NREL NATIONAL RENEWABLE ENERGY LABORATORY

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

Genevieve Saur
NREL

June 7, 2017

Project ID # TV042

Overview

Timeline and Budget

- Project start date: June 2016
- Project end date: May 2019
- Total project budget: $2.1M
  - Total recipient share: $1.74M (NREL) $360k (PNNL)
  - Total federal share: $2.1M
  - Total DOE funds spent*: $382k (NREL), $32k (PNNL)

* As of 3/31/17

Partners

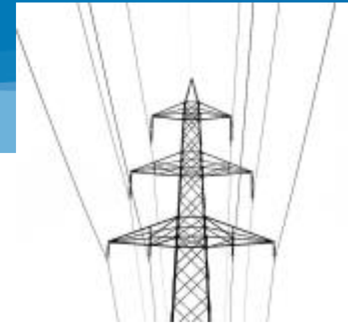
- PNNL, Washington State University University of Colorado – Boulder (collaborators)
- Humboldt University, Doosan, Plug Power, Ballard, Fuel Cell Energy (review)

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)

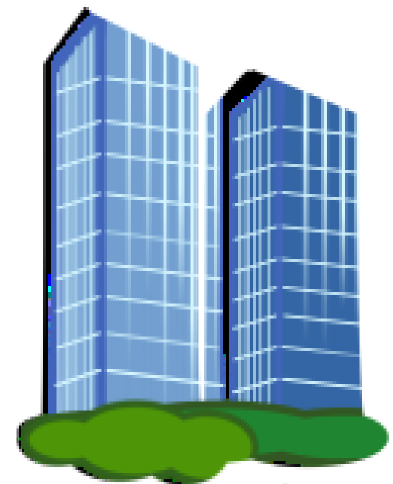
https://energy.gov/sites/prod/files/2016/01/f28/Grid%20Modernization%20Multi-Year%20Program%20Plan.pdf



PROBLEM

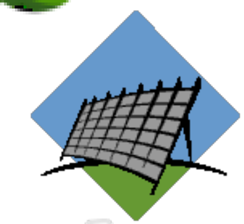
Current building control strategies

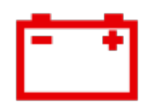
- can be simplistic
- rely on assignment of value to resources



OBJECTIVE

- **Create an open-source novel energy dispatch controller (EDC)**
  - Optimized dispatch for building components
  - Participation in ancillary grid services
- **Create a planning tool for building component sizing using simulated dispatch**





Relevance - Impact

FCTO project in Grid Modernization Lab Call

- **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

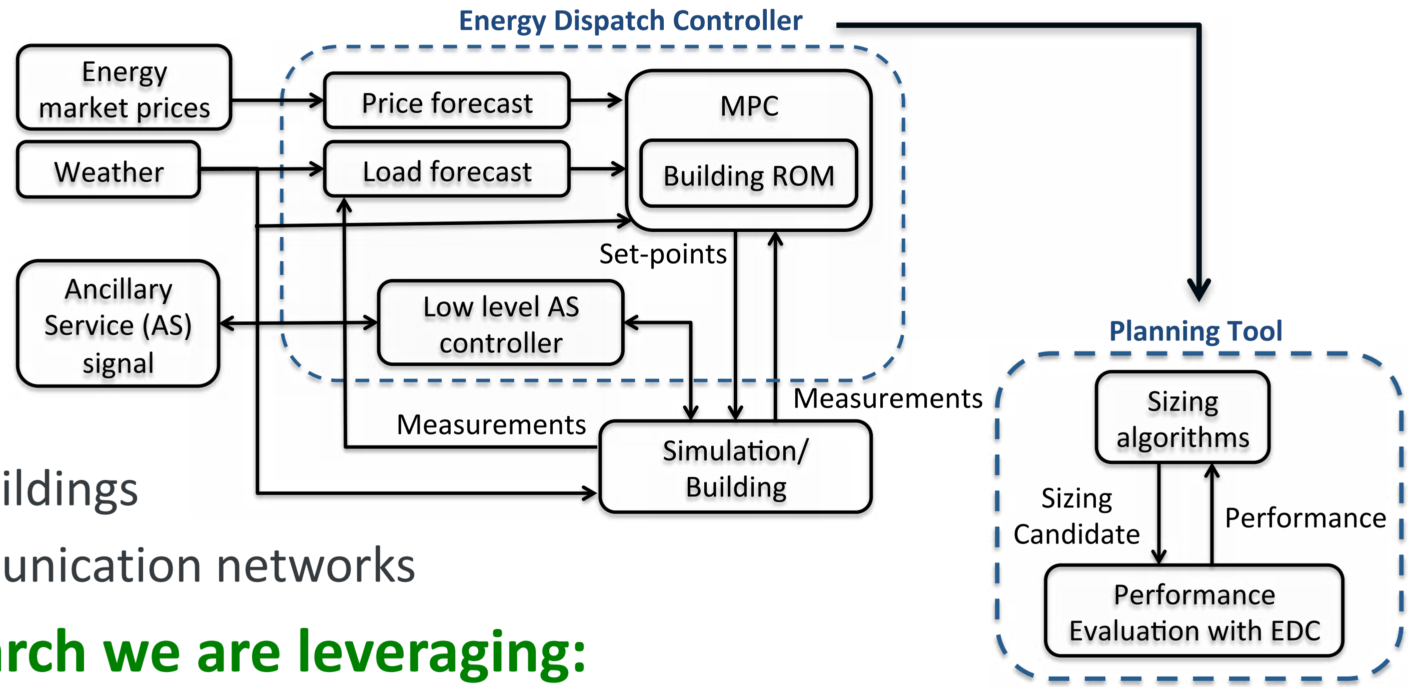
- **Support fuel cell market development**
  - Quantify economic benefit of integrated CHP
  - Inform the industry of favorable characteristics

