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Session 1: Advancing Controls in Thermal Energy Storage

S4B Annual Meeting – Control Thrust Area

Chair: Dr. Tim LaClair, NREL Building Thermal Energy Science Group

Presenters: Dr. Marco Pritoni (LBNL), Dr. Xin Jin (NREL), Dr. Xiaobing Liu (ORNL), Dr. Min Gyung Yu (PNNL)

Stor4Build Annual Meeting
August 26–27, 2024
Oak Ridge National Laboratory

Agenda

- Overview of TES control development
- Design controls for TES integrated with HVAC systems
- Implementation of controls for TES-HVAC
- Development of grid-interactive advanced control framework for energy storage
- Laboratory and field tests of controls for TES-HVAC
- Summary and plan for future R&D
- Q&A

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Overview of TES Control Development

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Control is critical to TES-integrated HVAC systems

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- Desirable features of TES control:
  - **Robust**: automated operation in all conditions (install and forget)
  - **Smart**: maintain room temperature or other services (e.g., hot water availability) while shifting electric demands to maximize benefits
  - **Grid-interactive**: help to relief stress of electric grid
  - **Low cost**

- The TES control development includes:
  - **Software:** control strategies
  - **Hardware:** sensors, actuators, controllers, and communications

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Model-Based Design of Controls for HVAC-TES integrated systems

Presenter: Marco Pritoni, LBNL
Contributors: Michael Wetter, Donghun Kim, Peter Grant, Armando Casillas, Remi Patureau, Weiping Huang

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TES integrated with HVAC

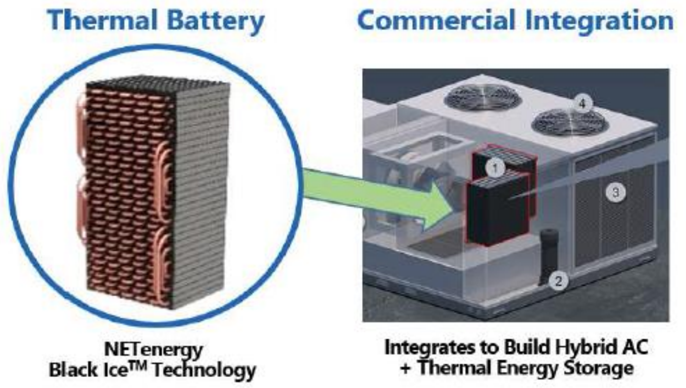
Large Commercial w/ Built-Up HVAC and District Systems

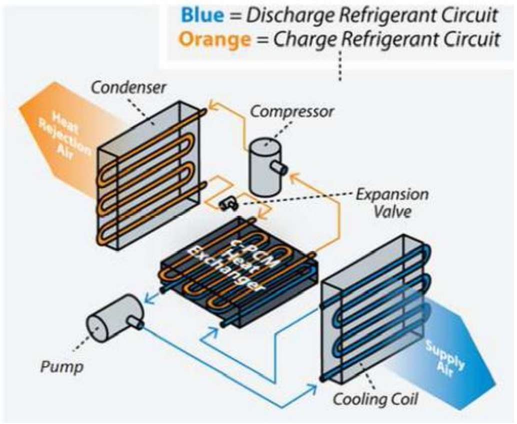
- Custom controls, hard to scale.
- Electrification requires increasingly complex systems, hard to design.
- Most MEPs do not have tools for or experience with TES

Small Packaged Systems (sometimes integrated with HP)

- **Field assembled systems**: unclear how to control them
- **Factory-integrated systems**:
    - have integrated control
    - may not able work optimally in complex use cases (dynamic prices);
    - may not control in coordination with other end-uses (e.g. DHW)

TES-integrated HVAC at NREL & LBNL



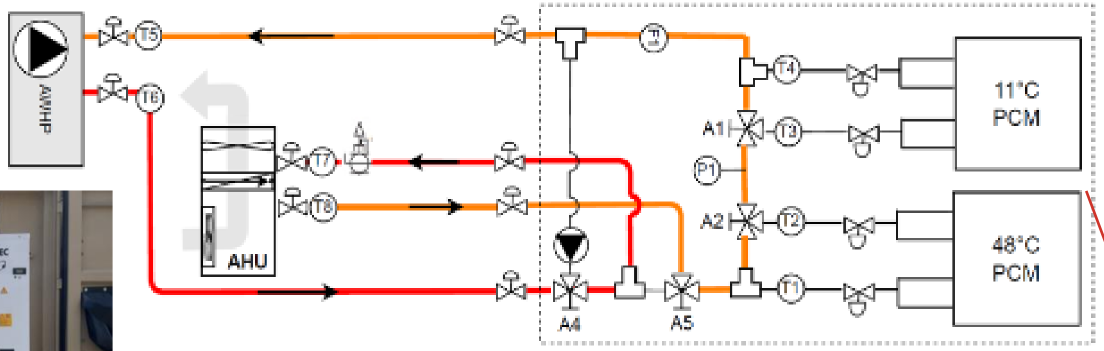


A TES-integrated rooftop unit

- Refrigeration cycle charges the PCM during night or when electricity prices are low
- Glycol circuit discharges the PCM and provides conditioned air to the thermal zone

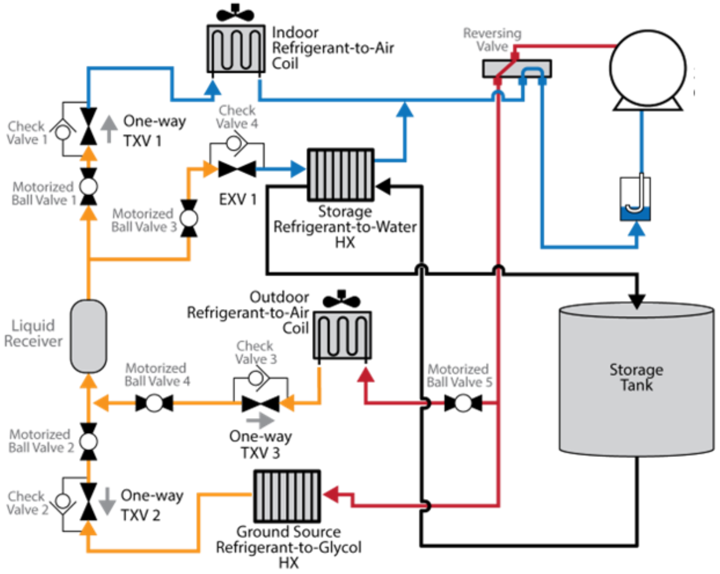
Packaged TES-integrated Heat Pump

- Air-to-Water Heat Pump
- Hydronic Distribution
- PCM Hot and Cold Storage
- Fan Coil for Zone Delivery



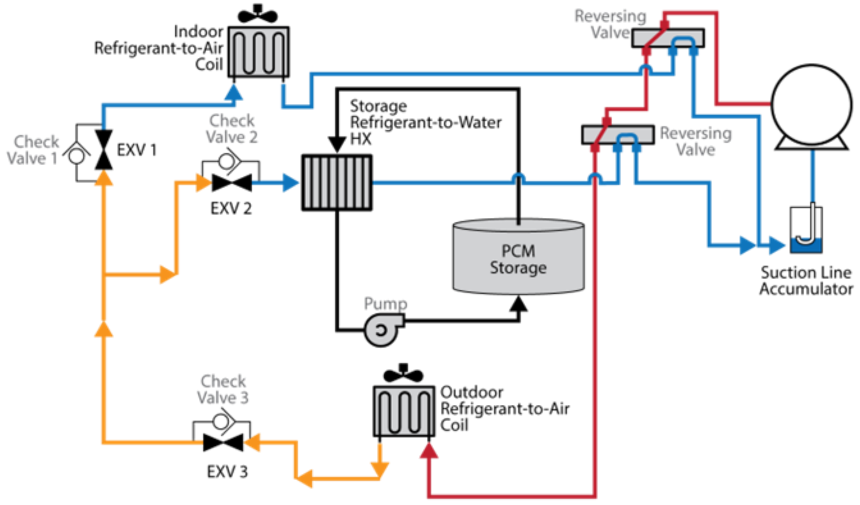
ORNL made several inventions on heat pump integrated with TES

Dual source heat pump with TES for direct heating and cooling



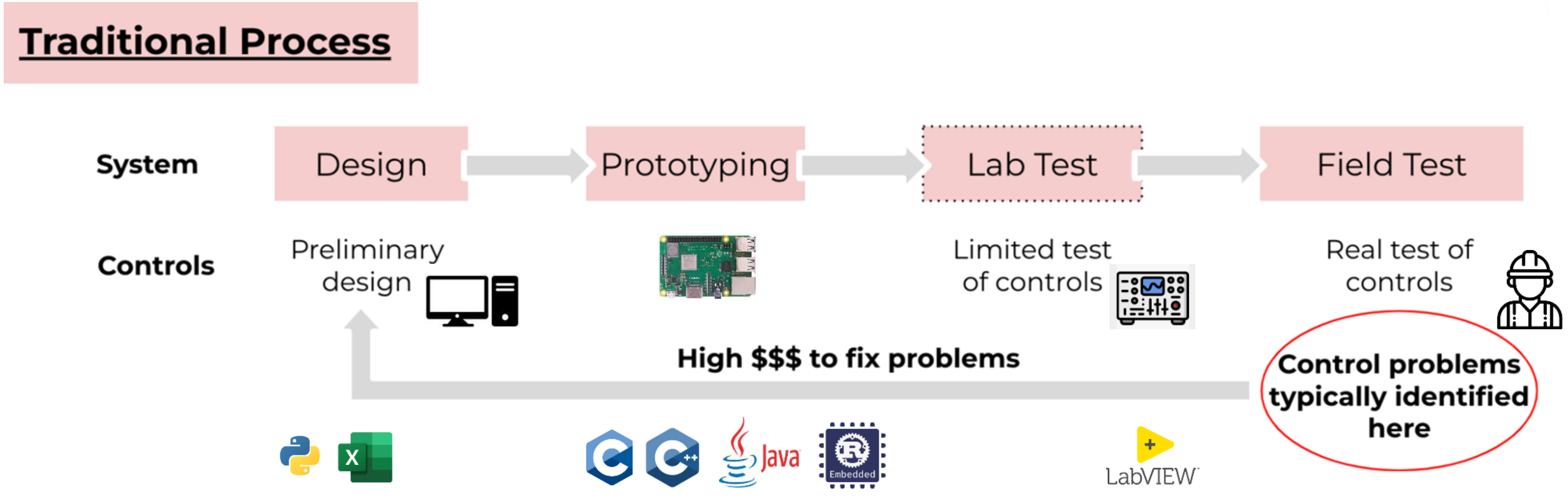
Lingshi Wang, Xiaobing Liu, Bo Shen, Xiaoli Liu, Anthony Gehl, Liang Shi, and Ming Qu. "Experimental Performance Analysis of a Dual-Source Heat Pump Integrated with Thermal Energy Storage." *IGSHPA Research Track*, Las Vegas NV, Dec 6-8, 2022.
Provisional Application 63/446,366

