Optimal Stationary Fuel Cell Integration and Control (Energy Dispatch Controller)

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Project ID # TV042

Overview

Timeline and Budget

- Project start date: June 2016
- Project end date: Sept 2019
- Total project budget: $2.26M
  - Total recipient share: $1.74M (NREL) $520k (PNNL)
  - Total federal share: $2.26M
  - Total DOE funds spent*: $1.028M

* As of 3/31/18

Partners

- PNNL, Washington State University University of Colorado – Boulder (collaborators)
- Humboldt University, Doosan, Plug Power, Ballard, Fuel Cell Energy (review)

Barriers

- 4.2.3 Utilizing open standards and middleware software approaches to enable integration of EMS, DMS, and BMS. (GMI[1])
- 4.3.3: Develop efficient linear, mixed-integer, and nonlinear mixed-integer optimization solution techniques customized for stochastic power system models, novel bounding schemes to use in branch and bound, and structure exploiting algorithms. Demonstrate the cost-benefit achieved by these techniques relative to existing ones. (GMI[1])

[1] Grid Modernization Initiative (GMI) https://energy.gov/sites/prod/files/2016/01/f28/Grid%20Modernization%20Multi-Year%20Program%20Plan.pdf

Relevance – Project Goal

- **Project part of DOE's Grid Modernization Initiative (GMI)**
  - Funded by Fuel Cell Technology Office (FCTO)
- **Project Goal:** Create an open-source tool set to foster growth in fuel cell integrated buildings with emphasis on optimal control dispatch
  - Stationary fuel cells can be used for combined heat and power (CHP) to meet building's electrical and thermal loads
  - Integrated building controls can be used to minimize operating costs
  - Forecasts of load and resources can aid in grid ancillary market participation.

- **Project directly addresses GMI barriers:**
  - Creating open source tools for use with energy management system (EMS), distribution management system (DMS), and building management system (BMS)
  - Developing efficient optimizations for system modelling and cost benefit analysis with comparisons to existing techniques

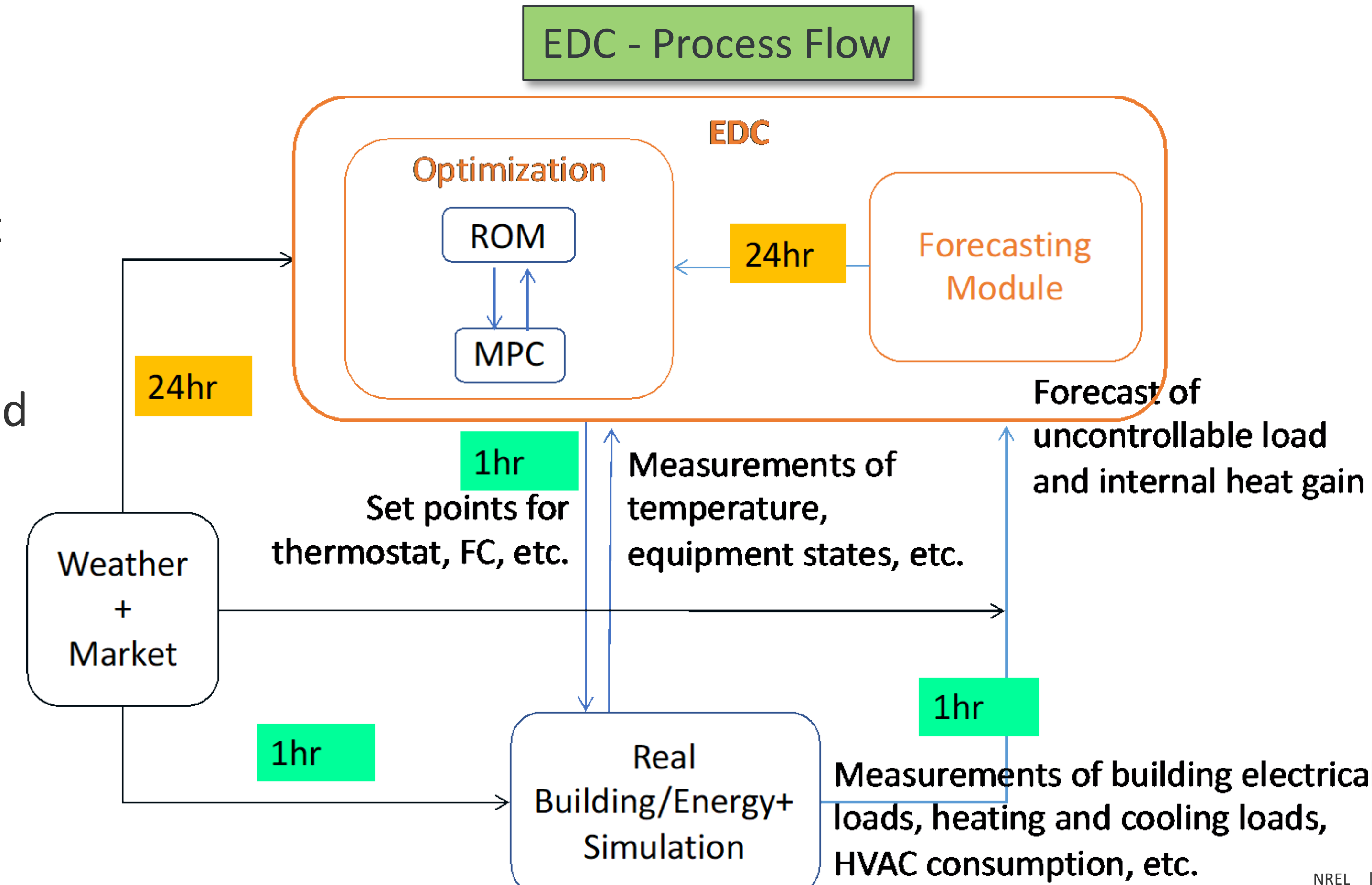
Relevance – Tools Objectives

➢ Energy Dispatch Controller

- Minimize building operating costs, while maintaining occupant comfort
- Allow participation in grid ancillary services using load and equipment forecasts from model predictive control approach