Relevance – Current Year Objectives

Initial formulation of the MPC algorithm is complete

- **EDC Optimization (Model Predictive Control (MPC))**
- **GUI**
  - Complete initial GUI screens to provide interface for testing and feedback (FY17 GNG)
- **Building Design Framework**
  - Create interface for providing building specification and design
- **Co-simulation Environment**
  - Create a functioning co-simulation environment for testing EDC

Approach – Cross-functional approach

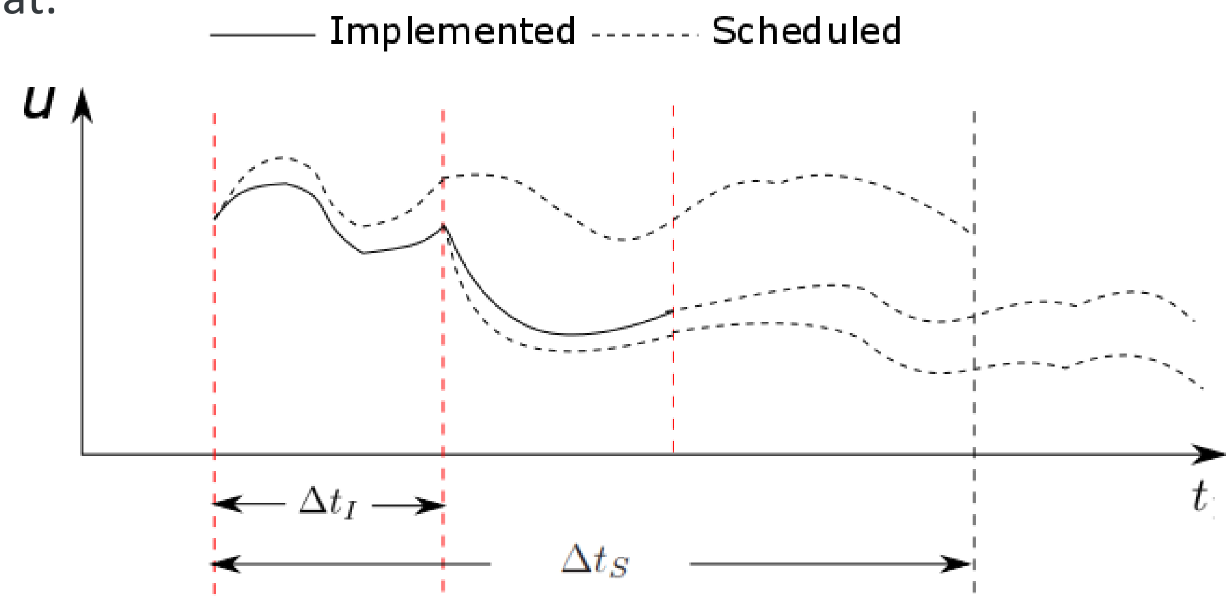


- **Team expertise**
  - fuel cells
  - power systems
  - commercial buildings
  - building communication networks
- **Tools and research we are leveraging:**
  - DG-BEAT - System design and planning tool for FC integrated building simulation
  - HEMS - Home energy management system algorithms based on MPC
  - Open Studio - User Interface and SDK to support whole-building energy modeling using EnergyPlus simulation engine
  - Energy Plus - DOE's flagship whole-building energy simulation engine
  - VOLTTRON - Communications backbone for interfacing controller and hardware

Approach – Implementation of MPC

MPC approach provides forecasts of load and predicted operation which allows participation in grid services.

- **The EDC adopts model predictive control (MPC) strategy**
  - Determine the optimal operation of the next 24-hour period, using reduce-order building model and forecast information. Implement 1 hour period. Repeat.