Air source HP (heating and cooling storage)

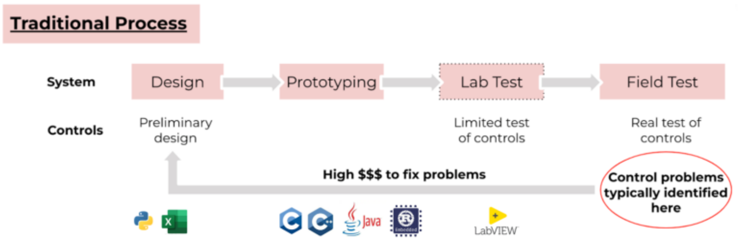


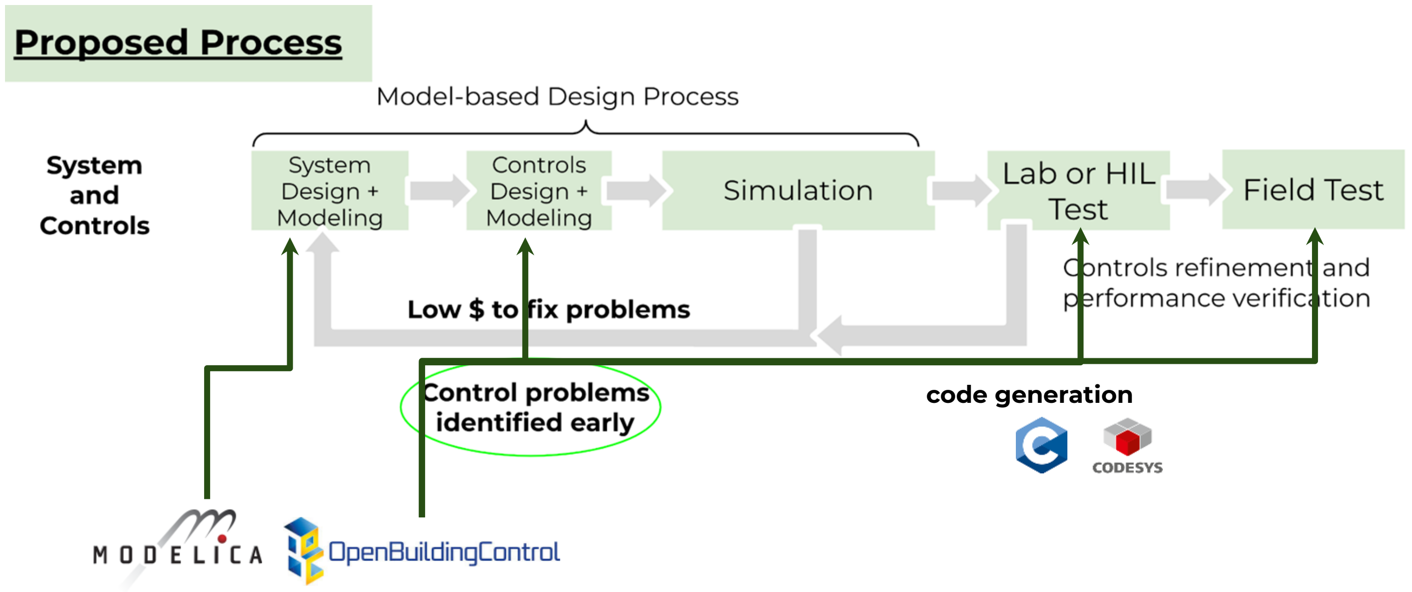
Bo Shen, Kyle Gluesenkamp, Zhenning Li, Jie Cai, Philani Hlanze, Zhimin Jiang "Cold Climate Integrated Heat Pump with Energy Storage for Grid-Responsive Control", [ASHRAE and SCANVAC HVAC Cold Climate Conference 2023]
Provisional Application 63/446,366

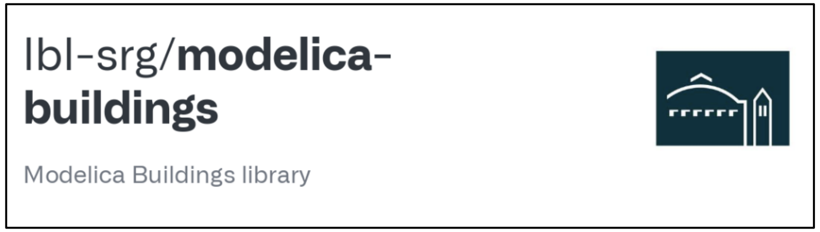
Traditional Control Development for TES integrated with HVAC



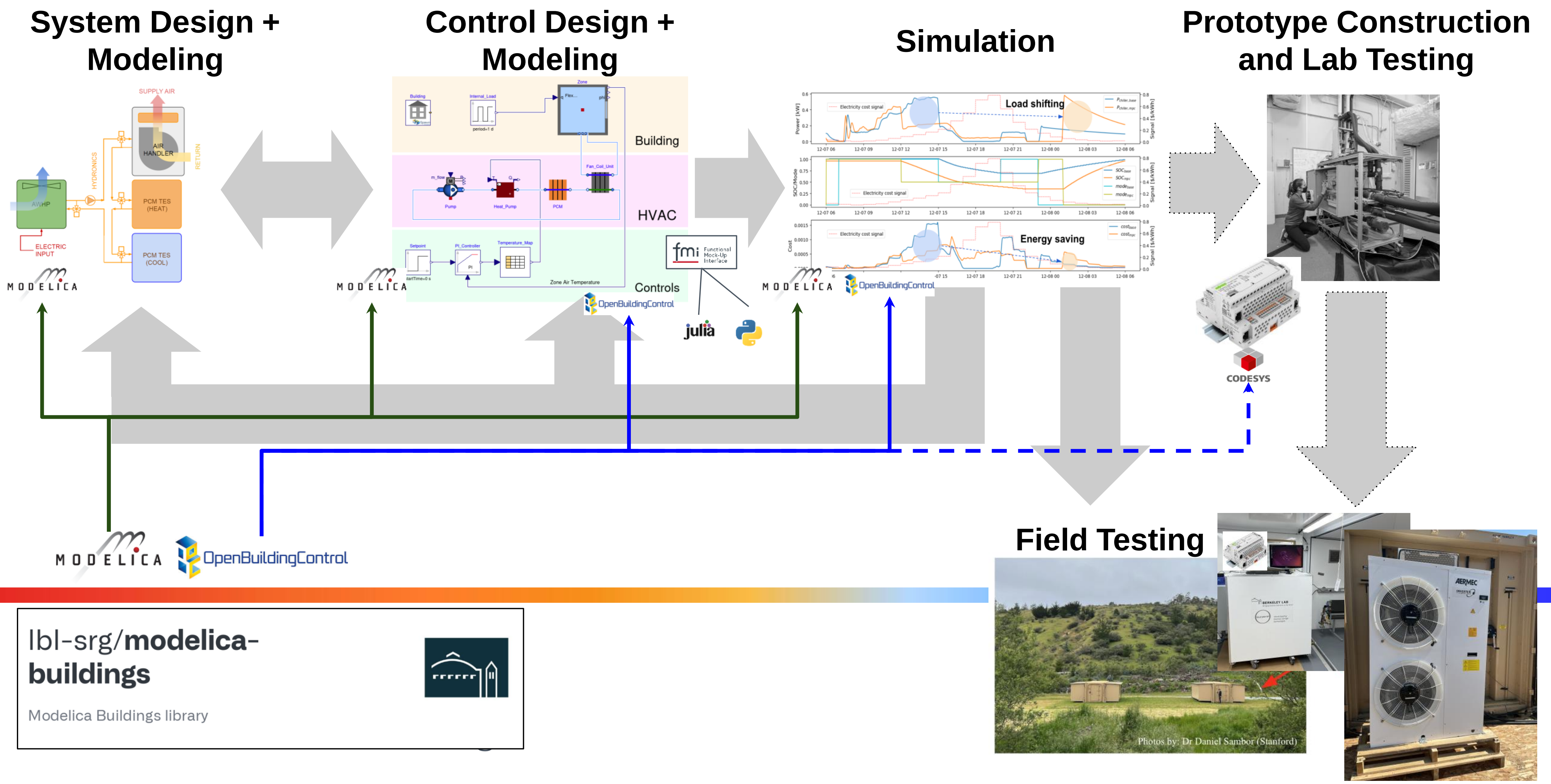
Proposed Process for Control Design







Model-Based Design of Packaged HP+TES + Controls



The approach works also with Large Buildings Districts

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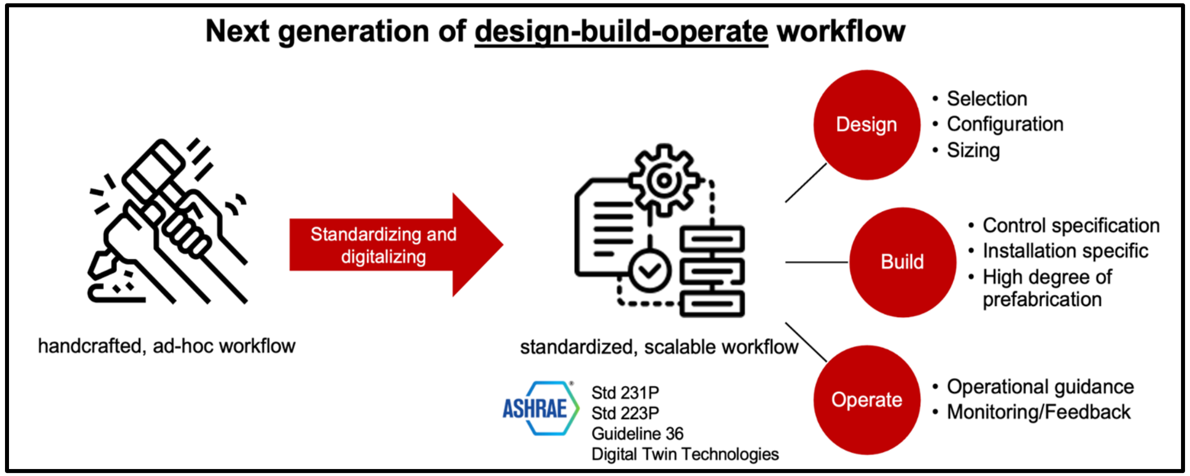
Platform-Based Design for HP + TES systems

Enabling fully digitalized product R&D for faster time to market and higher system-level performance

BERKELEY LAB

- **Come see our poster !**



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Implementation of TES Controls

Presenter: Xin Jin, NREL

Contributors: Rohit Chintala (NREL), Xiaobing Liu (ORNL)