➢ Planning Tool

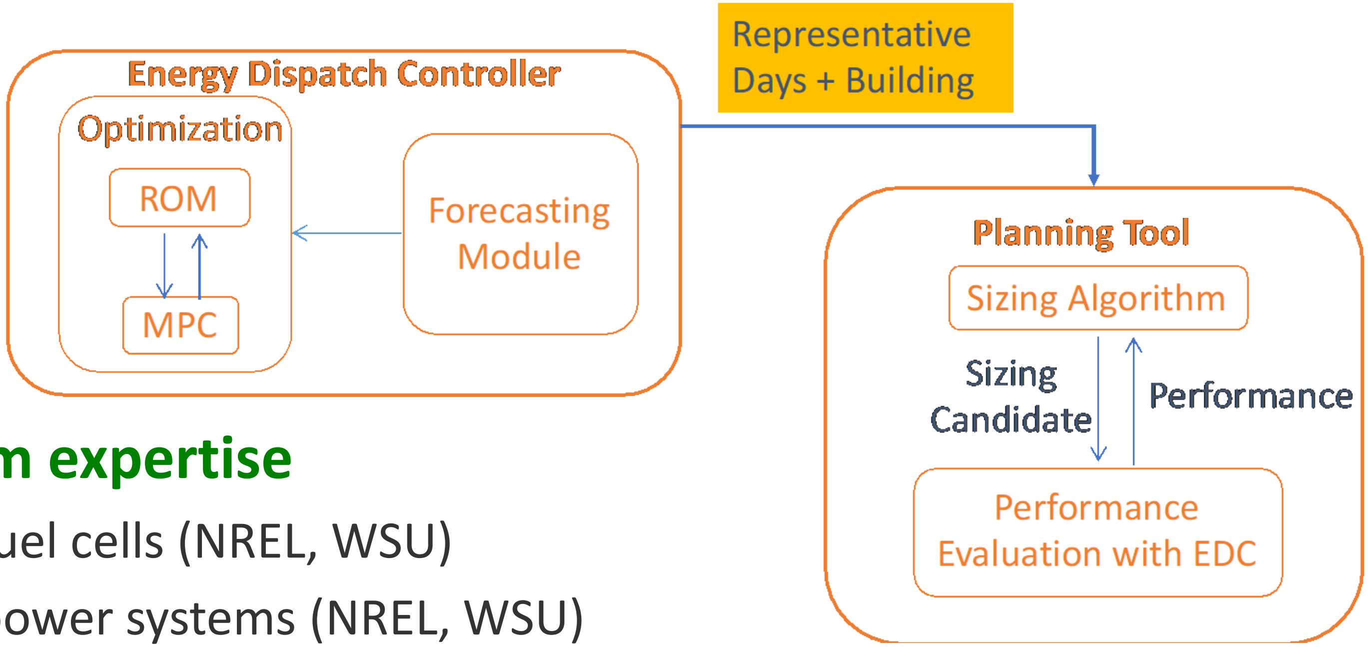
- Determine building component sizing using simulated dispatch and economic evaluation



Relevance - Impact

- **Modernize energy management and control of buildings**
  - Reduce energy bills and emissions
  - Maximize benefits of CHP, storage and renewable generation
- **Support grid modernization**
  - Characterize ancillary service opportunities
  - Increase grid reliability and security using flexible, dispatchable energy resource
- **Support fuel cell market development**
  - Quantify economic benefit of integrated CHP
  - Inform the industry of favorable characteristics

Approach – Cross-functional approach



- **Team expertise**
  - fuel cells (NREL, WSU)
  - power systems (NREL, WSU)
  - optimization techniques (NREL, WSU, PNNL)
  - commercial buildings (NREL, PNNL)
  - building communication networks (PNNL)
- **We are leveraging tools and skills across several different groups both intra- and inter-lab at NREL and PNNL and with academia.**
  - Developing modules for this project that have extensible applications

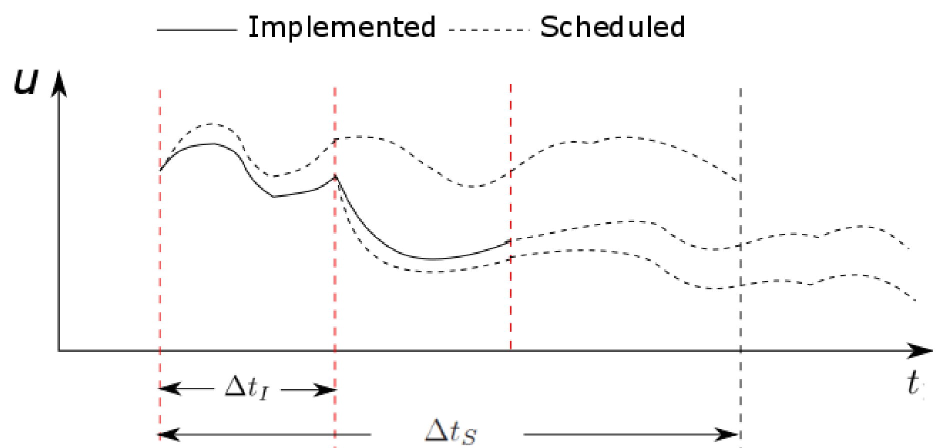
Approach: Model Predictive Control

Initial formulation of the optimization problem is complete. Iterative improvements through testing have begun.

What is the Energy Dispatch Controller?

- The EDC manages building operation in real time.
- It uses MPC to forecast 24 hr moving windows and implement for 1 hr.

What is the objective?



- The objective is to minimize building operation costs.
- Electricity bill + Natural gas bill – Ancillary service payment

What are the decision variables?

- The EDC can make decisions (operational set-points) for building variables.
- Temperature set-point, fuel cell electrical and thermal output, battery charging and discharging, ancillary service capacity.

What constraints does it have?