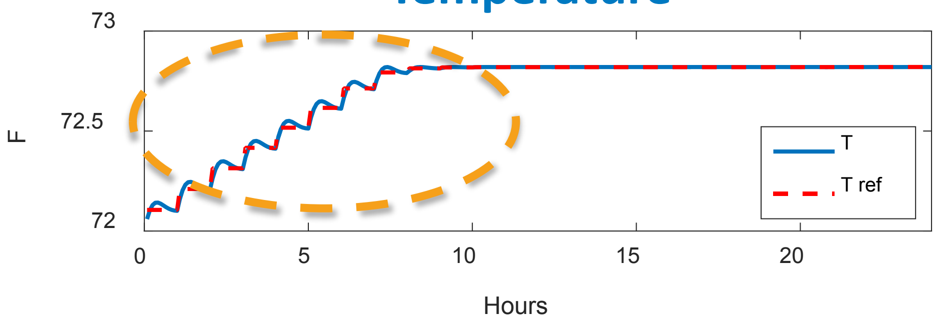
- **Initial MPC formulation will be completed by end of year (FY17)**
- **Evaluation in co-simulation environment will be started (FY17)**

Accomplishments: Preliminary Results -Cooling, constant prices

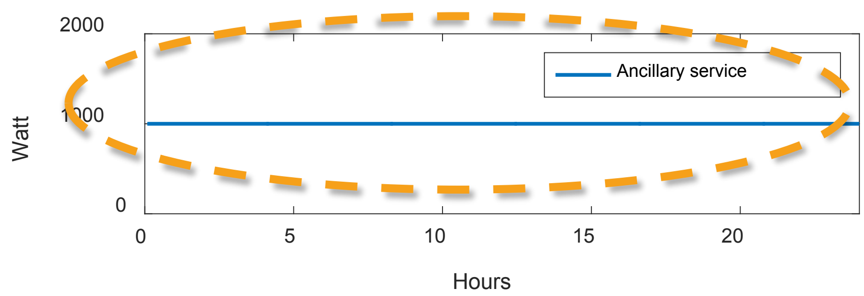
Reduce chiller power

1. **Temp set-points increase gradually to avoid large overshoot.**
2. **Ancillary service at max, introduce a temp buffer (73°F max) .**

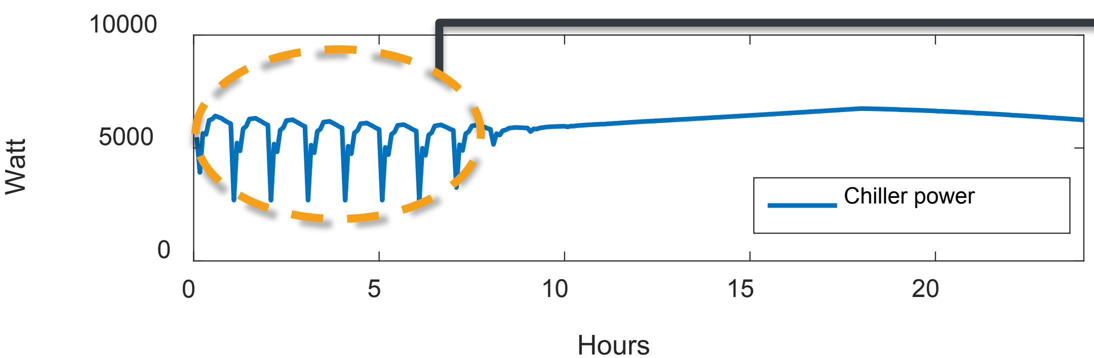
Temperature



Ancillary Services



Chiller

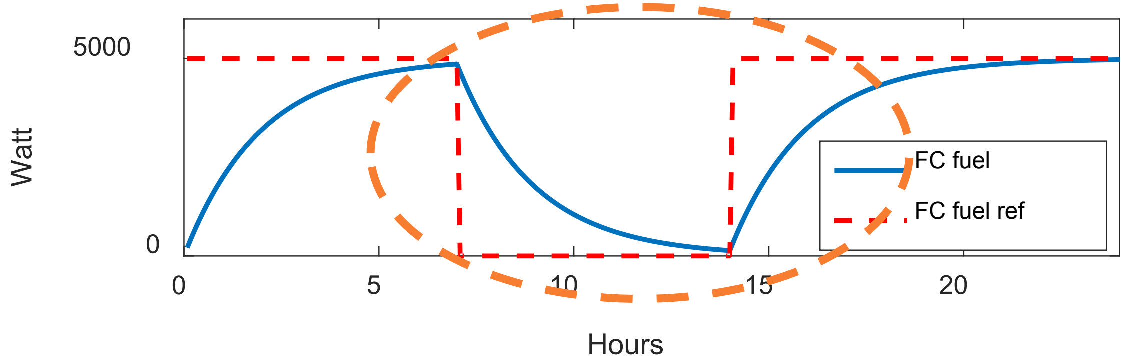


We will want to reduce/fix cycling and other negative effect as we iterate improvements during evaluation