Control Algorithms

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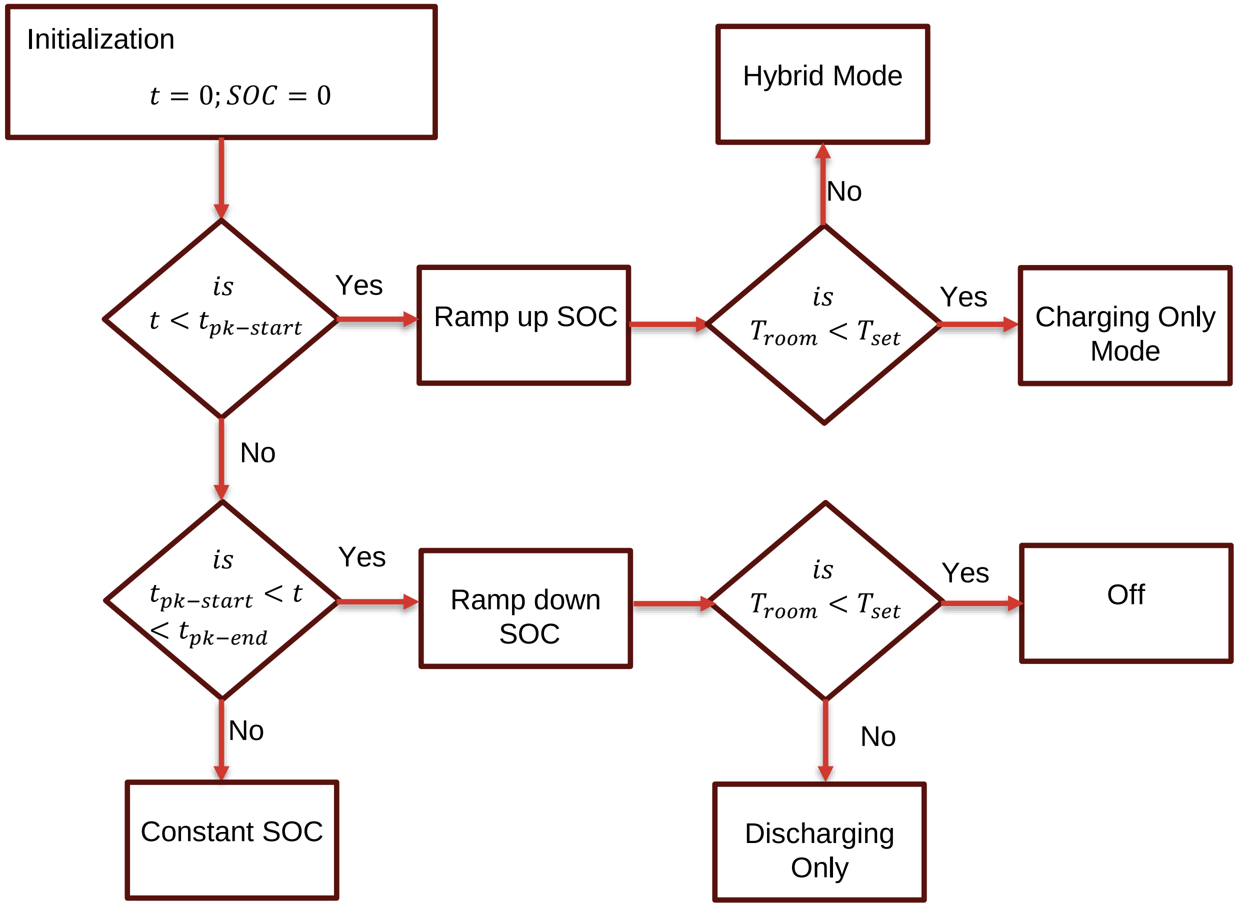
Rule-Based Controller (RBC)

- Operation by TES governed by a set of rules.
- Rules developed by expert opinion and domain knowledge.
- Doesn’t adapt to different objectives or different operating conditions.



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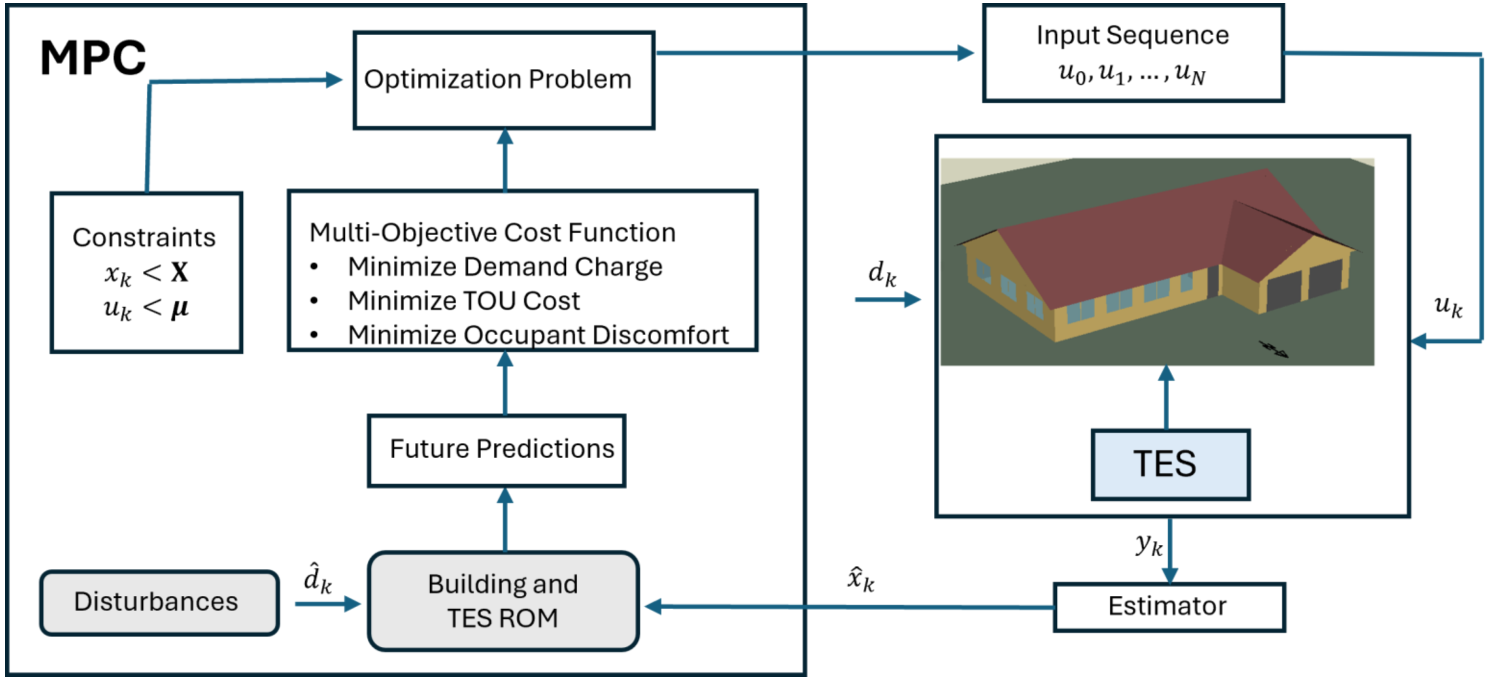
Control Algorithms

Model Predictive Control (MPC)

- Real-time optimization.
- Can adapt to different objectives and operating conditions
- Needs
  - Reduced order Models (ROMs)
  - Forecasts
    - weather
    - building load
  - Hardware - Processor to perform real-time optimizations, appropriate sensors, and communication interface.
  - Software – MPC algorithm



Control Algorithms

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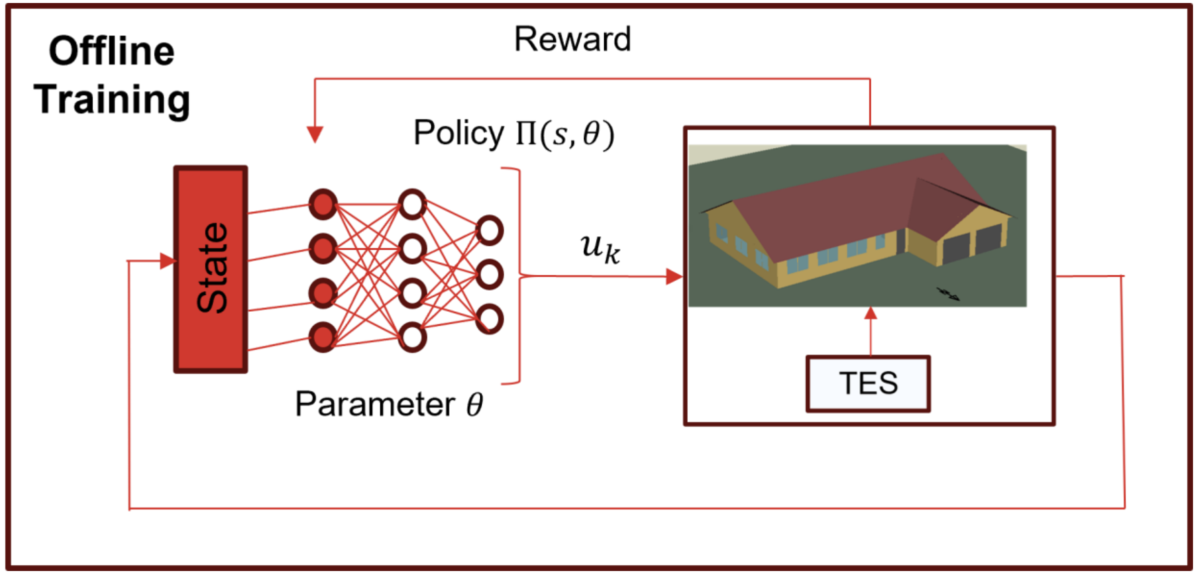
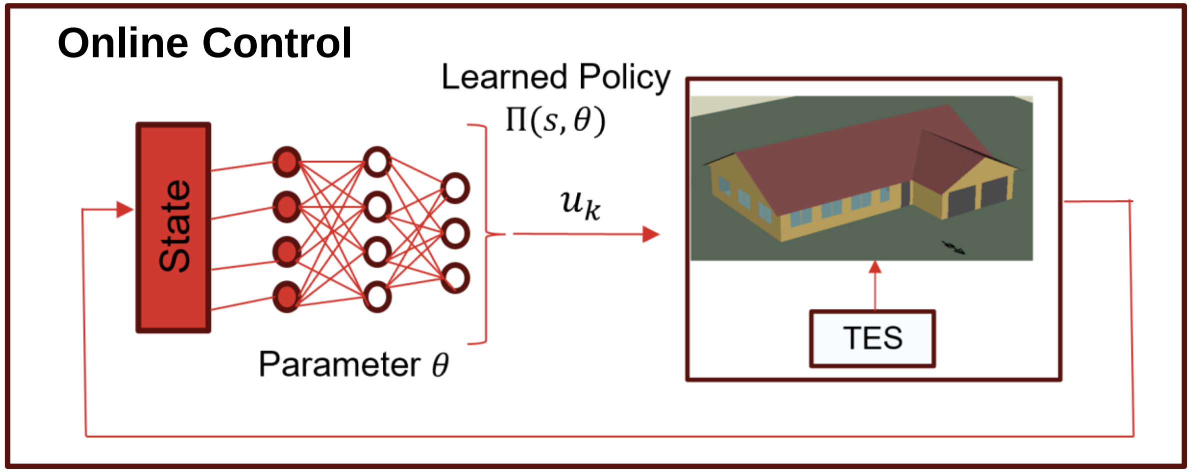
Learning-Based Control

