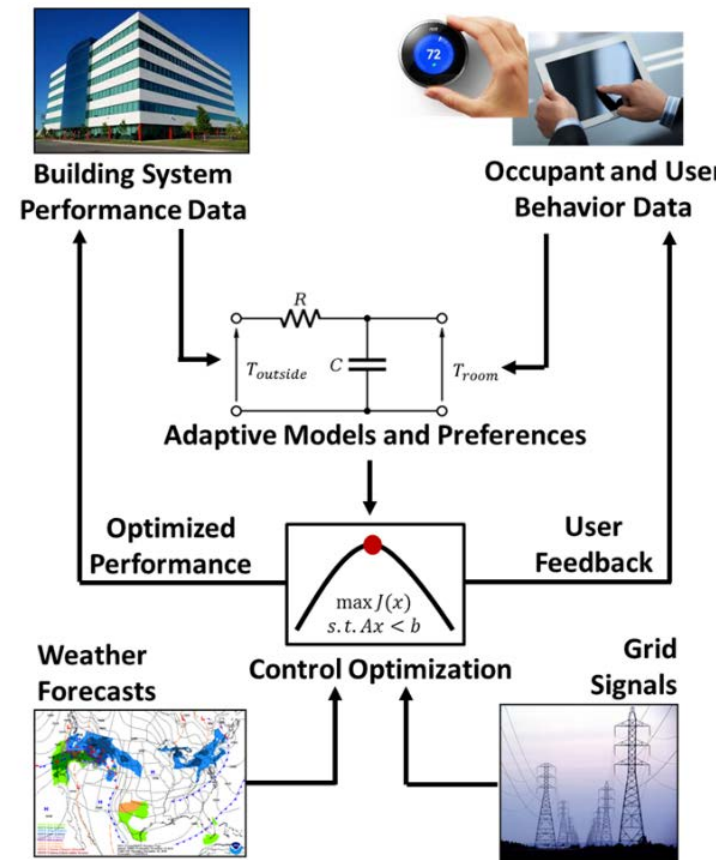
Hierarchical Occupancy Responsive Model Predictive Control at Room, Building, and Campus Levels

2017 Building Technologies Office Peer Review



U.S.-China Clean Energy Research Center
Building Energy Efficiency (CERC-BEE)

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

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Project Summary

Timeline:

Start date: April 1, 2016

Planned end date: March 31, 2021

Key Milestones

1. Room level occupant module (FY17Q3)
2. Building level MPC, in progress (FY17Q4)
3. Room level demonstration plan (FY17Q3)

Budget:

Total Project $ to Date:

- DOE: $380,000 (Y1: $430k)
- Cost Share: $820,000 (Y1: $967k)

Total Project $:

- DOE: TBD (Y2 ask: $500k)
- Cost Share: TBD (Y2 est: $1,600k)

Key Partners:

Johnson Controls	Tsinghua University
United Technologies	China Academic of Building Research
Disney	Ministry of Housing & Urban-Rural Development
Lutron	
Lend Lease	

Project Outcomes:

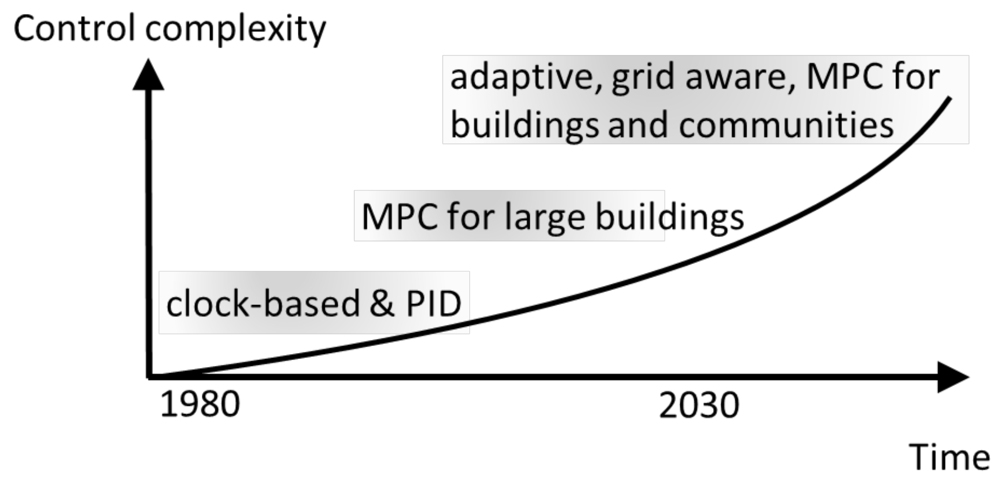
- Building and district scales occupancy-responsive MPC commercialization
- MPC software for robust and rapid deployment
- Demonstration on multiple real sites
- Distribution of open-source for industry adoption and research collaboration