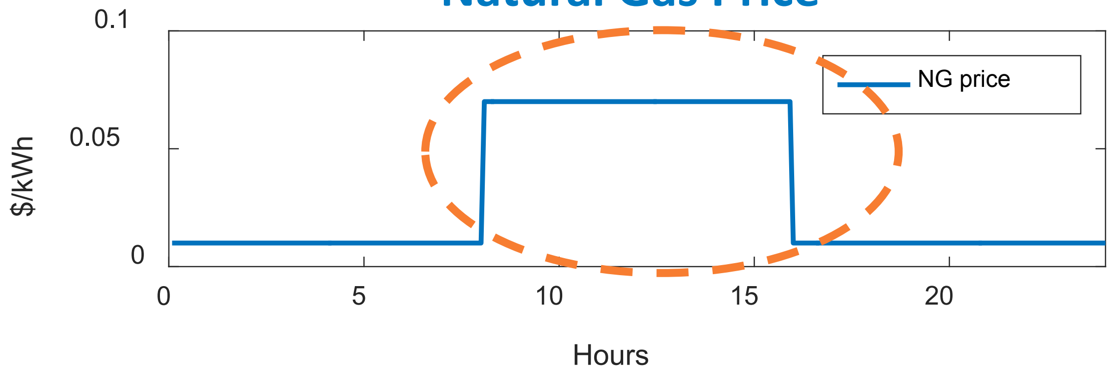
Accomplishments: Preliminary Results -Cooling, natural gas price

Fuel cell set-points at maximum when NG price is low, at zero when NG price is high.
- **FC thermal output not needed in this cooling scenario**

Fuel Cell



Natural Gas Price

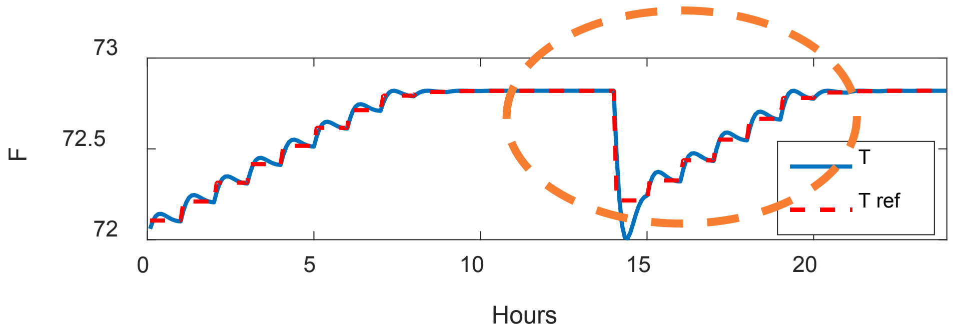


Accomplishments: Preliminary Results -Cooling, electricity price

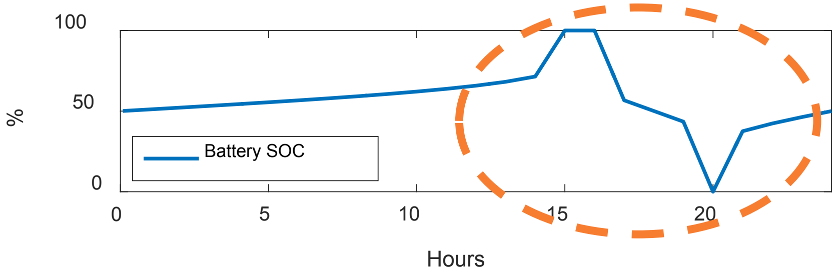
Pre-determined electricity price effects:

- **Pre-cooling before the electricity price goes up.**
- **Battery charging at low price, discharging at high price.**

