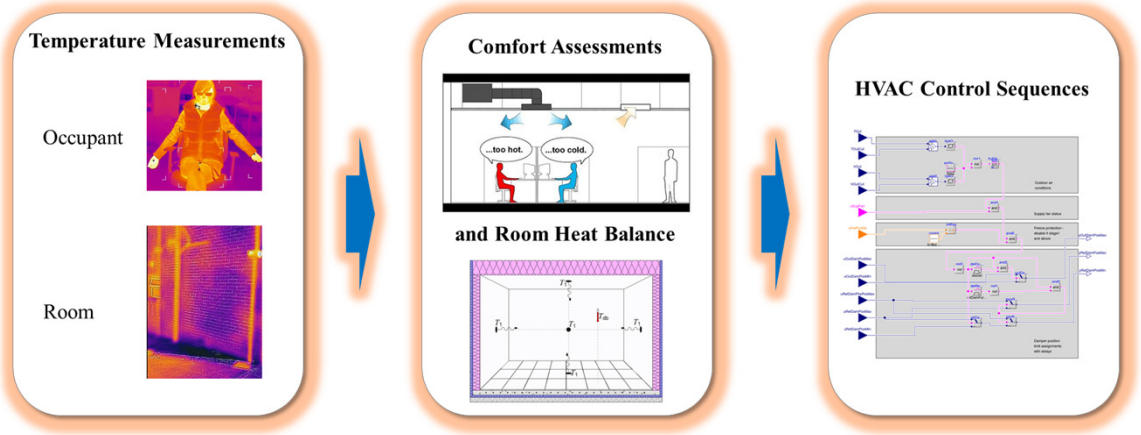
Using a Wide-View Infrared Biometric Sensor to Improve Occupant Comfort & Reduce Overcooling in Buildings via Closed-loop Control:

Approach:

- Map occupant skin surface and non-human room surface temperatures
- Predict and validate occupant comfort from the distribution of measured skin surface temperatures
- Develop a closed-looped MPC algorithm for HVAC using both outputs
- Field test in a commercial building

Highlights:

Use of radiant temperature of human skin as an input to determine the desired comfort level, as well as "closing the thermal comfort loop" in HVAC controller operation.



BERKELEY LAB

moviTHERM advanced thermography solutions

DAIKIN

Berkeley UNIVERSITY OF CALIFORNIA

***Under negotiations; commencing 2019**

Cross-cut Strategies

- **Miscellaneous Electric Loads –**
  - *Improve characterization of these loads for inclusion in energy savings targets and controls development strategies*
- **Interoperability –**
  - *Collaborate with stakeholders to accelerate semantic interoperability solutions*
- **Cybersecurity –**
  - *Do no harm, incorporate and regularly update security features into sensors and controls solutions; expand AFDD and adaptive control strategies to include cyber-related threats*

Questions and Discussion