- Learns optimal policy offline from historic BAS/simulation data.
- Computation requirements for online implementation of learned policy is low.
- Poor performance on ‘unseen’ operating conditions





MPC Hardware Implementation

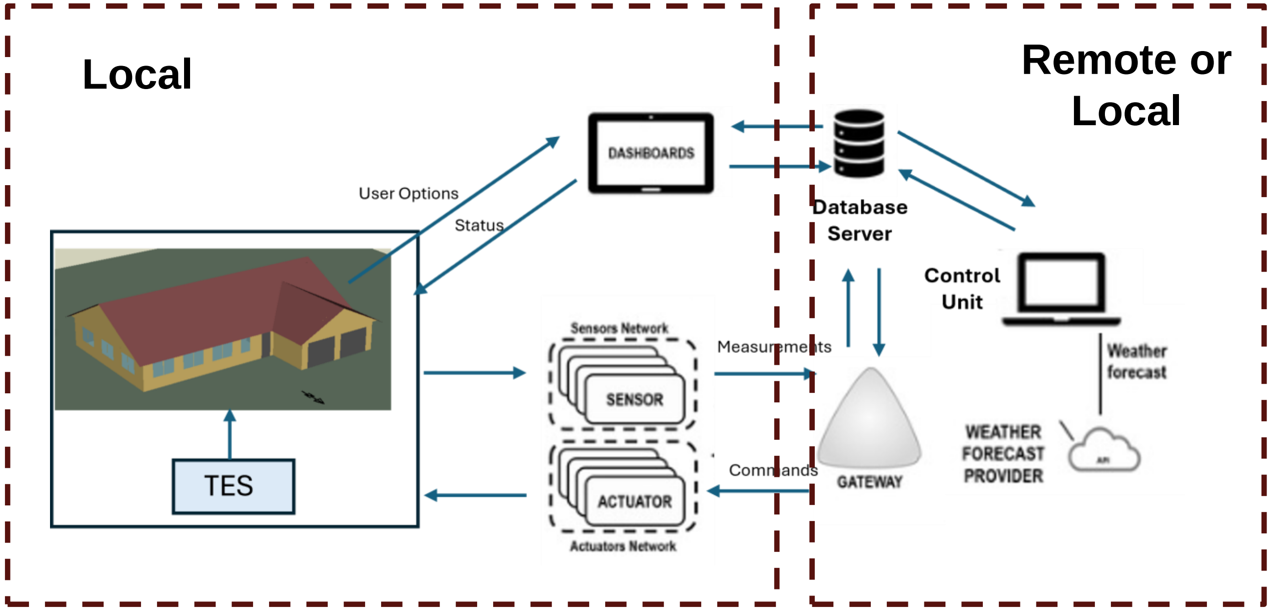
Hardware Requirements

- Sensors to provide state information
  - Room temperature
  - TES state-of-charge (or estimation)
- Computing resources for MPC optimization
  - Remote cloud computing
  - Locally through PLC, integrated computing modular, or standalone computing platform
- Data and Communication Interface
  - APIs for weather forecast
  - BACnet or MODBUS
    - Controllers and actuators connected through a local network via MODBUS or BACnet TCP.
  - IOT such as VOLTTRON

Cloud Computing

vs

Onboard Computer



Preliminary Results - NREL

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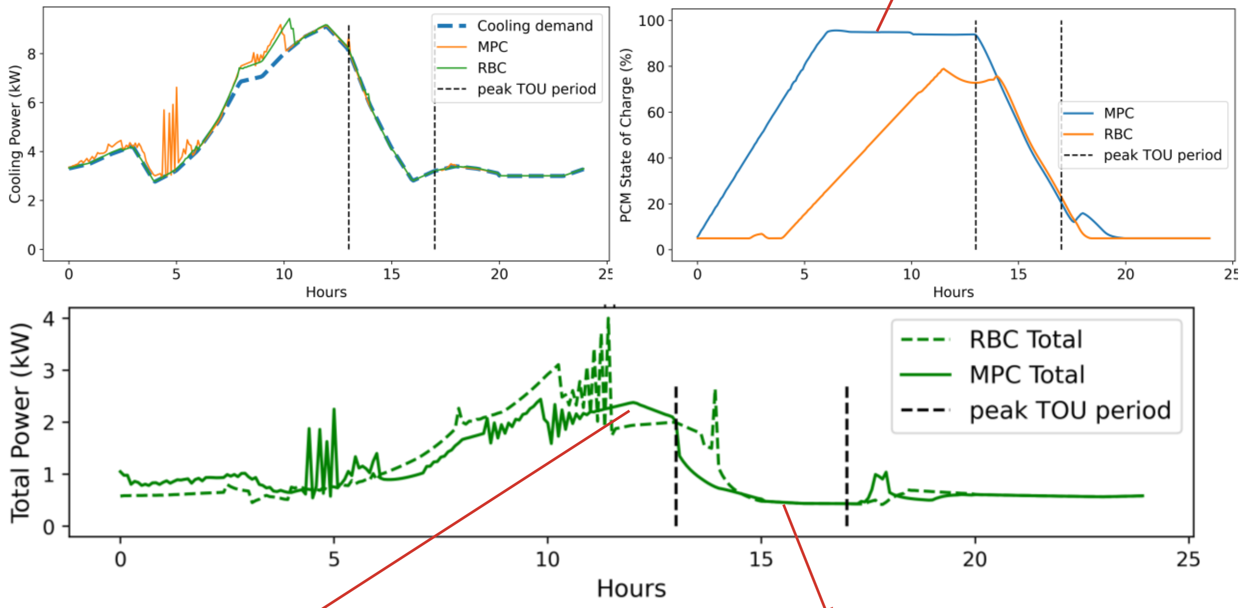
Results from Simulation Validation

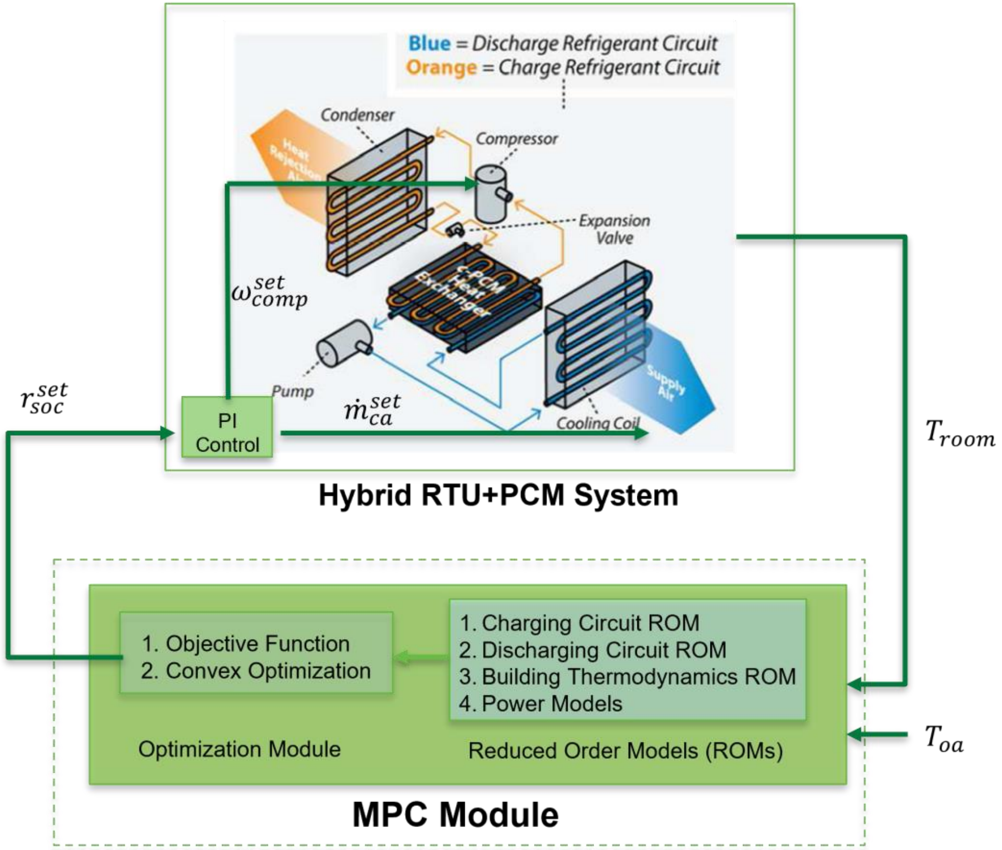
- Savings of up to 7% over RBC by just optimizing SOC trajectory of PCM

A more desirable SOC trajectory



Lower peak power

Lower power consumption during peak hours



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Advanced TES Controls

Development of Grid-Interactive Advanced Controls Framework for Storage Systems

120 kW – 250 kWh
Li-ion Battery

~550 ton-hours of
ice storage system

Three 8,000-gal water tanks (~187 ton-hours) five
626-gal phase-change tank (~200 to 225 ton-hours)

Photo from iStock-1411304340

Presenter: Min Gyung Yu (PNNL)

Contributors: Srinivas Katipamula, Woohyun Kim, Roshan Kini and Min Gyung Yu

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Today’s Agenda

- Motivation, Current Approach, Innovation and Benefits of Advanced TES System Controls
- Overview of the General Framework for Grid-Interactive Advanced Controls
- Overview of Eclipse VOLTTRON™ - an Opensource Internet-of-Things Platform
- Next Steps