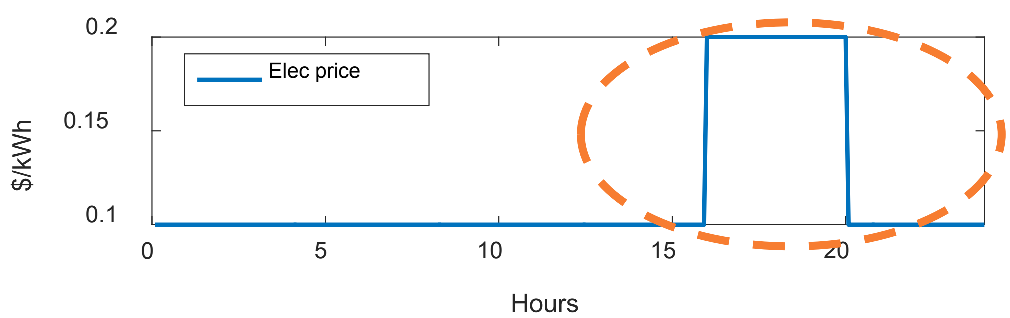
Temperature



Battery

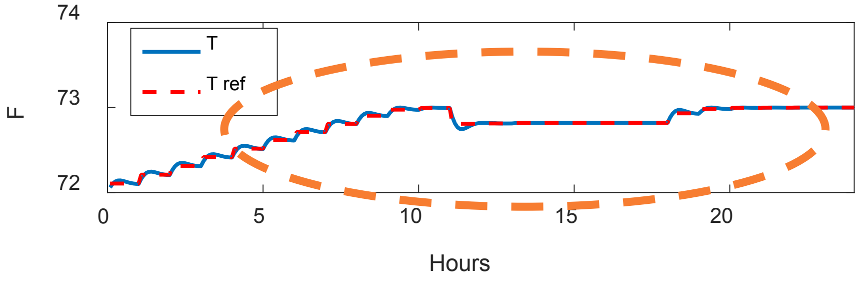


Electricity Price

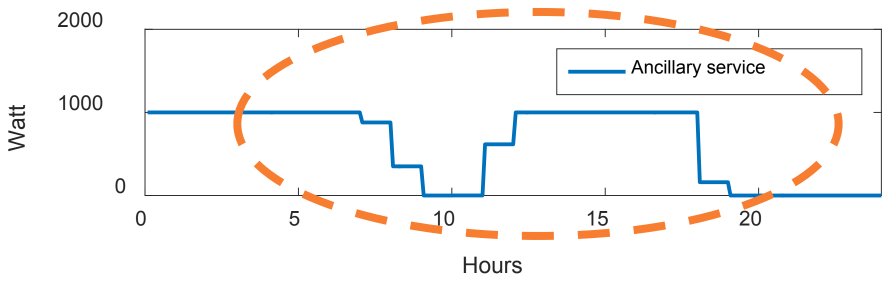


Ancillary service is provided when the compensation is high, or the temperature is not close the constraint boundaries (73ºF).

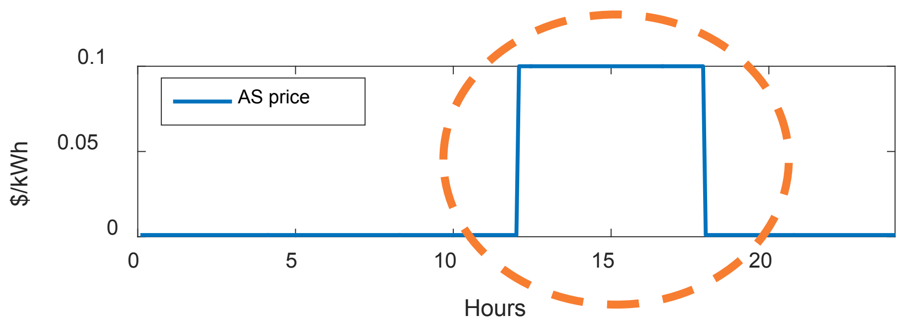
Temperature



Ancillary Service



Ancillary Service Price

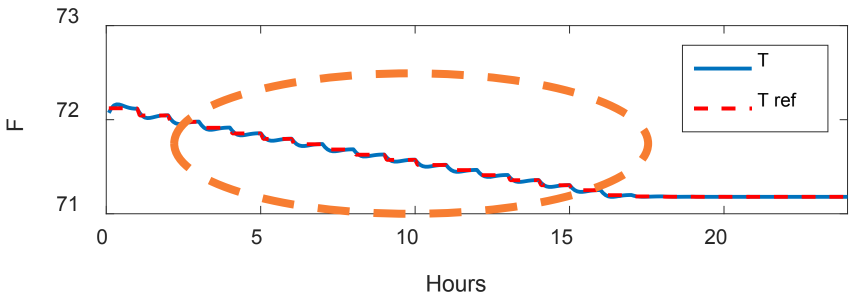


Accomplishments: Preliminary Results -Heating

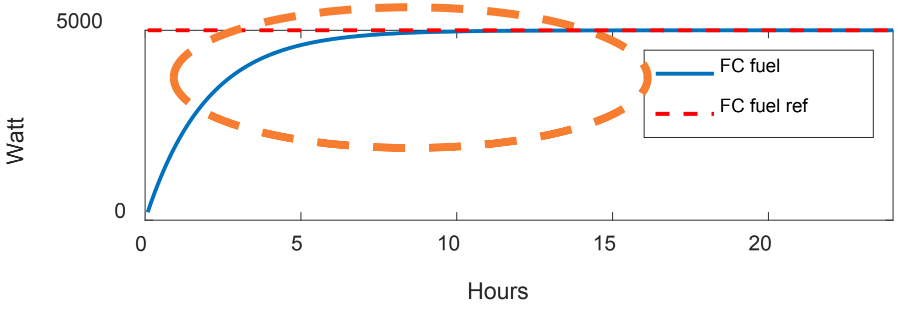
When heating needed:

- **Temperature set-points gradually decreases to the boundary.**
- **Compared to the cooling mode, the FC will be dispatched at higher NG price, since the thermal output is used.**