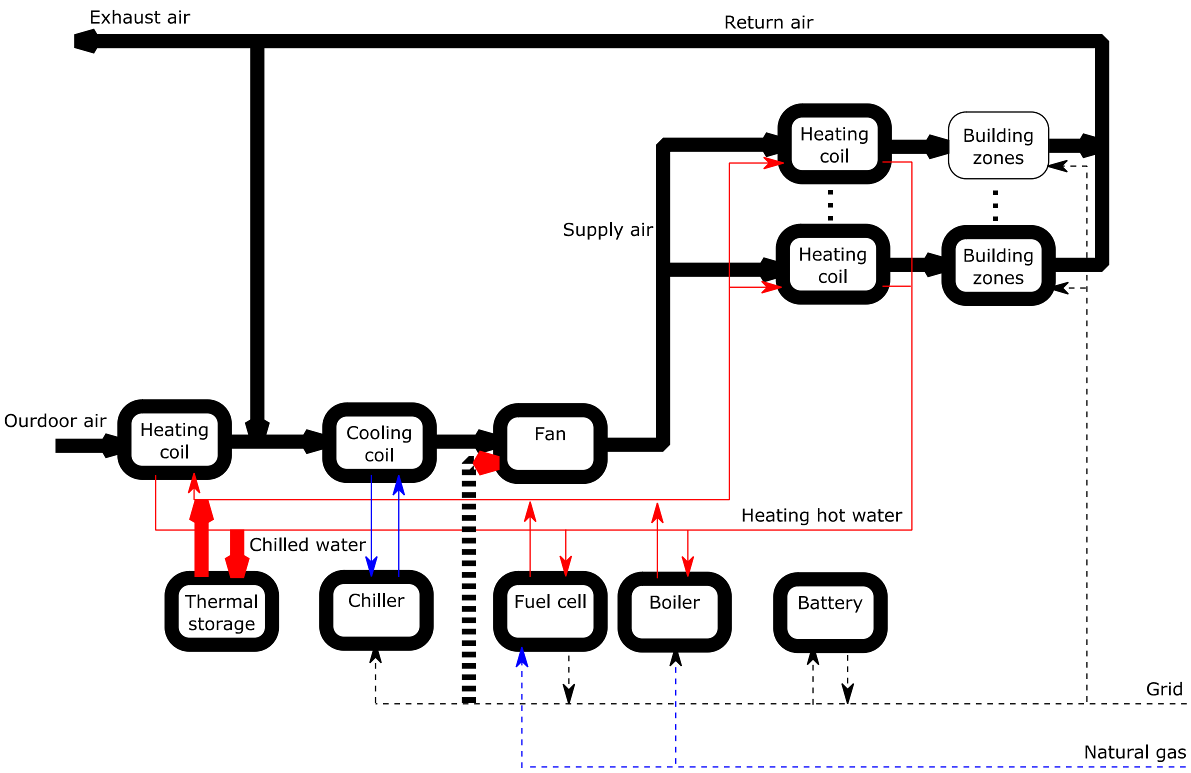
- Model prediction (ROM, forecasting), Comfortable temperature bounds, Equipment limits

Approach: Model Structure

The model structure used in the EDC can represent most building structures and be extended into novel configurations.

Model structure

- Electrical loop
- Hot water loop
- Chiller water loop
- Air loop
- Natural gas loop

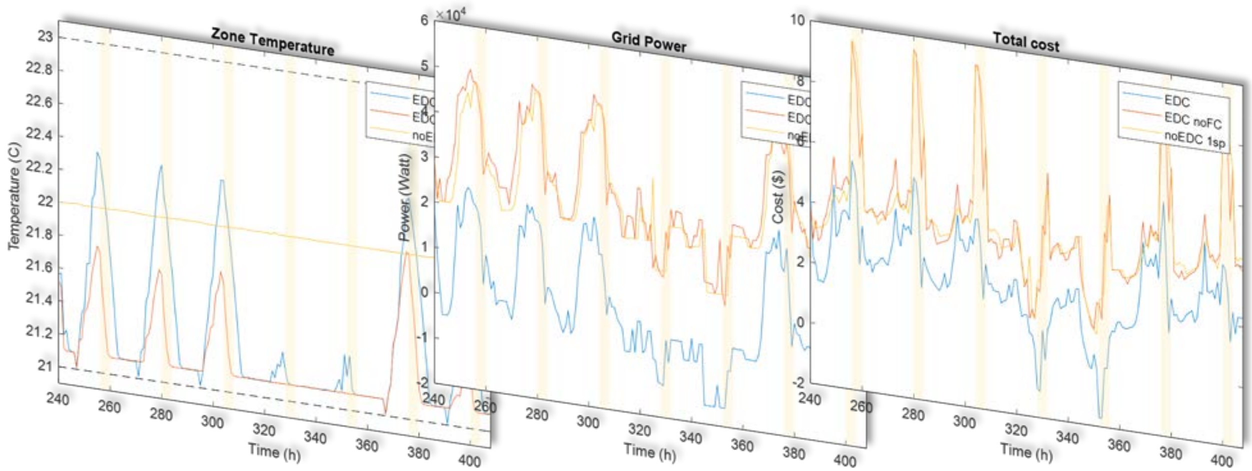


Additional equipment needed for different building types can be added into appropriate loop as well as novel configuration.