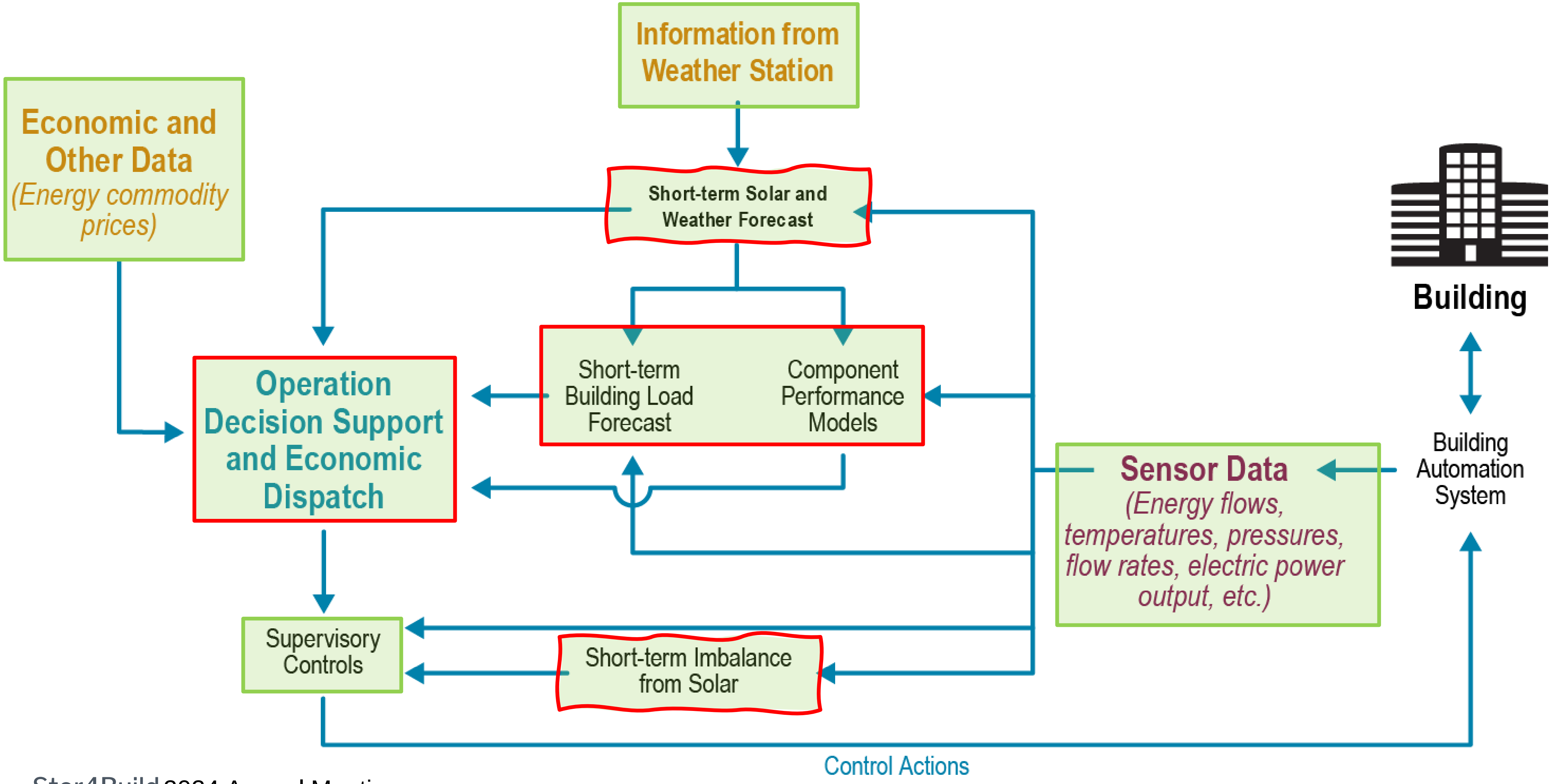
Motivation, Current Approach, Innovation and Benefits of Advanced TES System Controls

- Building-integrated (including homes) TES system will add more complexity to control various building systems “optimally”
- To maximize the return-on-investment, TES system must minimize the energy cost

- Currently, integration of TES system with the grid is customized for each installation using simple control rules, for simple utility rates, which is not cost-effective and may not minimize the energy cost
- Innovative, easy to deploy, fully automated, opensource control for individual TES system and aggregated TES controls across the distribution network is needed

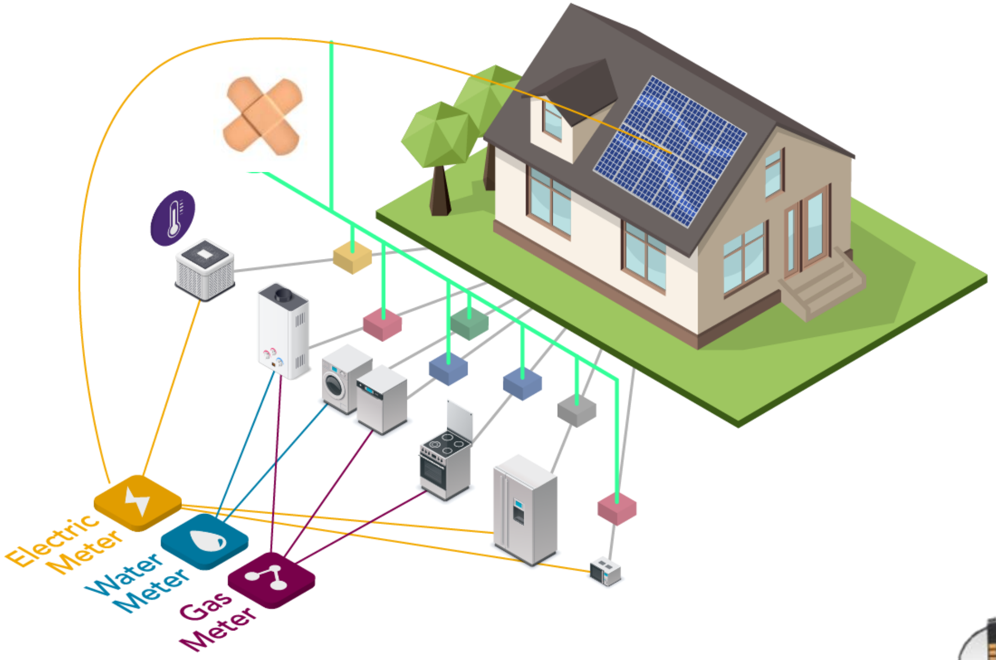
- Advanced TES controls are critical and will provide significant benefits
  - Seamlessly control building-integrated storage with existing building systems, while maximizing benefits
  - Cost-effectively integrate TES systems with the grid
  - Reduced utility bills
  - Utilities can mitigate variable renewable generations
  - Accelerate electrification of buildings, and benefit society from reduced emissions

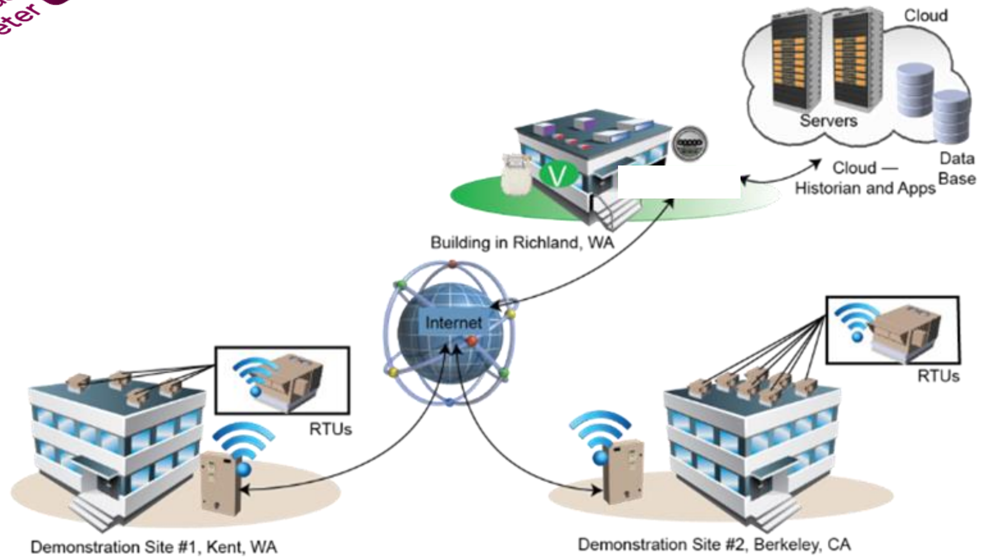
Overview of the Framework



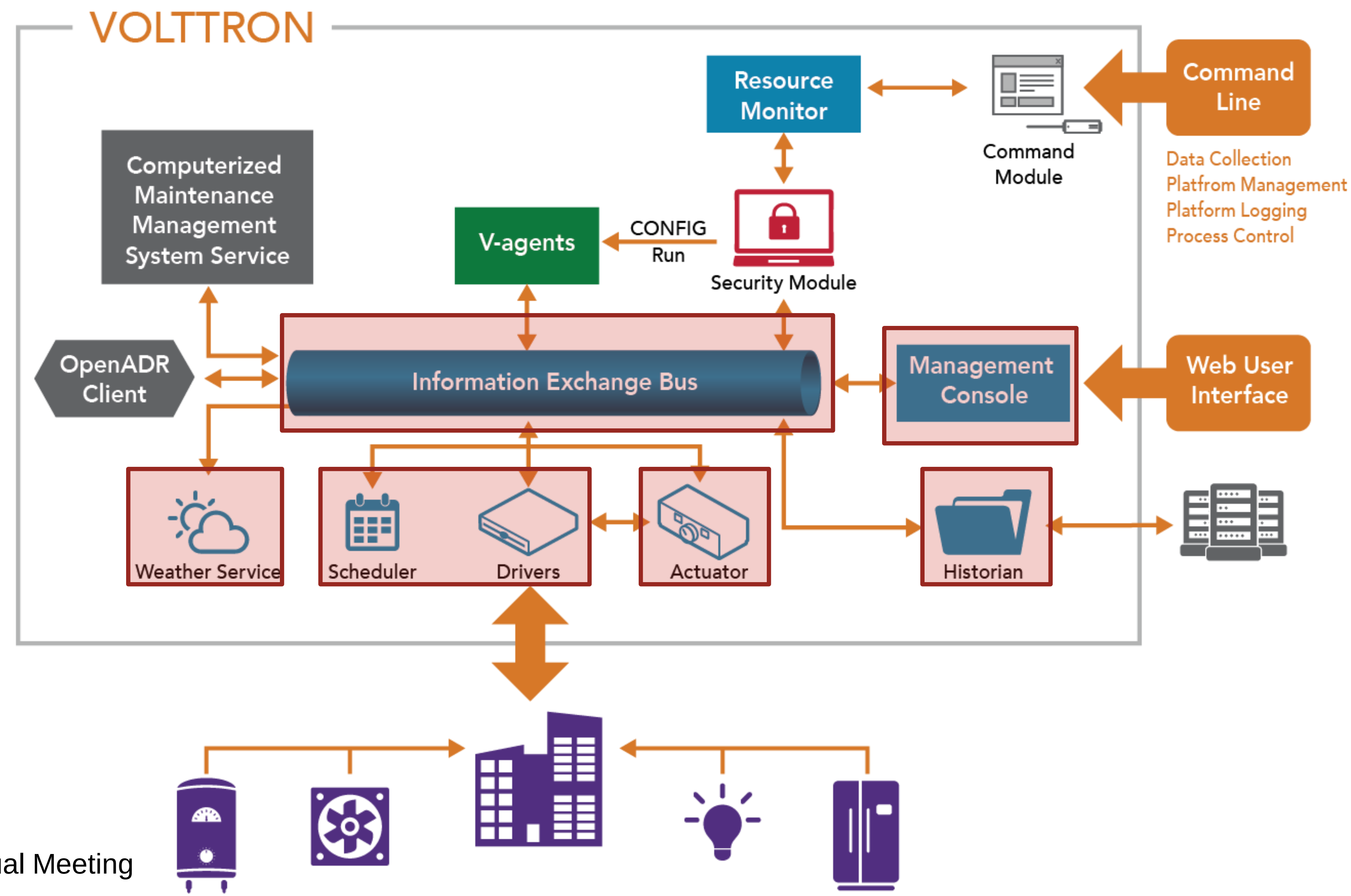
Eclipse VOLTTRON™

- An Internet-of-Things platform for sensing and controls
- Supports deploying of distributed sensing and control applications for buildings