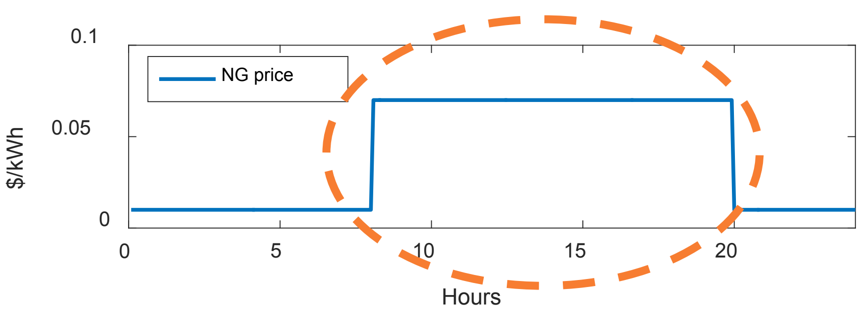
Temperature



Fuel Cell



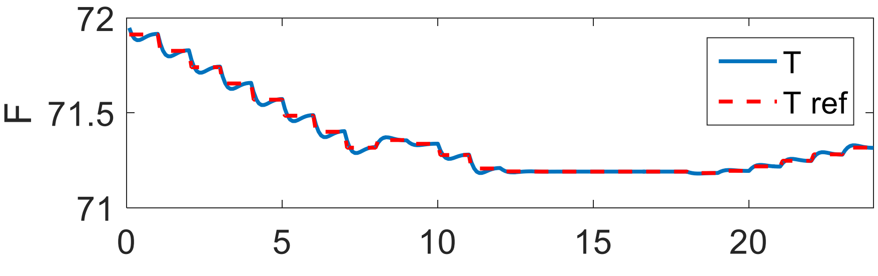
Natural Gas Price



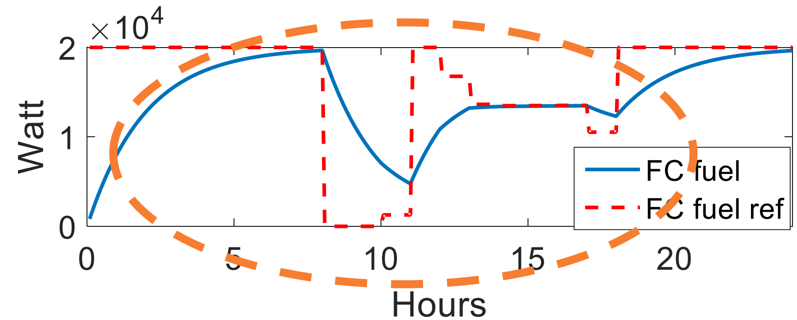
Excess heat from FC:

- **Fuel cell part load operation: not economic to generate only electricity, so the output is determined by the heating load.**