Accomplishments: Energy Dispatch Controller

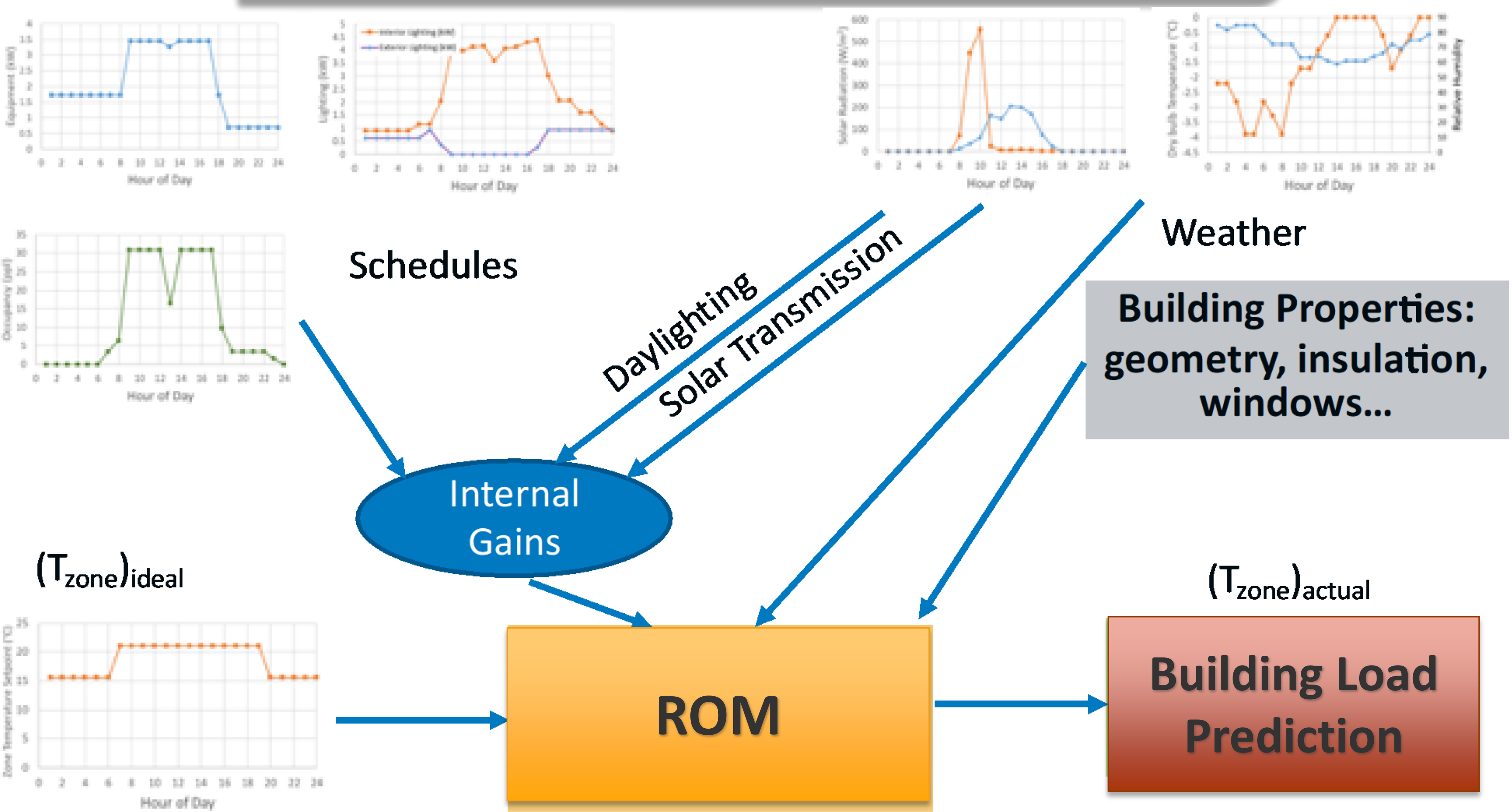
Improvements to EDC being made as testing begins and more modules come on-line.

- Recent additions to EDC:
  - Added fuel cell on/off decision; requires mixed integer programming
  - 2nd order ROM for building
  - ROM running at faster time step to make full use of 2nd order model
- Improved fuel cell model
  - now injecting heat to hot water loop
- Running closed-loop simulation with temperature feedback



Accomplishments: Reduced Order Building Model

The ROM is created from static and dynamic elements of the building system.



Courtesy: McLarty, D. et al, Washington State University

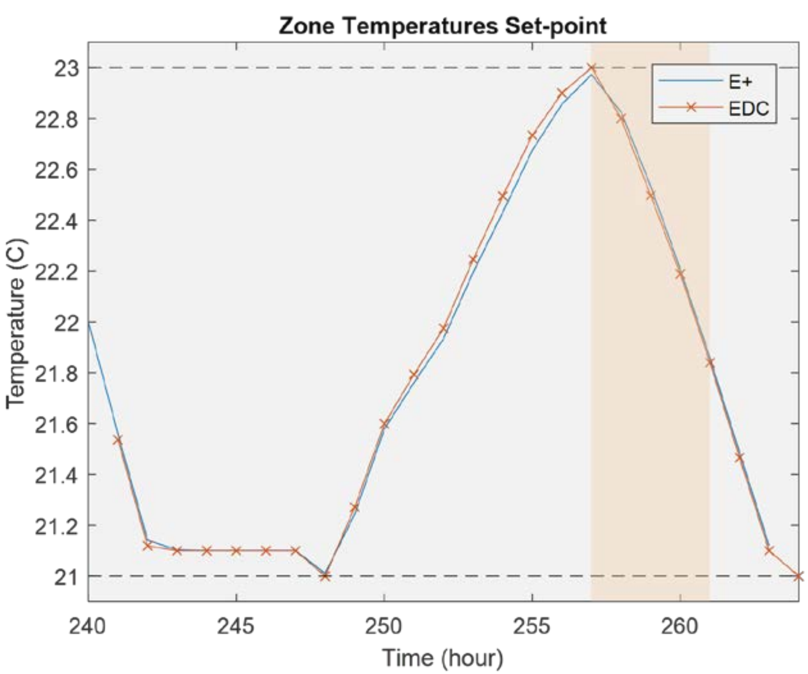
Accomplishments: Reduced Order Building Model

ROM mismatch error can be reduced by:

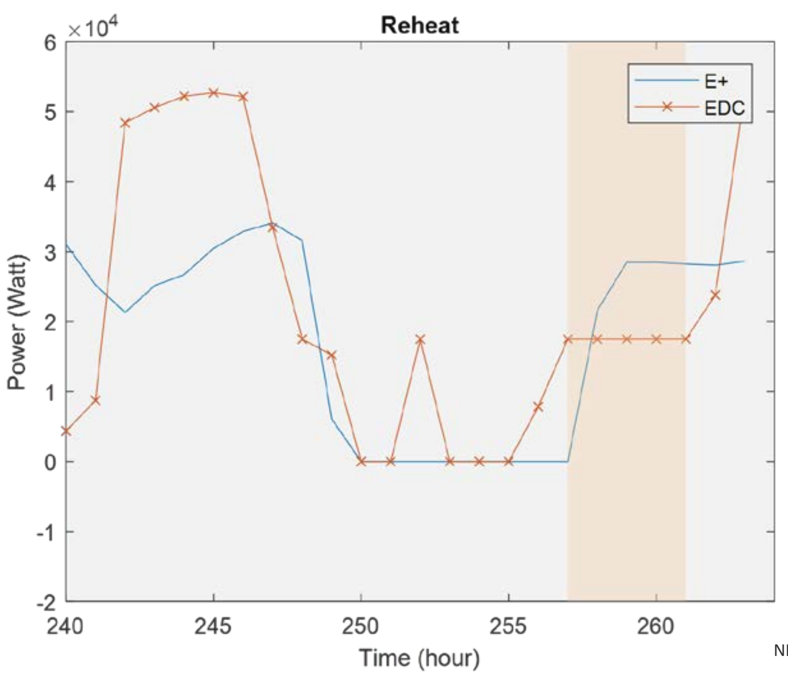
1) Improving initial ROM
2) Improving ROM through training with real data
3) Refinements to the optimization problem

Impact of ROM mismatch

Zone temperatures track well



Power required for heating shows the mismatch



Accomplishments: Reduced Order Building Model

ROM development is on-going.

ROM development

- Harder then anticipated
- Evaluated several iterations
- Current model include a wall zone (slow response rate) and an air zone (faster response)

Areas of ROM evaluation - impact on solvability of optimization

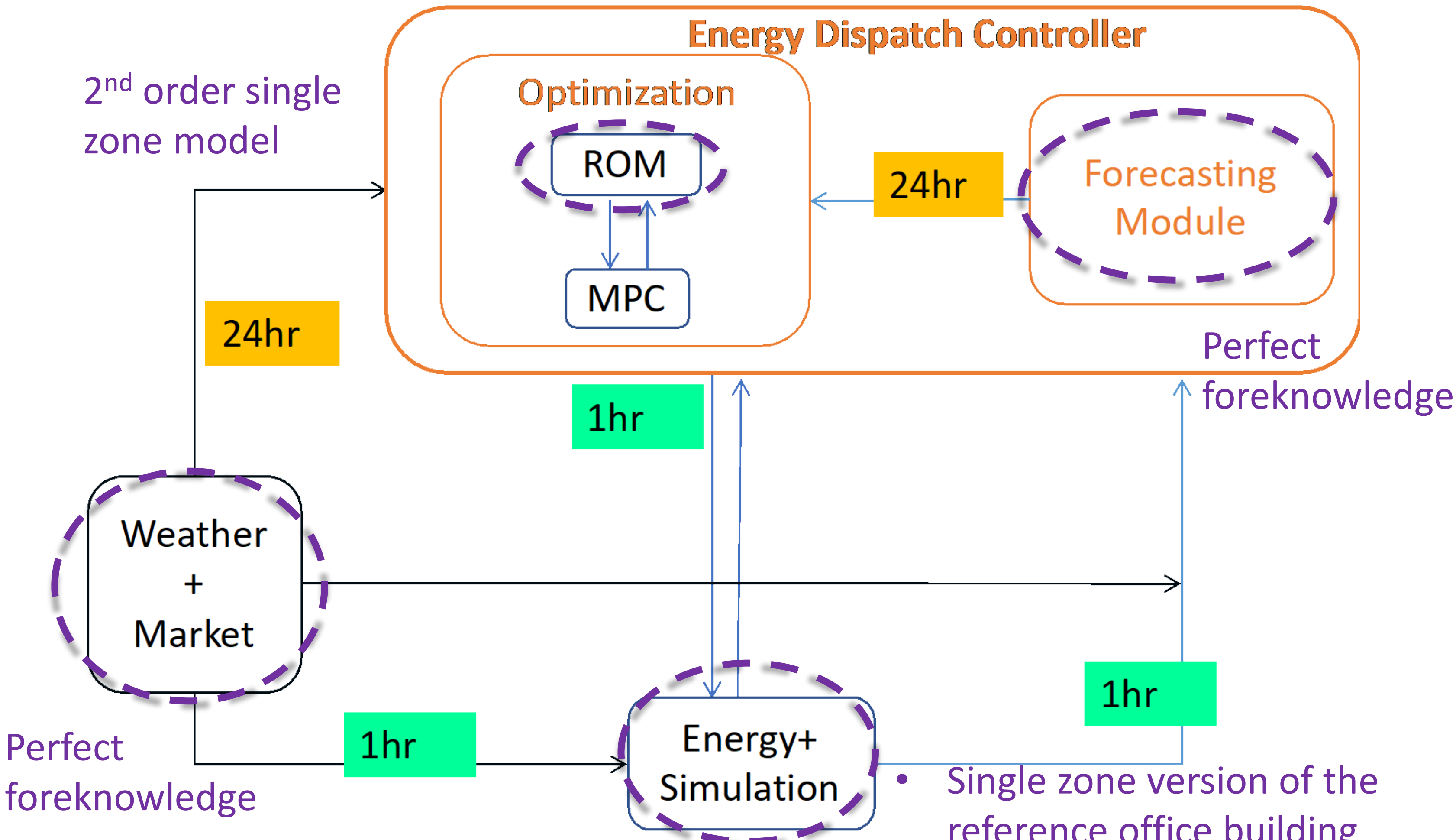
- 1^{st} order -> 2^{nd} order models
- Use of local linearization with second order models
- Time step size - capturing dynamics
  - The different time responses between the wall zone and air zone has required evaluation of the time step and impact on the optimization
  - Oscillations and instabilities occur when the time step is too large for a transient response factor.

Further work

- *WSU, NREL, and PNNL are continuing development on the ROM*
- *Currently evaluating of where errors can be fixed, e.g. ROM vs forecasting*

Accomplishments: Co-Simulation Testing

Co-simulation with temperature feedback running.



- Single zone version of the reference office building
- Fuel cell simulated in Matlab
- Simplified HVAC control logic

Accomplishments: Co-simulation Testing

Testing parameters

- Prices:
  - Electricity: normal rate $0.1/kWh, peak hour rate $0.2/kWh.
  - Natural gas: low case, $0.03/kWh, high case, $0.08/kWh.
  - Ancillary service: 0.03/kW
- FC capacity: 25kW electricity, 17.5kW heat
- Building load: peak approx. 50kW electricity, 30kW heat
- EDC temperature range: 21 - 23 degC

Parameters used were for initial trial runs. Scenarios will be developed to test a wide range of conditions and provide analysis of the different modules and overall performance and economics of the EDC.