Purpose and Objectives

Problem Statement:

Conventional building control systems unable to meet future building system requirements effectively:

- Energy cost reduction
- Electric grid integration
- Fault detection and diagnosis
- Occupant-responsiveness



Project Objectives:

- Development of free, open-source, occupant-responsive Model Predictive Control (MPC) software
- Demonstration at room, building, and campus level
- Enable scaling and commercialization of the technology

Purpose and Objectives

Target Market and Audience:

- Address directly key technologies of the current DOE Multi-Year Plan and DOE Quadrennial Technology Review 2015.
- Enable startup and major control companies to enter this new market segment in both the U.S. and China.
- Strong U.S. and China industry consortium with key players of JCI, UTC, Disney, Lutron, and Lend Lease.

Purpose and Objectives

Energy and Other Impacts of Project:

- **Potential energy savings** of MPC technology in commercial buildings ~20%, or ~1.9 Quad in U.S. and 1.0 Quad in China.
- **Long-term goal** if MPC in all commercial buildings, savings would be $6 B per year alone in US.
- **Peak demand** potential 40-50% reduction in electric energy consumption during peak hours due to MPC (Kintner-Meyer and Emery 1995), 2-3 W/sqft.
- **Added benefits of MPC** are grid stabilization and greater levels of grid-scale renewables as MPC help shed elec loads.
- **Reduces risk of blackouts** of electricity grid, which can have significant economic benefits, estimated as the avoided costs of $16 - 22 billion, and an anticipated loss of 136,000 jobs just in California (National Energy Policy 2001)
- **Estimated savings of 30%** for commercial buildings can be achieved by integrating occupancy-responsive MPC for behavior-related energy savings (Dong and Lam 2014).

Global Benefit

- Optimize building operations in U.S. and China to reduce energy use and environmental impact
- Provide software platform to test, evaluate, and scale MPC technologies by researchers and industry
- Establish a strong foundation for future international collaborations on MPC and other advanced building technologies

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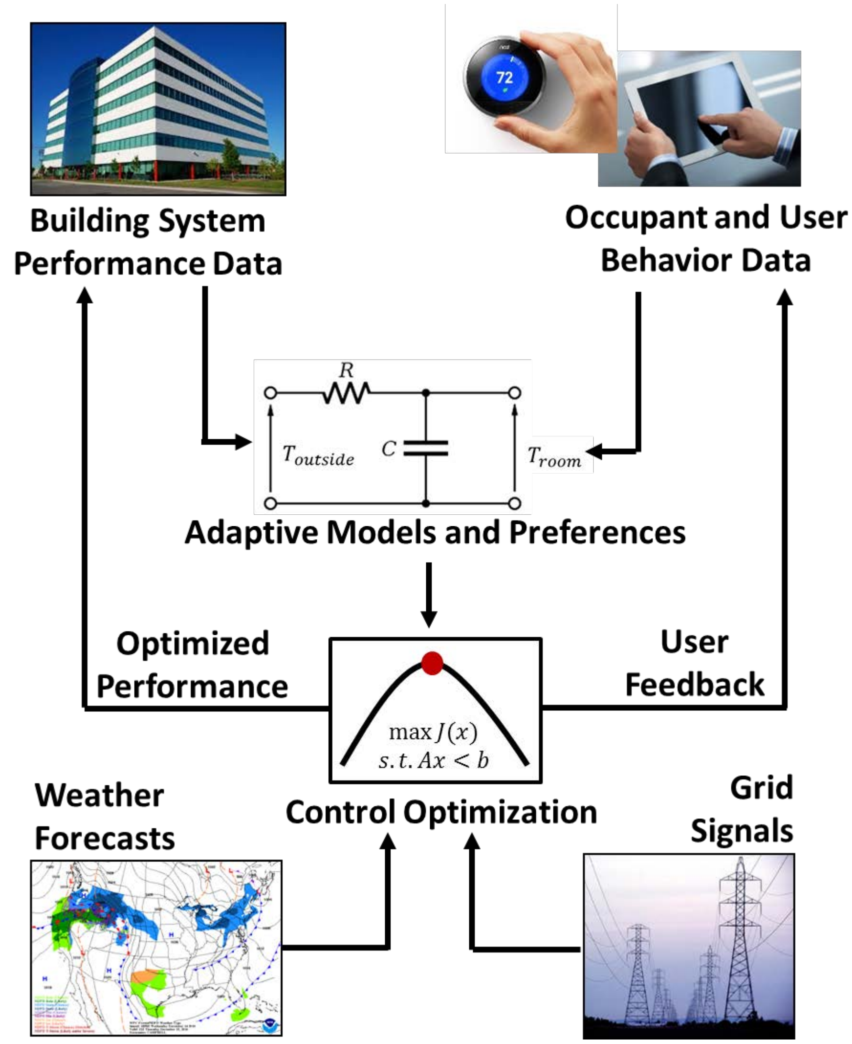
Approach