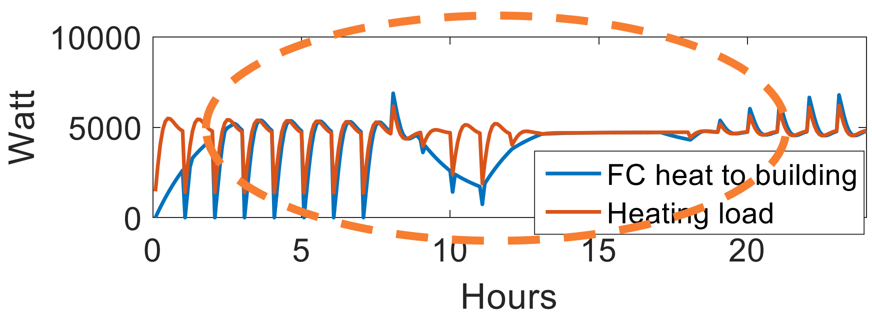
Temperature



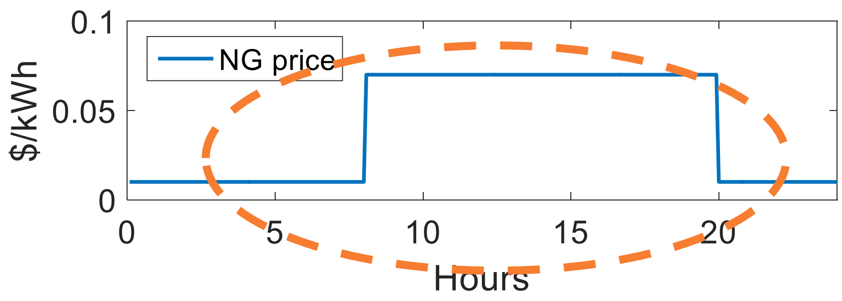
Fuel Cell



Heating Load



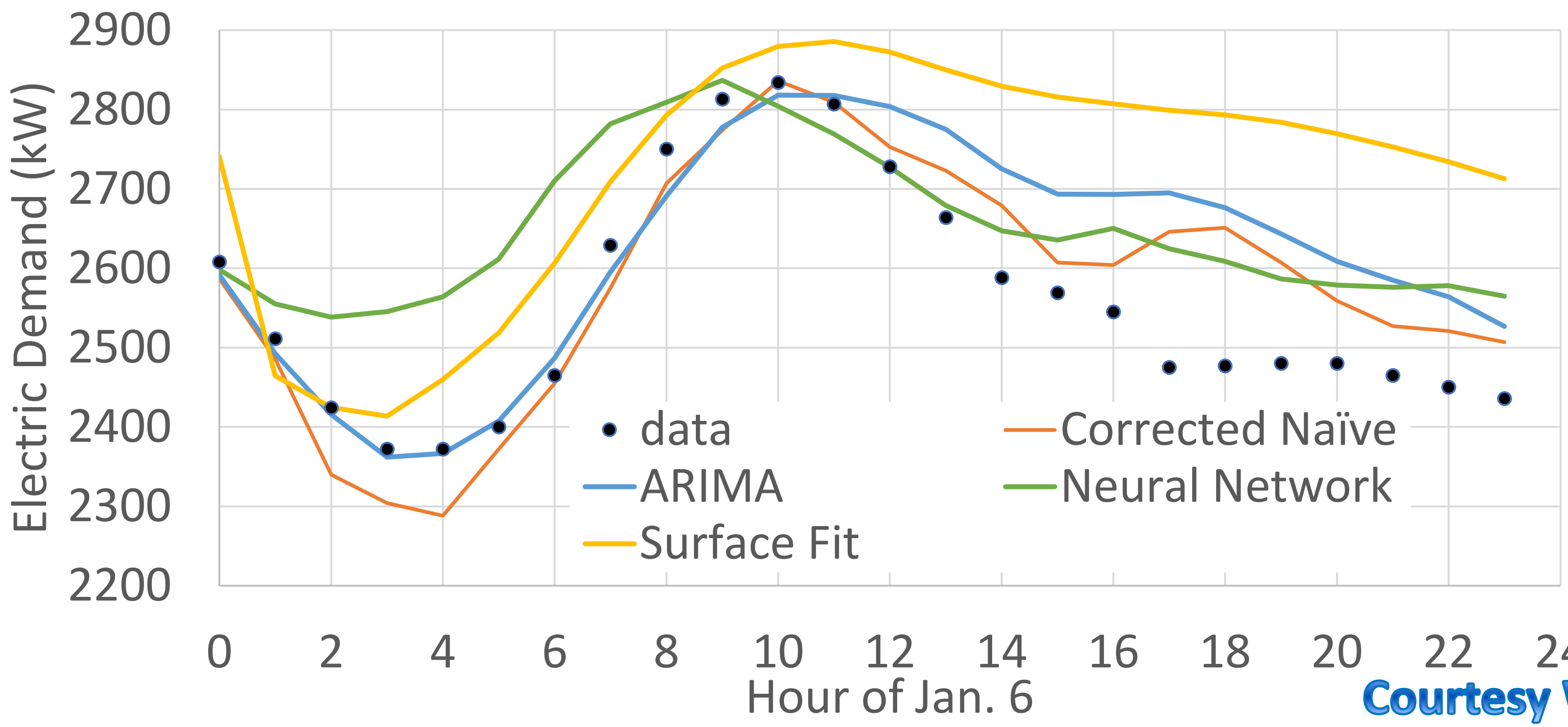
Natural Gas Price



Accomplishments: Forecasting

Task: Whole-building forecast for uncontrollable electric loads

- 4 Methods:
  - Corrected Naïve, aka simple exponential smoothing: single calibration constant
  - ARIMA, autoregressive integrated moving average: multiple calibration points
  - Neural Network: trained by previous week, and compatible with machine learning
  - Surface Fit: best guess from historical data, i.e. time and weather