Accomplishments: Co-simulation Testing

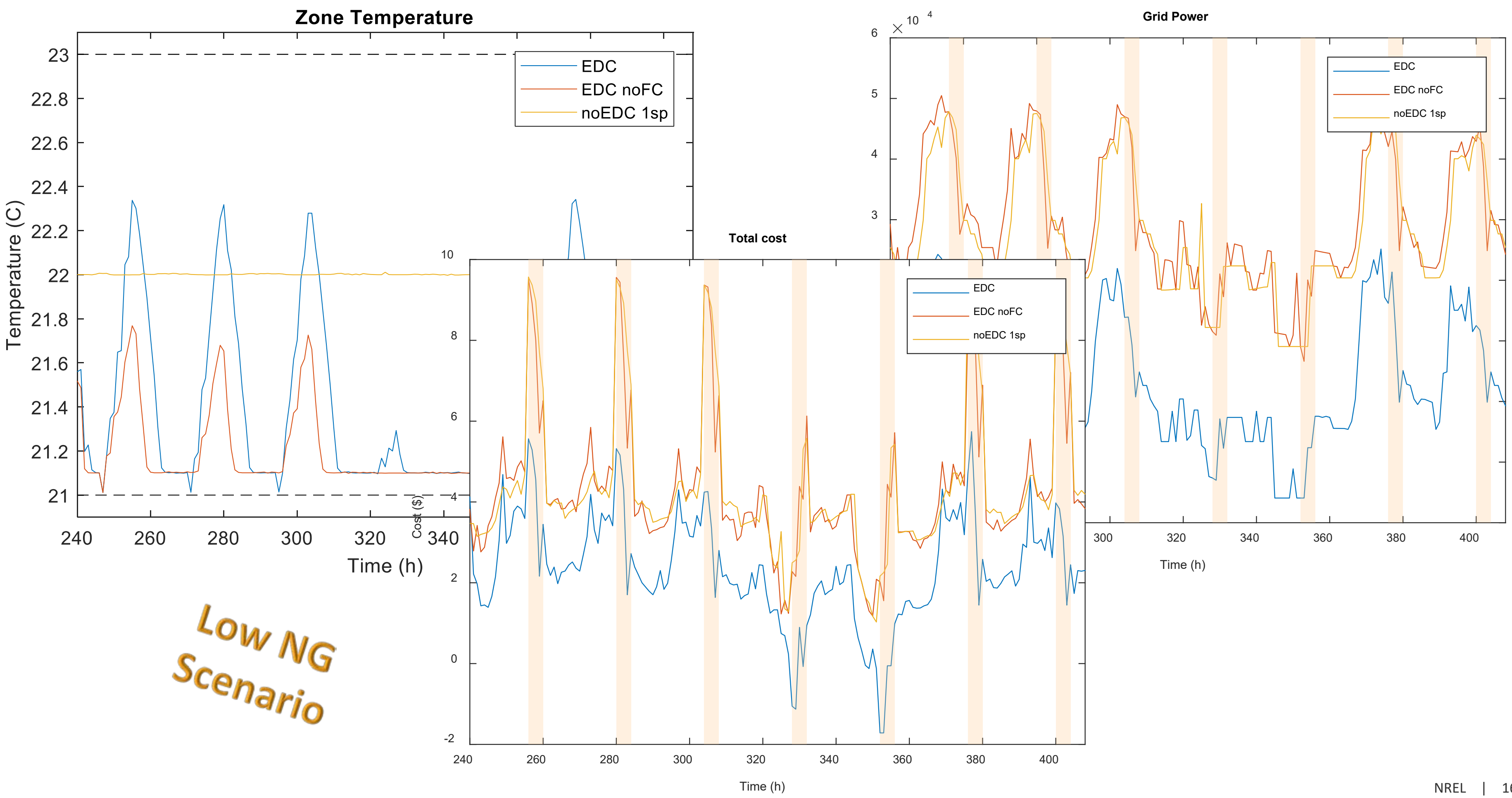
We are using different scenarios to test EDC performance and quantify costs.

Low NG Cost Scenario	Total cost	Electricity cost	Natural gas cost	Ancillary services payment
EDC	398	81	321	5
EDC, no FC	733	611	127	5
No EDC, no FC, 1 set-point	747	594	153	
No EDC, no FC, 2 set-points	691	572	119	

- Cost saving of EDC vs. EDC no FC is 45.7%
- Cost saving of EDC vs. No EDC no FC 1 set-point is 46.7%
- Cost saving of EDC vs. No EDC no FC 2 set-point is 42.4%