Approach:

- **Develop** - hierarchical, occupancy-responsive model predictive control software (MPC) framework
- **Demonstrate** - multiple buildings sites, showcase robustness and verify performance improvements
- **Distribute** - open-source for industry adoption and research collaboration

Key Issues:

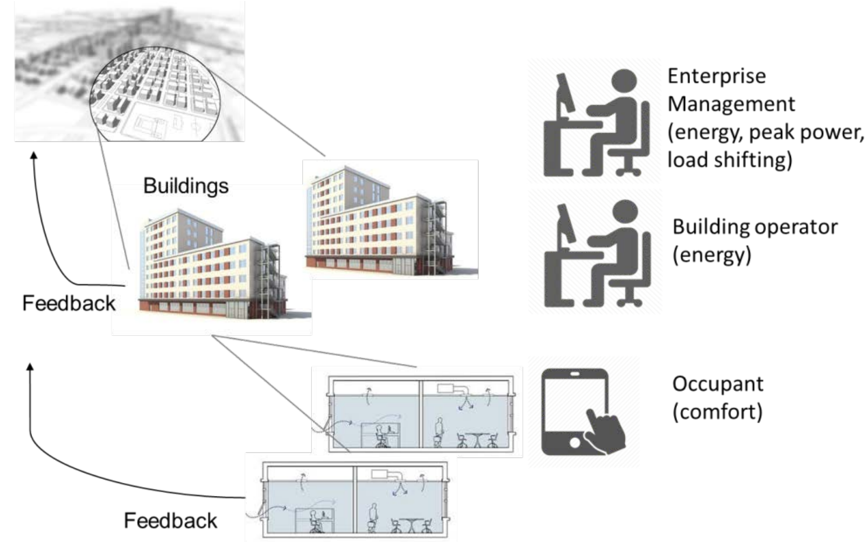
- Delay getting data from demo building due to processing of IP/NDA agreement
- Data from other buildings used in Year 1 to test MPC emulation platform and develop and validate occupant module



Approach

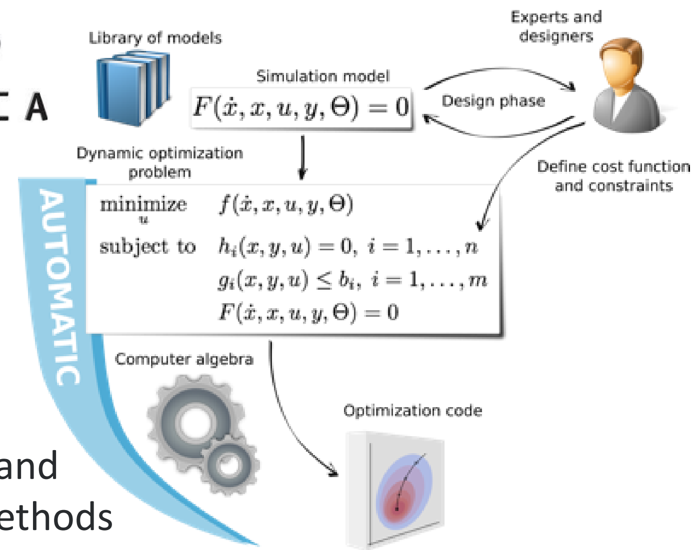
Distinctive Characteristics

- **Data-driven model identification *reduces*** model setup, calibration, and maintenance effort.
- **Hierarchical MPC *enables*** occupant input and feedback at different levels.
- **Modeling and optimization methods *solves faster*** than conventional method (Wetter et al 2015).
- **Occupant integration *detects*** occupant presence (Jia and Spanos 2017) and predict behavior (IEA EBC Annex 66).
- **Open-source software standards *facilitate*** collaboration, scaling, and longevity.