Internet-of-Things Platform: Eclipse VOLTTRON™



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Laboratory and field tests of advanced controls for TES integrated with HVAC

Capabilities of test facilities at national labs

Test results of advanced control for TES-integrated HVAC systems

Presenter: Xiaobing Liu, ORNL

Contributors: Marco Pritoni (LBNL), Xin Jin (NREL), Srinivas Katipamula (PNNL), Yiyuan Qiao (ORNL), Sen Huang (ORNL)

TES facilities: materials to systems innovation

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Distributed building thermal storage reduces the electricity infrastructure needed for decarbonization

Material preparation


Temperature and Humidity Controlled Glovebox


Ball mill


Vacuum Oven


Sonicator Bath


Shaker


Hot Plate

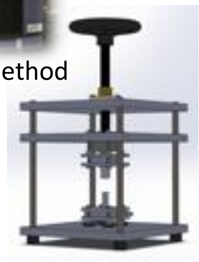
Material and component development and characterization

milligram-scale → gram-scale → kilogram-scale


Differential Scanning Calorimeter


T-history Method


Neutron scattering

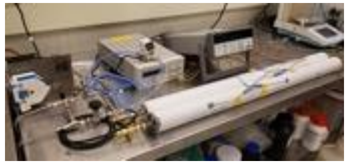

1-D hot bar


T-h “Tower”


ASTM Heat Flow Meter


ASTM Heat Flow Meter

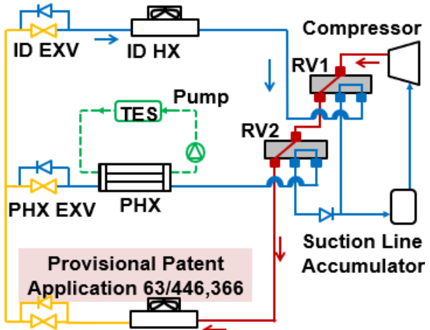

Heat Exchanger Test Stands



Heat exchanger design and fabrication


ORNL-developed PCM heat exchanger and low-cost salt hydrate PCM

Prototype development and evaluation



ORNL-developed TES-ready HP configuration enables peak demand shifting

RTU modified at ORNL for charging and discharging of TES

Prototype field evaluation

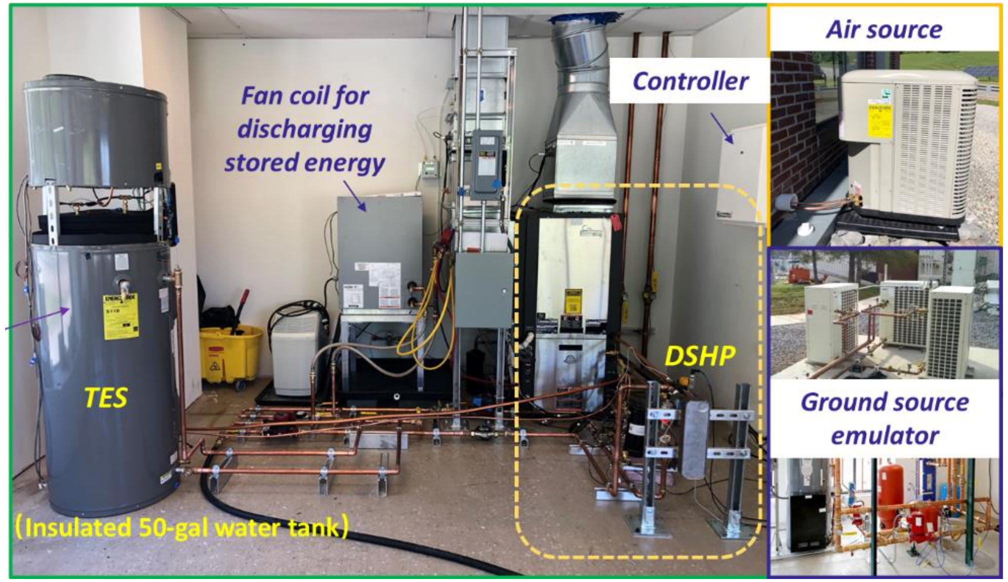

Yarnell Station unoccupied research home


Flexible Research Platform (FRP2) unoccupied

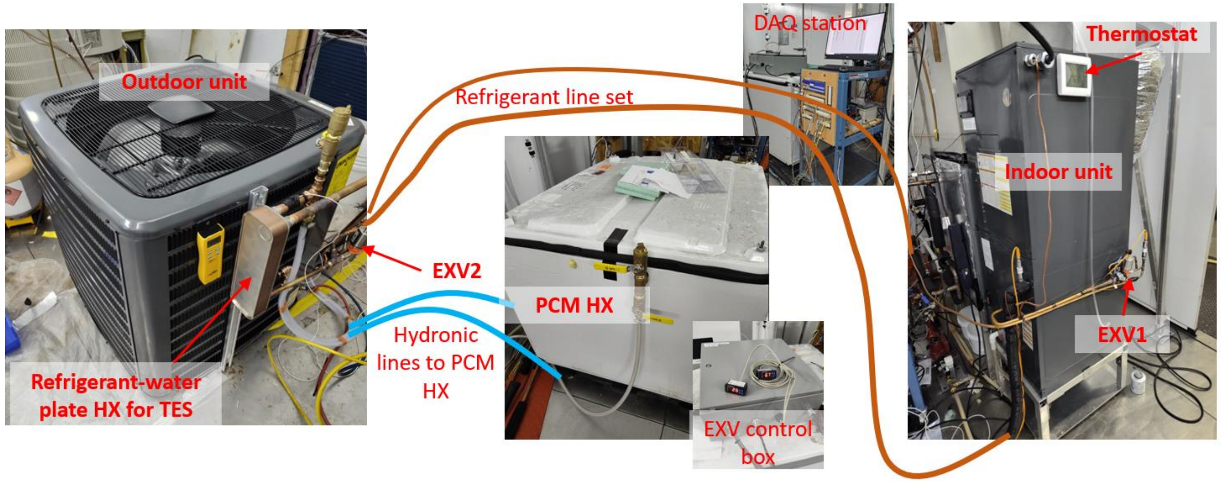
ORNL developed a testbed for HP-TES

Flexible Research Platform (FRP) at ORNL

- Implemented in a real building exposed to real weather and with emulated occupancy and internal heat gains
- Instrumented with 500+ sensors, including an on-site weather station
- Can be configured for various HP-TES systems
- Has been used to test TES heat exchangers, phase change materials, and control strategies

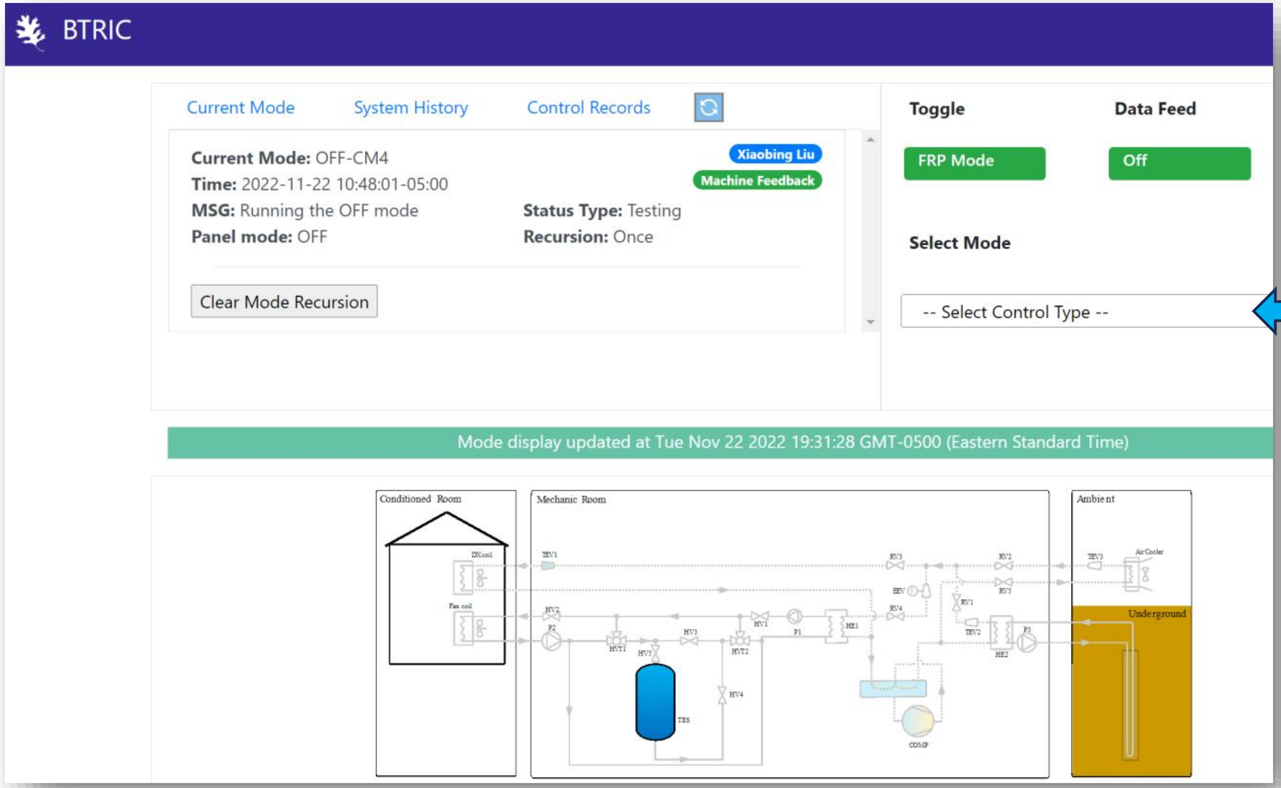


Testbed of HP-TES in ORNL's FRP

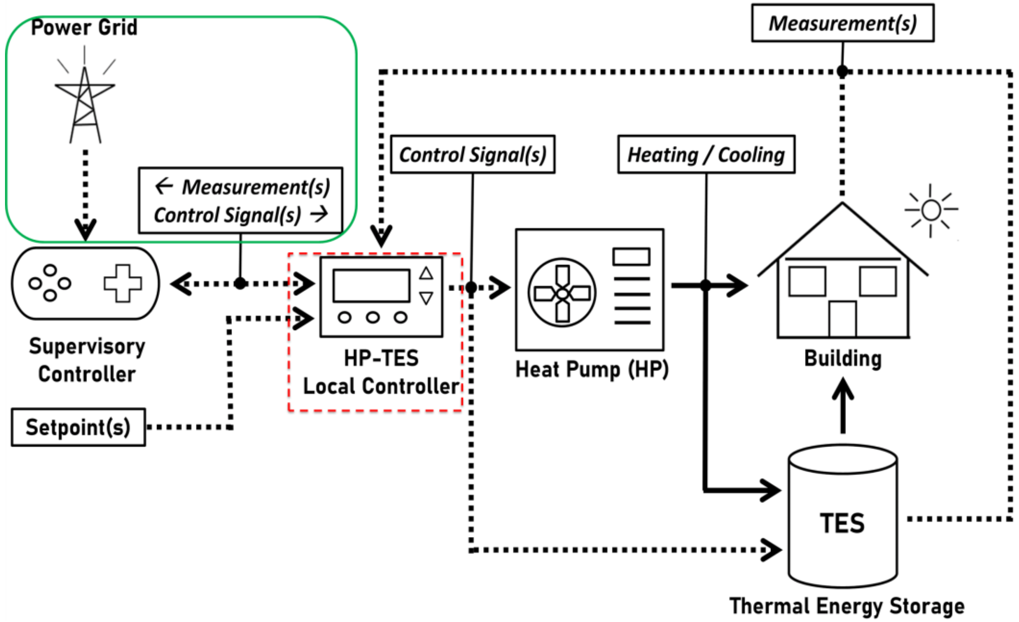


TES-ready split heat pump for new and existing residential buildings

The test bed has a cyberinfrastructure to remotely control and monitor the performance of HP–TES system