Accomplishments: Co-simulation Testing

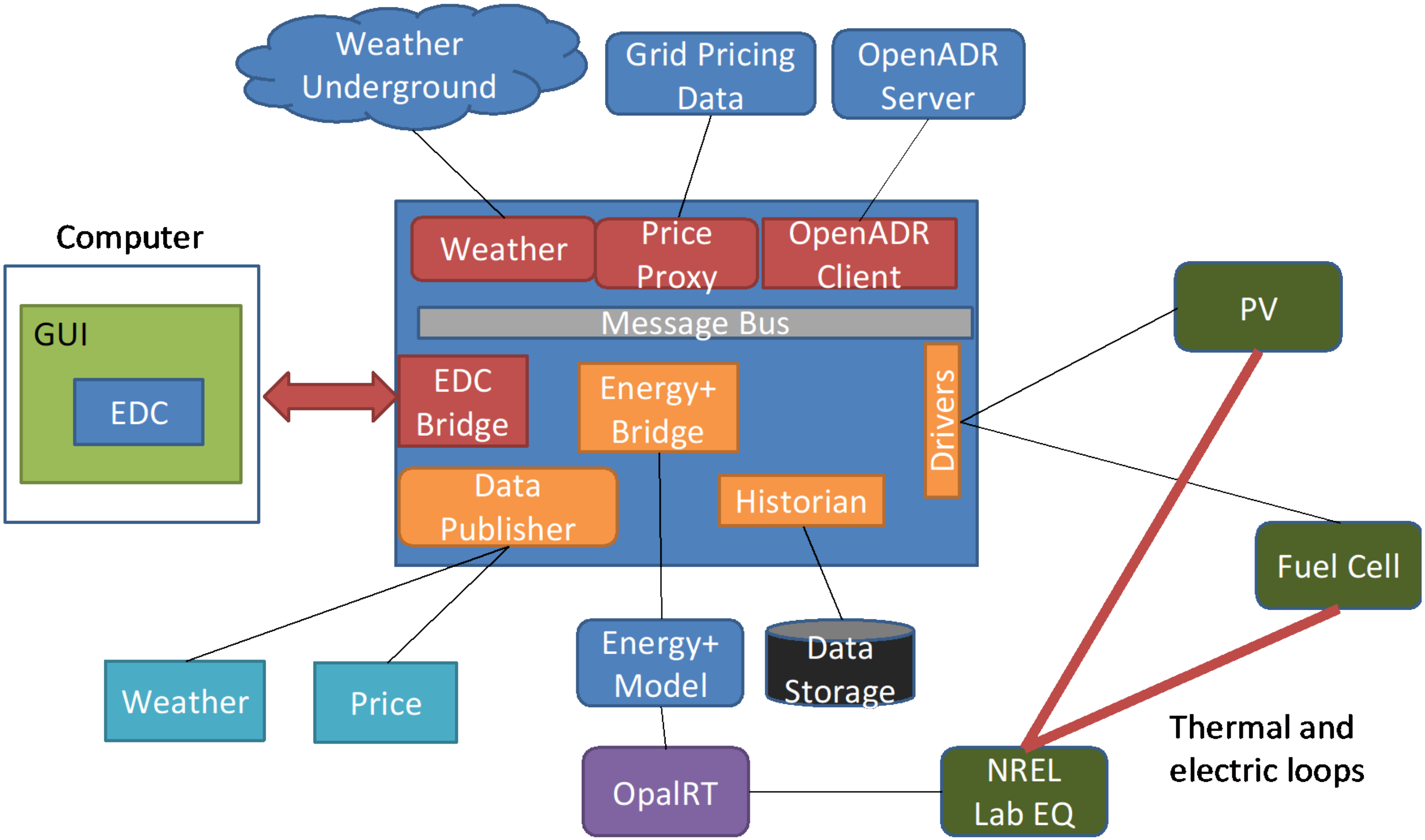
Development of graphs and analytics to dig into EDC performance.
- **Scenario development is forthcoming**



Low NG Scenario

Accomplishments: Communications Bus

- **Goal is seamless communication bus using VOLTTRON agents.**
  - **Docker containers will allow minimal configuration.**

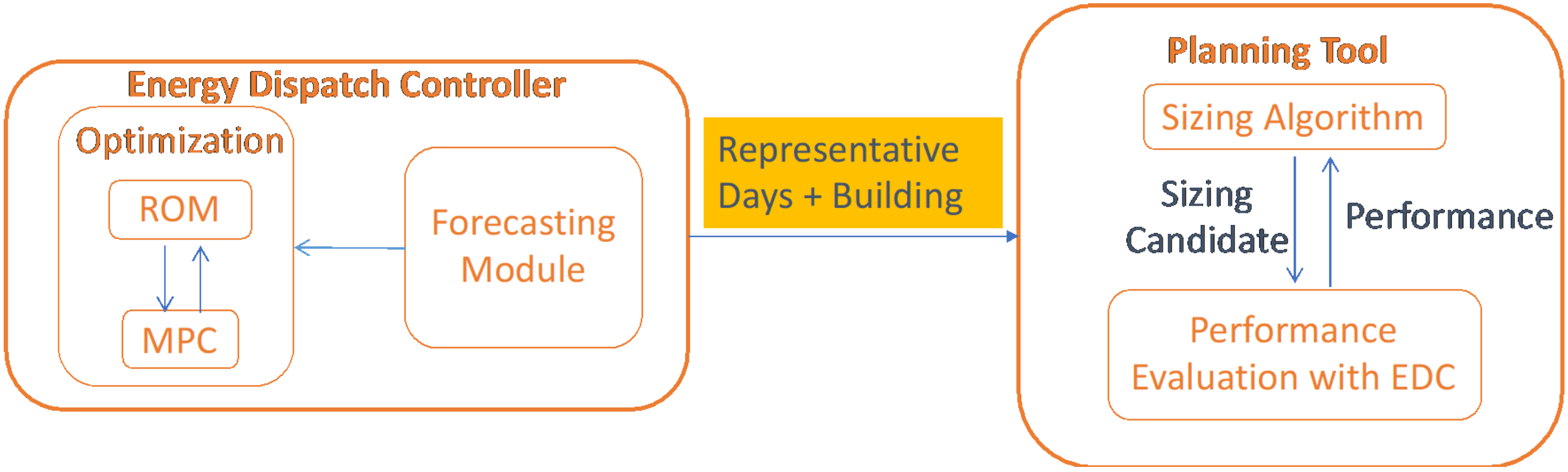


Accomplishments: Planning Tool

Integration begun and underlying modules are being developed.