Hierarchical MPC

MODELICA



New modeling and optimization methods

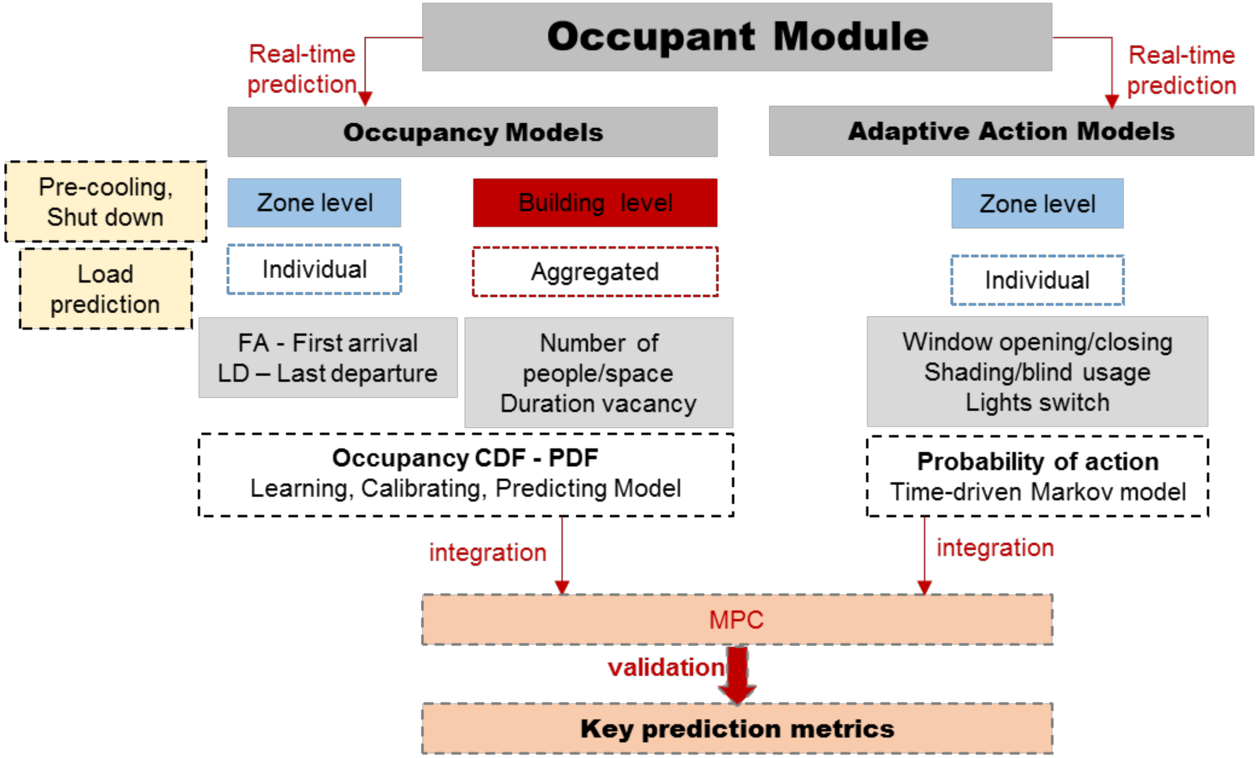
Progress and Accomplishments

Accomplishments (1/3 pages)

Subtask 1.1: Occupant Module Development at the Room Level

Developed architecture for occupant behavior (OB) module to exchange information between occupants and MPC at room and building level

- **Adaptive Action Models** predict occupant behavior and preferences
- **Occupancy Models** predict occupant presence in rooms and building using the queueing approach



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Progress and Accomplishments

Accomplishments (2/3 pages)