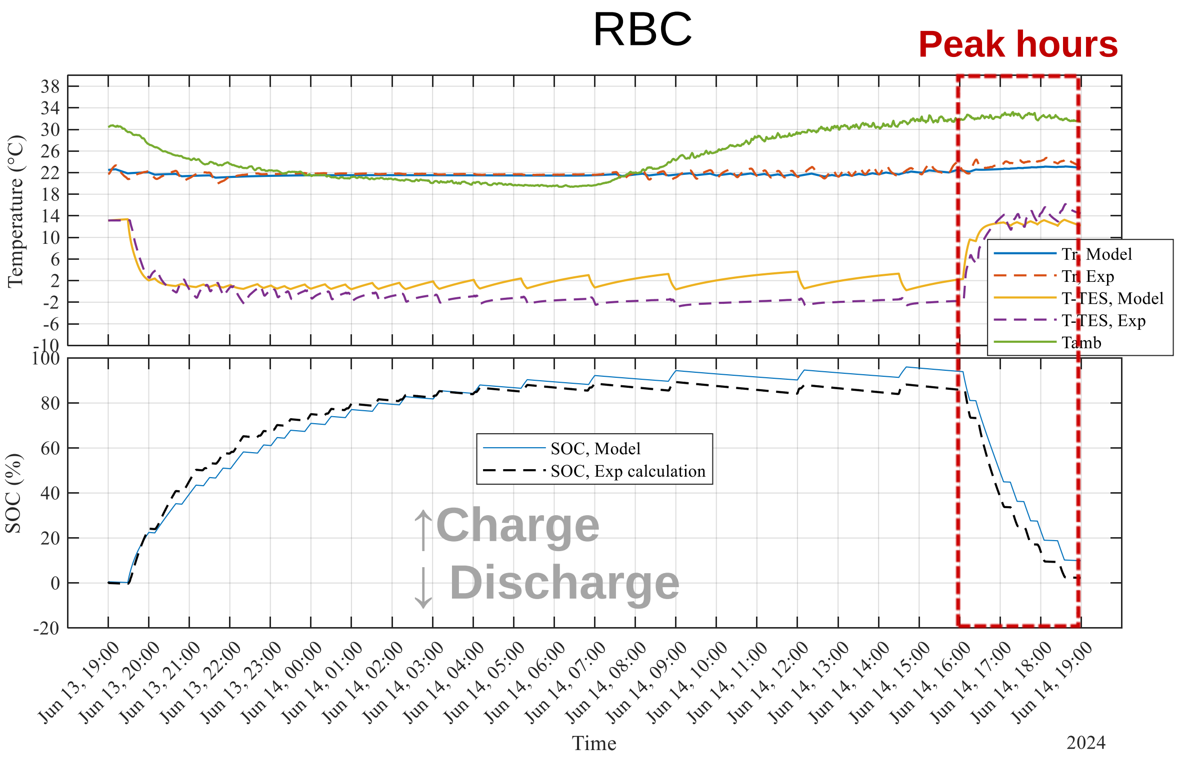


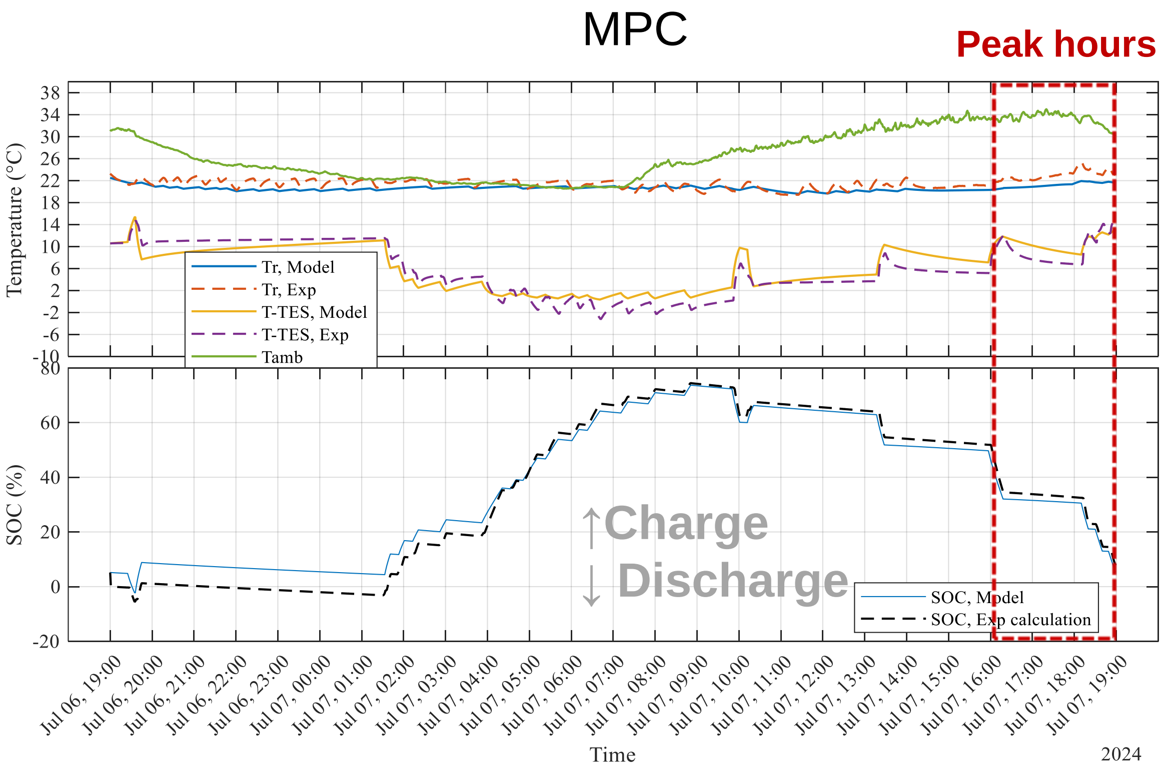
- *Manual selection from more than 14 operation modes*
- *Automated operation with rule-based control*
- *Automated operation with model predictive control*



Field tests were conducted to compare MPC against RBC for HP-TES at ORNL's FRP

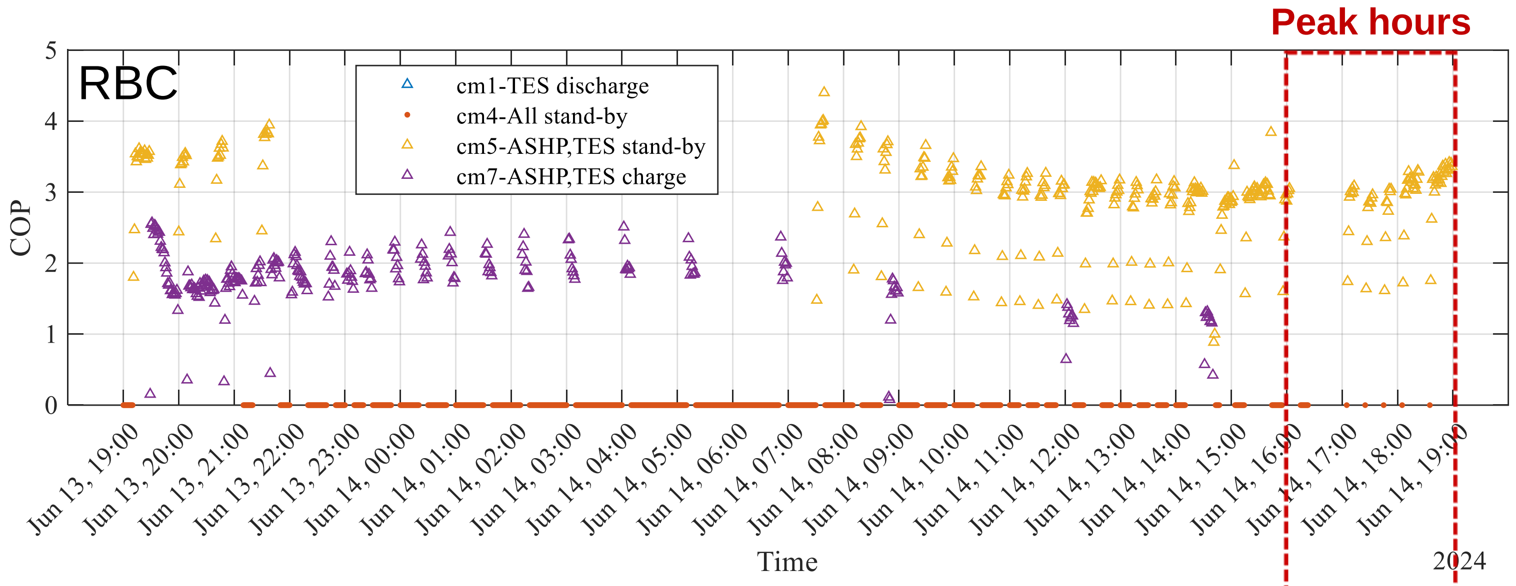
- Models used in MPC has been **validated** with experimental data
- Both RBC and MPC can **maintain room temperature at setpoint** and **shift electric demand**