Integration of the planning tool with EDC

- Goal is to size generation and storage equipment for best economic benefit
- Economic evaluation module begun - Run EDC against idealized building or historical load data
- Representative days module begun - Use representative days to make optimization manageable
- Several reference buildings with equipment selection module complete - More buildings and equipment being added



Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

- "The project appears to be well designed, but it is not clear how difficult it will be to get the knowledge and solutions out of the laboratory and into real-world adoption. Some of the control strategies will be completely dependent on the local market and its ability to provide ancillary services."
  - *The most important outcome will be to try to optimize building operation and reduce operating costs regardless of any ancillary markets. Ancillary market participation might increase the benefit, but is not required. We also want to position building operation for a future in which these ancillary markets might exist and explore how we can leverage the building asset on the grid.*
- "By using Energy+, the project team may have better adoption, but Energy+ appears to be used mostly by national laboratories and DOE rather than commercial building owners or other end users. "
  - *EnergyPlus and its related interface OpenStudio have been adopted by a number of large corporations of building energy analysis. These include Xcel Energy, Bonneville Power Adminstration, Los Angeles Department of Water and Power. The tools are being used in outside of research heavy national laboratories.*
- "For FuelCell Energy molten-carbonate fuel cells (MCFCs) and Doosan phosphoric acid fuel cells (PAFCs), the fuel cell cannot be shut down because of heat-up (startup times) and must be run continuously at partial power. It is not clear that the project has addressed this characteristic of these fuel cells."
  - *We have integrated the functionality for the dispatch controller optimization to turn on and off the fuel cell which takes into account time and cost of the start-up/shut-down cycles. However it is unlikely that most high temperature fuel cells would optimize to a daily/weekly shut down solution unless the building or market conditions changed to warrant an extended shutdown.*

Collaboration and Coordination

- **NREL – Transportation and Hydrogen System Center –** Fuel cells, modeling, optimization, coordination, and management
- **NREL – Power Systems Engineering Center**— Buildings control optimization, ancillary markets
- **NREL- Commercial Buildings Group**— Buildings models and control optimization
- **Washington State University**—Building controls optimization, ROM, GUI, ancillary markets
- **Pacific Northwest National Laboratory**—Buildings interface and communications backbone (VOLTTRON), ancillary market work, and ROM
- **University of Colorado at Boulder** – Buildings controls expertise and review
- Consulting and review - Humboldt University, Doosan Fuel Cells America, Plug Power, Inc, Ballard, Fuel Cell Energy

Thanks to our team:
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Remaining Challenges and Barriers

- The MPC optimization problem has many approach trade-offs
  - Researching numerous ways to keep it tractable while reducing error
  - Refining the optimization problem to include more elements of the building
- ROM development is challenging and can never be perfect
  - Working on parallel research to evaluate different methods
  - Investigating if ROM mismatch error can be minimized with training or forecasting
- Planning tool
  - Solution space is very large with finite and continuous sizing options
  - Comparing strategies that will provide the best result

Proposed Future Work

- EDC & optimization algorithms
  - Development of a set of testing scenarios
  - Refinements as a result of analysis of performance behavior
- ROM
  - Continue development and evaluation of ROM
  - Develop strategies for minimizing error due to ROM mismatch
  - Expand building selections to full commercial office and large hotel
- Forecasting
  - Implement forecasting module
- Communications backbone
  - Continue to develop VOLTTRON agents and agent refinements
  - Configure for integration with hardware-in-the-loop testing
- Planning Tool
  - Implement modules needed to start evaluations
- Hardware-in-the-loop (HIL) testing
  - Prepare for move to lab testing of EDC in FY19

(Any proposed future work is subject to change based on funding levels.)

Technology Transfer Activities

- Objective is to release all code as open source by end of project
  - The target audience includes building managers and building control companies, ancillary service aggregators.
- Benefits
  - Reduce building energy cost with better integrated controls
  - Position building participation in the changing ancillary market environment

Summary

FY18 Progress

- EDC
  - Initial formulation of the optimization problem is complete and testing has begun.
  - Implemented functionality for fuel cell start-up and shutdown in optimization
  - Evaluated several iterations of ROM and are investigating improvements
  - Investigating ways to improve EDC performance with training and forecasting
  - Initial ancillary services work is begun
- Testing and Validation
  - Held stakeholder seminars to elicit feedback on project, approach, and perspectives
  - Co-simulation environment with Energy+ is running
- Communications Bus
  - Started work on creation and revision of VOLTTRON agents
- Planning Tool
  - Integration of EDC into Planning Tool begun

FY19 Plans

- Testing and validation activities including HIL testing in a lab

Thank You

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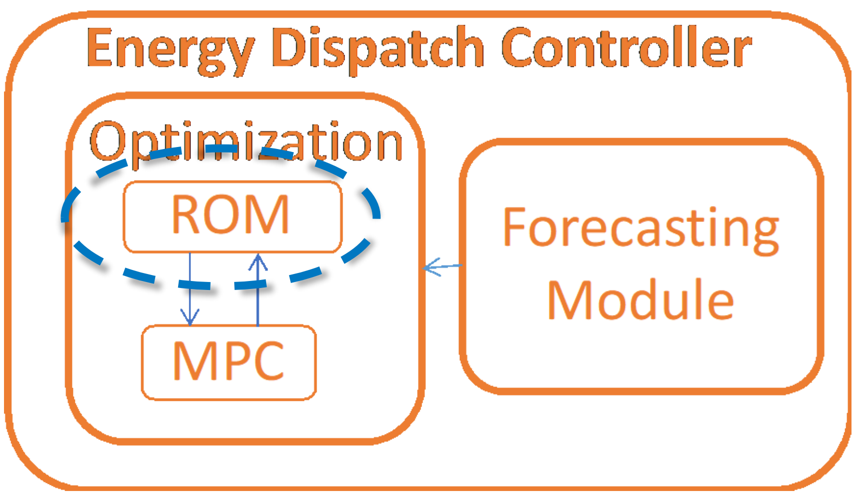
Technical Back-Up Slides

Accomplishments: Reduced Order Building Model

The ROM is a RC model to represent the building.

Why is a ROM needed?

- Model predictive control (MPC): at each time step, calculate the optimal operation of the next 24-hour.
  - Need a model to predict the building behavior.
  - Need to know how power consumption and temperature evolves under the controllable inputs (thermostat set-points, fuel-cell operation set-points, battery charging/discharging, etc.) and uncontrollable inputs (weather, building occupancy loads, etc.).
  - The model needs to be "simple" for the optimization problem to be tractable.



Accomplishments: Reduced Order Building Model

The ROM is a RC model to represent the building.

How is the ROM created?

- Model inputs: weather, solar radiation, internal heat gain (occupants, equipment).
- Model outputs: zone temperature, HVAC system power consumption (chiller, fan, boiler).
- ROM is the creation of a RC model to represent the building
- Current model include a wall zone (slow response rate) and an air zone (faster response)