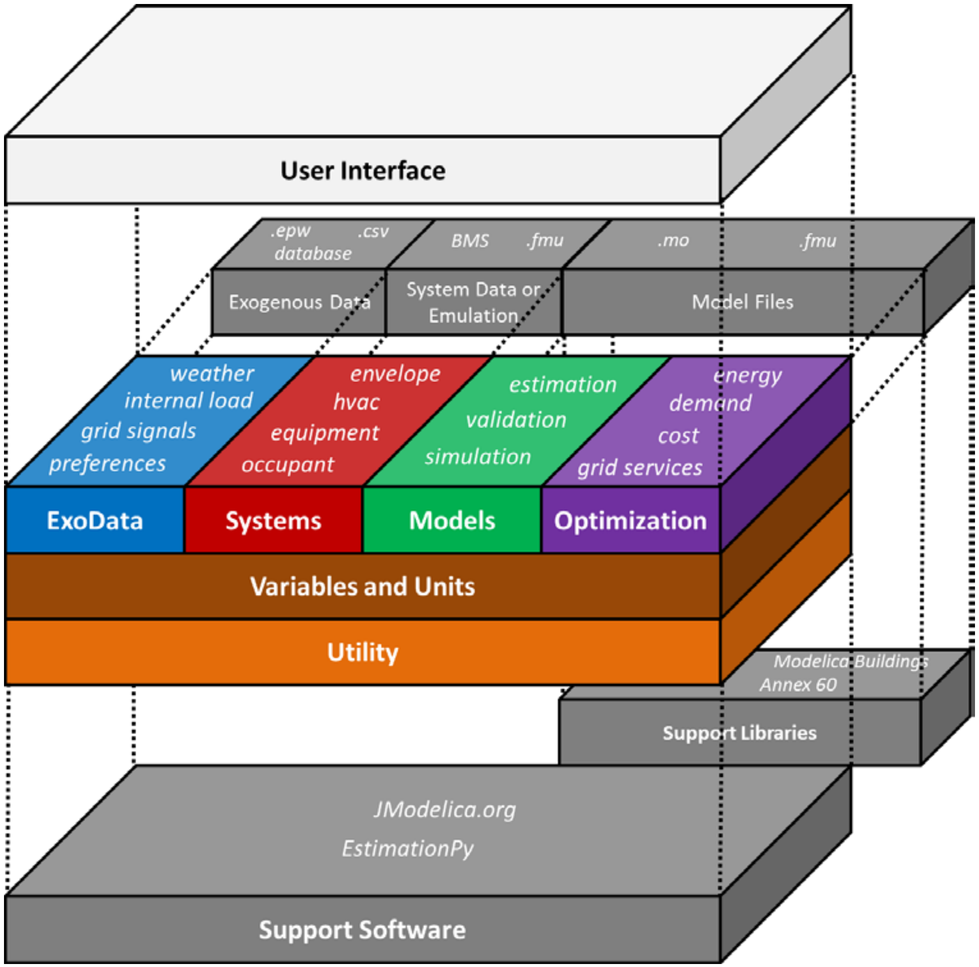
Subtask 1.2: Development of Building-level MPC

Modules for:

- External data collection (e.g. weather, grid signals)
- Real or emulated system interactions
- Data-driven model learning and validation
- Control optimization

Design:

- Python scripting
- Extensible architecture
- Automated optimization problem formulation



MPCpy (Blum and Wetter 2017)

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Progress and Accomplishments

Accomplishments (3/3 pages)

Subtask 1.3: Room-Level MPC Demonstration Preparation

- LBNL and JCI have identified the JCI HQ building in Milwaukee, WI as the site for MPC demonstration at the room level.
- Discussions between the two organizations are underway to determine the rooms, floors, and systems included in the demonstration and the scope of experiments.

JCI HQ Building

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Progress and Accomplishments

Market Impact:

- JCI has offered Milwaukee and Shanghai buildings as demonstration sites for occupant-integrated MPC platform as well as active engagement during demonstration process.
- LBNL has initiated the process of open-source licensing for distribution of MPC software code.
- A commercialization plan will be developed in Year 2.

Awards/Recognition: N/A

Lessons Learned:
Features of MPC to be tested in site are limited to existing systems, sensors, and controls of the demonstration building.

Project Integration and Collaboration

Project Integration:

- Provide the foundation for implementing MPC technologies in commercial buildings in both the U.S. and China
- LBNL research team has regular meetings and seminars with the industry partners
- Collaboration with two IEA EBC projects: Annex 60 Modelica & FMI tools, and Annex 66 occupant behavior modeling and simulation.
- Active communication and collaboration with China teams. China has strong interest to reduce energy use in buildings through advanced control technologies. The team at Tsinghua University, China has been doing research in building controls and district heating systems.