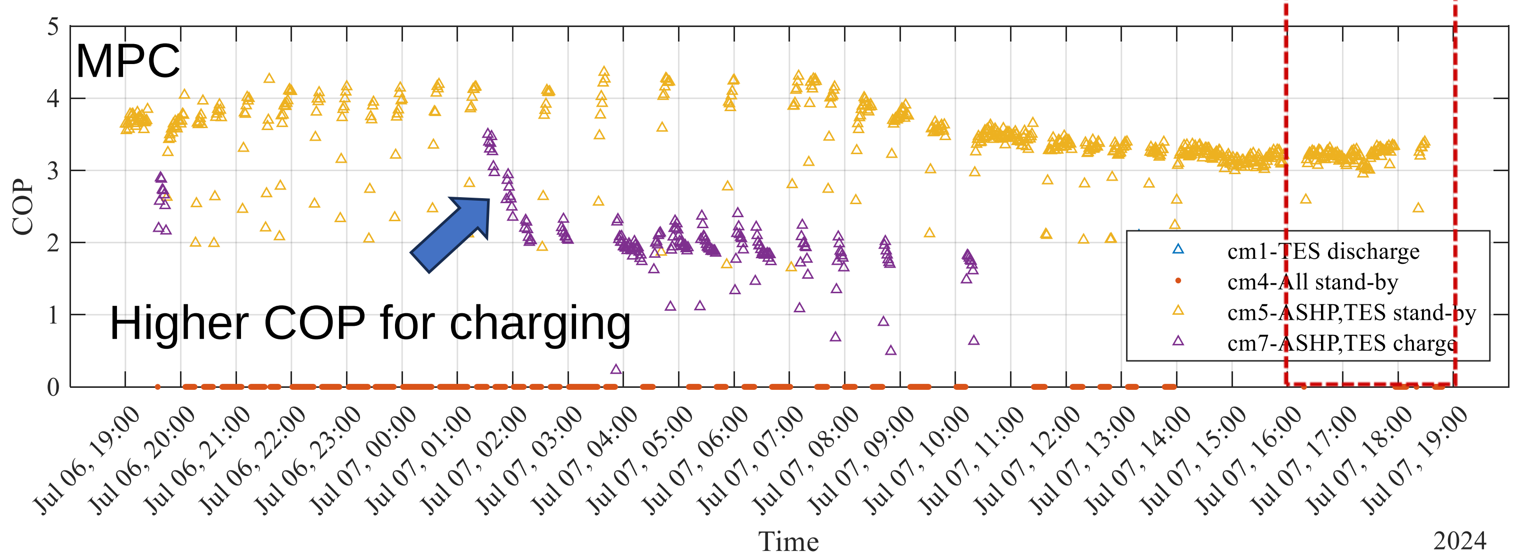


Field tests proved MPC is smarter than RBC

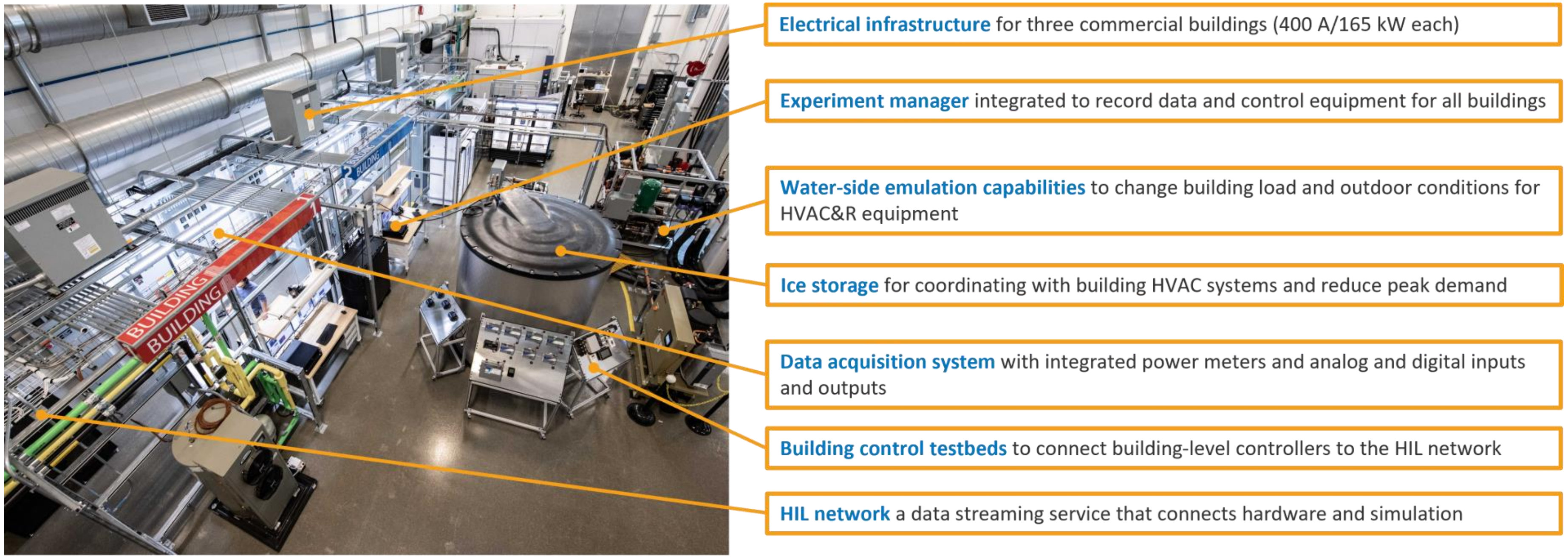
- RBC charged TES immediately after peak hours **regardless of ambient temperatu re**

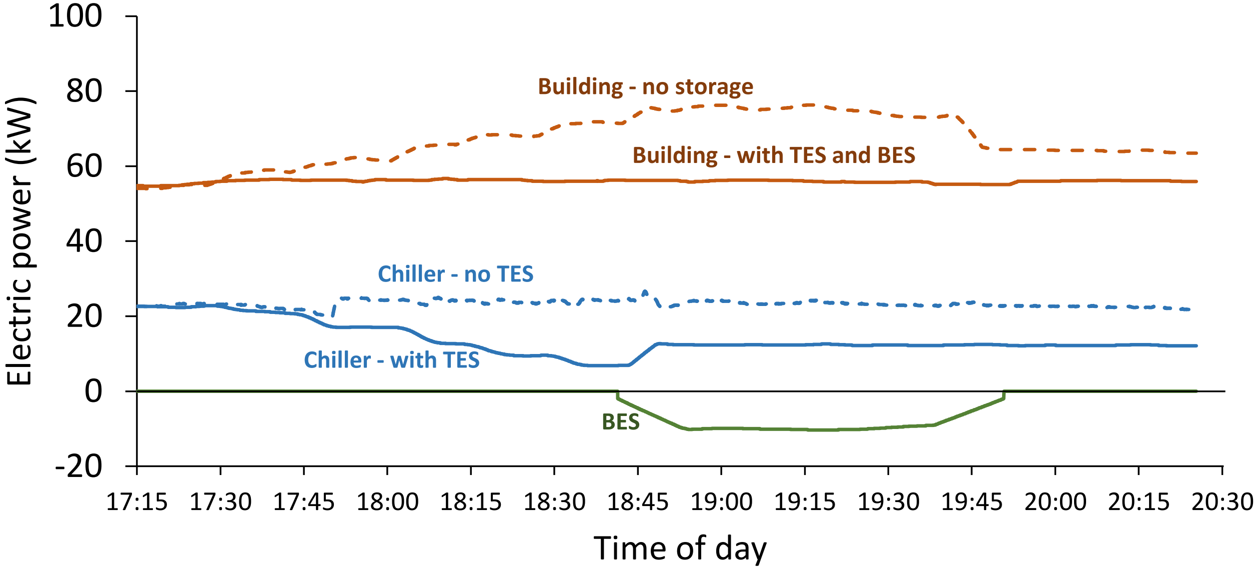


- MPC charged TES **when the ambient temperature was low** and stored just sufficient energy for shifting electric demand



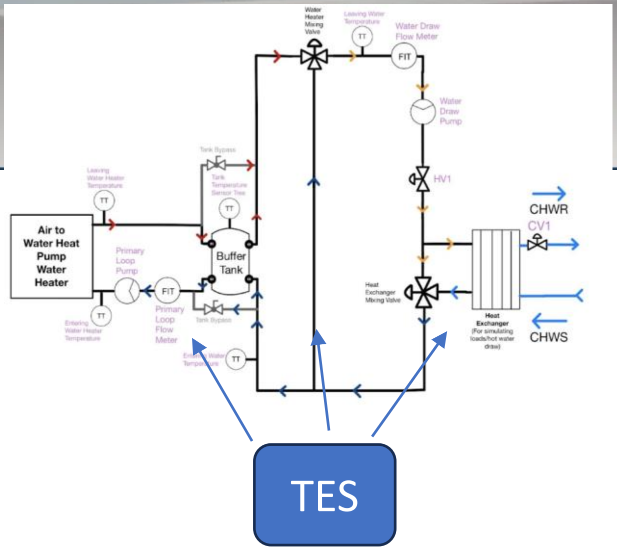
Hardware-in-the-loop test facility at NREL





Combined BES/TES control results in 25% demand reduction.

When chiller reaches maximum turndown, controller discharges battery to maintain load below the maximum.



- FLEXLAB key features:
  - Includes all major end-uses in commercial buildings (realistic load profiles and responses)
  - FLEX = equipment and components can be swapped
  - Physical "zones" captures and measures indoor occupant thermal and visual comfort
  - Side-by-side identical cells to test experiment vs baseline
  - Highly instrumented and capable of HIL tests.
  - Planned expansion: Low GWP HP test chamber
  - Planned expansion: water heater test rig/water distribution & TES

Laboratory and field test of TES Systems at PNNL

- Storage testbed is being used to test and validate grid-interactive advanced controls framework for storage systems
- In FY25, the framework will be tested at a partner site which includes hot/cold water storage as well as PCM-based cold storage

Coupled building-integrated battery and ice storage testbed at PNNL

120kW – 250 kWh
Lithium-ion battery

550 ton-hr
ice storage

Three 8,000-gal water tanks (~187 ton-hours) five 626-gal phase-change tank (~200 to 225 ton-hours)

Summary

- A holistic model-based design approach has been developed to improve controls of various TES-HVAC systems
- RBC and MPC have been implemented and tested; Both can maintain room temperature while shifting electric demand as needed
- MPC has demonstrated advantages over RBC but there are challenges for implementing MPC in real world
  - Lack of reliable measurement for SOC of TES
  - Significant effort is needed for developing accurate models for MPC
  - Control boards of HVAC equipment usually do not have needed computation power for MPC, and cloud-based implementation needs to protect privacy and cyber-security

Recommendations for further R&D

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- Work with industry to move TES control from the lab to pre-commercialization prototype systems
- Test grid-interaction of TES from multiple users on the same control platform (i.e., VOLTTRON)
- Improve flexibility and adaptability of advanced controls (i.e., minimal field work for implementing the advanced controls)
- Develop easy to use and plug-n-play control for low-income communities

Acknowledgements

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Questions/Comments ?

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Xiaobing Liu: liux2@ornl.gov

Questions

- What type of utility rate examples are of interest
  - Time-of-use (TOU), TOU with demand charge, day ahead real-time price (RTP), RTP, energy + demand charge, real-time emissions signal, etc.
- What TES system are of interest
  - Ice storage, chilled/hot water storage, and phase-change-material
- What communication protocols
  - BACnet and Modbus
- Optimization horizon
  - 24-hour, 1-hour, etc.
- What are the minimum sensor requirements
  - Temperatures and flows
- Is integration of battery energy storage system and/or distributed solar generation important
- How critical is field validation
- Do you need this in 5 years?
- Are we on the right track?