Project Integration and Collaboration

Partners, Subcontractors, and Collaborators:

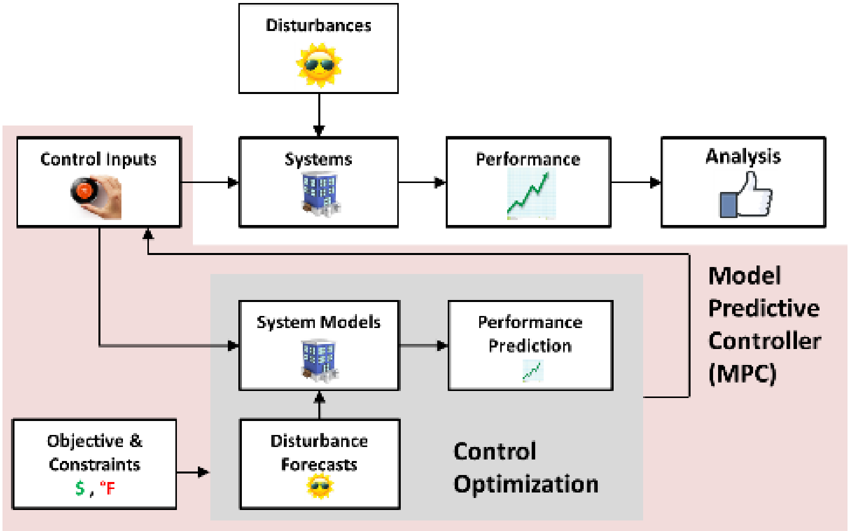
- U.S. industry partners
  - Johnson Controls, United Technologies, Disney, Lutron, Lend Lease
- China collaborators
  - China Academy of Building Research, Tsinghua University, Ministry of Housing & Urban-Rural Development

Communications

- **Publications:** Five peer-reviewed journal articles
- **Guidebooks, Reports:** MPC application guide and final technical report
- **Training sessions:** Two joint training sessions for U.S. and China researchers, industrial partners and interested parties
- **Workshops and Conferences:** Two public workshops to disseminate MPC technology. Present research findings at conferences (Blum and Wetter 2017)
- **Technology Demonstrations:** To demonstrate MPC technology at the JCI buildings in Milwaukee and Shanghai.

Next Steps and Future Plans

- **MPC technology** will be developed and tested in partner buildings
- After NDA/IP in place, **occupant module and demo plan** development will be completed using sensor data from the demo building
- **Real-time occupancy data** from sensors and from virtual sensing, (e.g. WiFi signals, Pritoni et al. 2017) for occupancy prediction model training
- **Adaptive occupant models** to predict preferences and interactions with controllable systems, e.g. shade positions, (D'Oca and Hong 2015, behavior.lbl.gov)
- **Library of component models** for building HVAC operation and indoor environment prediction will be completed in the first quarter of Yr 2
- **Commercialization plan** will be developed in Yr 2
- **Other potential U.S. companies** may join as project develops



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Project Budget

Variances: Room level demonstration plan was moved to FY17Q3 from FY17Q2, due to NDA/IP agreement delay.

Cost to Date: $1,397,000 ($430,000 DOE, $967,000 Industry in-kind contribution)

Additional Funding: N/A
We will reach out to other companies for potential participation.
LBNL team will also actively pursue other funding opportunities as cost-share.

Budget History					
April 1, 2016 - September 30, 2016; FY 2016 (past)		October 1, 2016 – March 31, 2017; FY 2017 (current)		April 1, 2017 - March 31, 2018 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$215,000	**$483,500**	**$215,000**	**$483,500**	**$500,000**	**1,600,000**

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Project Plan and Schedule

Timeline:

- Start date: April 1, 2016
- Planned end date: March 31, 2021

Schedule and Milestones:

FY16	BTO FY17	BTO FY18	BTO FY19	BTO FY20	FY21

CERC Y1	CERC Y2	CERC Y3	CERC Y4	CERC Y5
Q3 Q4 Q1 Q2	Q3 Q4 Q1 Q2	Q3 Q4 Q1 Q2	Q3 Q4 Q1 Q2	Q3 Q4 Q1 Q2

Tasks	Subtasks	Deliverables	Milestone
Task 1: Occupant module development at the room-level, MPC algorithm development at the building level	Subtask 1.1: Occupant module development at the room level	Deliverable 1.1: Room level occupant module	
	Subtask 1.2: Development of building-level MPC	Deliverable 1.2: Building level MPC	
	Subtask 1.3: Room level MPC demonstration preparation	Deliverable 1.3: Room level demnonstration plan	
	Milestone 1: Room level occupant module and building level MPC		M1
Task 2: Demonstration of the MPC at the room level; occupant module development at the building level	Subtask 2.1: Integration of the occupant module into MPC at the room level	Deliverable 2.1: Technical report- Room level module implementation into MPC	
	Subtask 2.2: Demonstration of room-level MPC	Deliverable 2.2: Technical report- Room level MPC demonstration	
	Subtask 2.3 Occupant module development at the building level	Deliverable 2.3: Building level occupant module	
	Subtask 2.4: Building level MPC demonstration preparation	Deliverable 2.4: Building level demnonstration plan	
	Milestone 2: Room level MPC demonstration and building level occupant module		M2
Task 3: Demonstration of the MPC at the building level; occupant module and MPC algorithm development at the campus level	Subtask 3.1: Integration of the occupant module into MPC at the building level	Deliverable 3.1: Technical report- Room level module implementation into MPC	
	Subtask 3.2: Demonstration of building-level MPC	Deliverable 3.2: Technical report- Building level MPC demonstration	
	Subtask 3.3: Development of campus-level MPC	Deliverable 3.3: Campus level MPC	
	Subtask 3.4: Occupant module development at the campus level	Deliverable 3.4: Campus level occupant module	
	Subtask 3.5: Campus level MPC demonstration preparation	Deliverable 3.5: Campus level demnonstration plan	
	Milestone 3: Building level MPC demonstration, and campus level occupant module and MPC		M3
Task 4: Demonstration of the MPC at the campus level	Subtask 4.1: Integration of the occupant module into MPC at the campus level	Deliverable 4.1: Technical report- Campus level module implementation into MPC	
	Subtask 4.2: Demonstration of campus-level MPC	Deliverable 4.2: Technical report- Campus level MPC demonstration	
	Milestone 4: Campus level MPC demonstration		M4
Task 5: Commissioning of MPC technology and the CERC demonstration buildings	Subtask 5.1 Development of MPC commissioning guide	Deliverable 5.1: Commisioning guide handbook	
	Subtask 5.2 Retro-commissioning of China CERC demonstration buildings	Deliverable 5.2: Report- Retro-commisioning results	
	Milestones 5: Publication of commissioning guides		M5
Task 6: Commercialization and dissemination	Subtask 6.1: Development of a commercialization plan	Deliverable 6.1: Commercialization plan	
	Subtask 6.2: Dissemination of results	Deliverable 6.2: Dissemination results	
	Subtask 6.3: Final technical report	Deliverable 6.3: Final technical report	
	Milestone 6: Project final report		M6

Cost of MPC - Example

$30,000 to deploy MPC for a 10,000 m^2 office building with 3-year payback.

Detailed assumptions:

For a 10,000 m2 (110,000 ft2) office building with an energy consumption of 50 kWh/m2 per year and a rate of $0.10/kWh, a 20% energy cost reduction due to use of MPC results in cost savings of $10,000 a year, corresponding to $1 per m2 annually. Assuming a 3-year targeted payback, the first cost for materials, configuration and commissioning for MPC can be $30,000. Assuming half of this cost will be for additional sensors, the allowed labor costs would be $15,000. At a technician rate of $100/hour, the maximum time for configuration and commission to achieve 3 year payback would be 150 hours, or 4 weeks. Conversely, because of the self-configuration of the state estimator that adapts its parameters automatically to the building, which we propose here, we estimate a labor time of about 5 days to configure the MPC for a building, which translates into labor costs of 5*8*100 = $4000, or $0.5/m2. Thus, the energy and cost targets are 20% -- or 10 kWh/(m2*a) for a 50 kWh/(m2*a) building -- at a labor cost of $0.5/m2, plus another $0.5/m2 for additional sensors if not already present for example to support continuous commissioning. Clearly, these numbers scale linearly in the energy use intensity, energy cost, energy saving, labor cost and required payback period, and thus exhibit significant variability. However, we think they are conservative as they do not include demand charges and the energy price does not assume time of use pricing, which improves the economy of MPC due to its load-shifting capabilities.