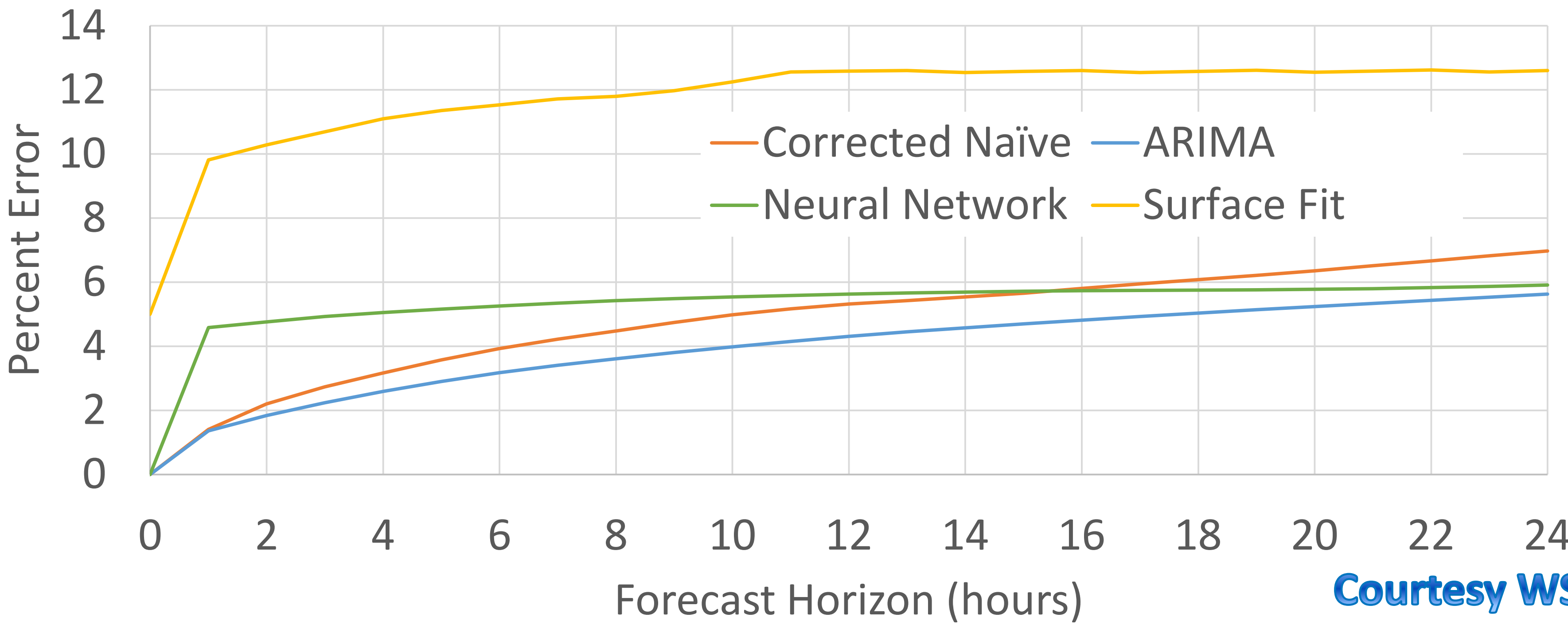
Courtesy WSU

Accomplishments: Accuracy of forecasting

Evaluation of forecast methods underway

- **Combination of methods may provide best forecast window**

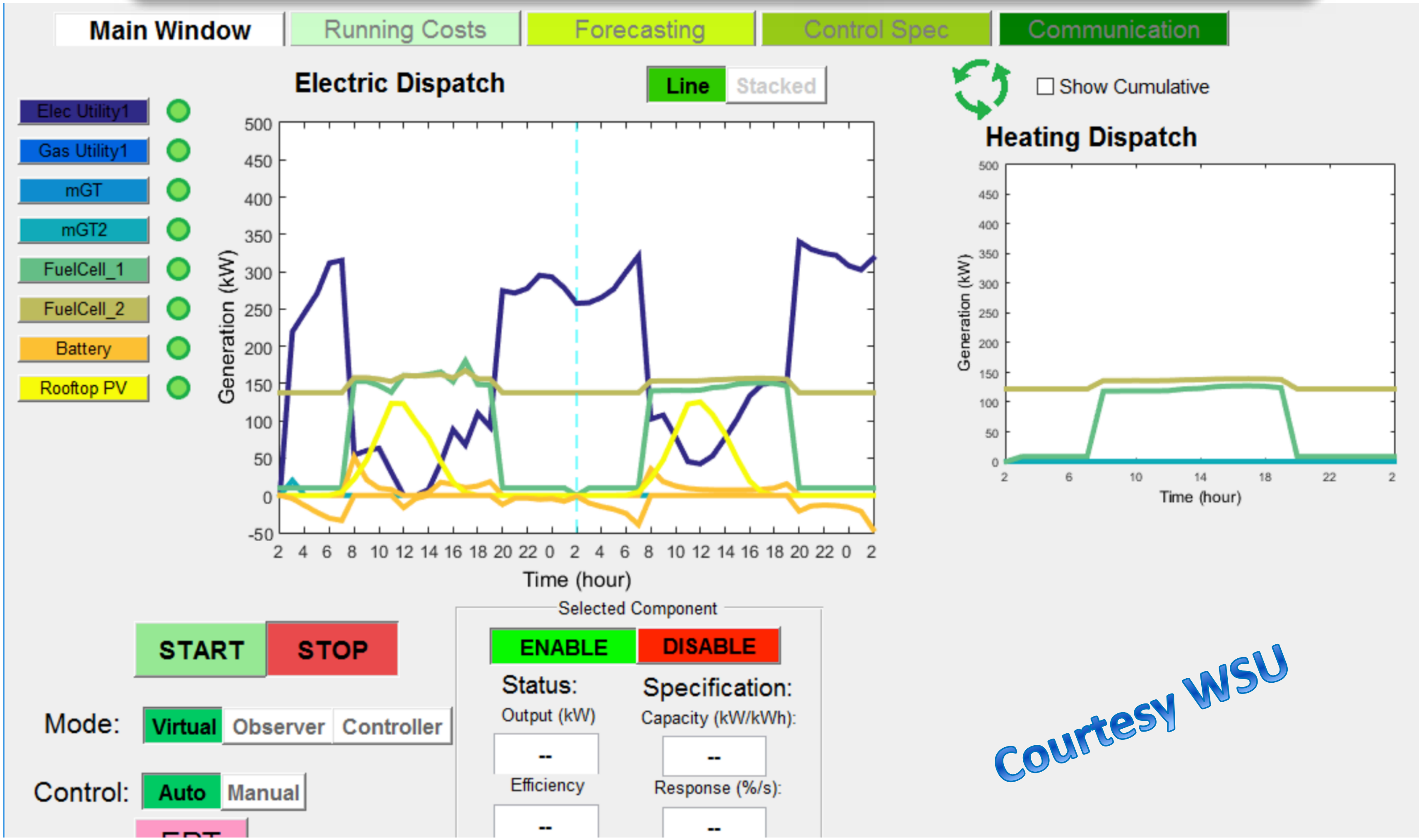
- ARIMA method shows greatest accuracy over 24-hour horizon when forecast is repeated each hour for an entire year
- Neural network with machine learning adjusts more quickly to outliers/extreme events
- Possible combination of models to create probability window of forecast



Courtesy WSU

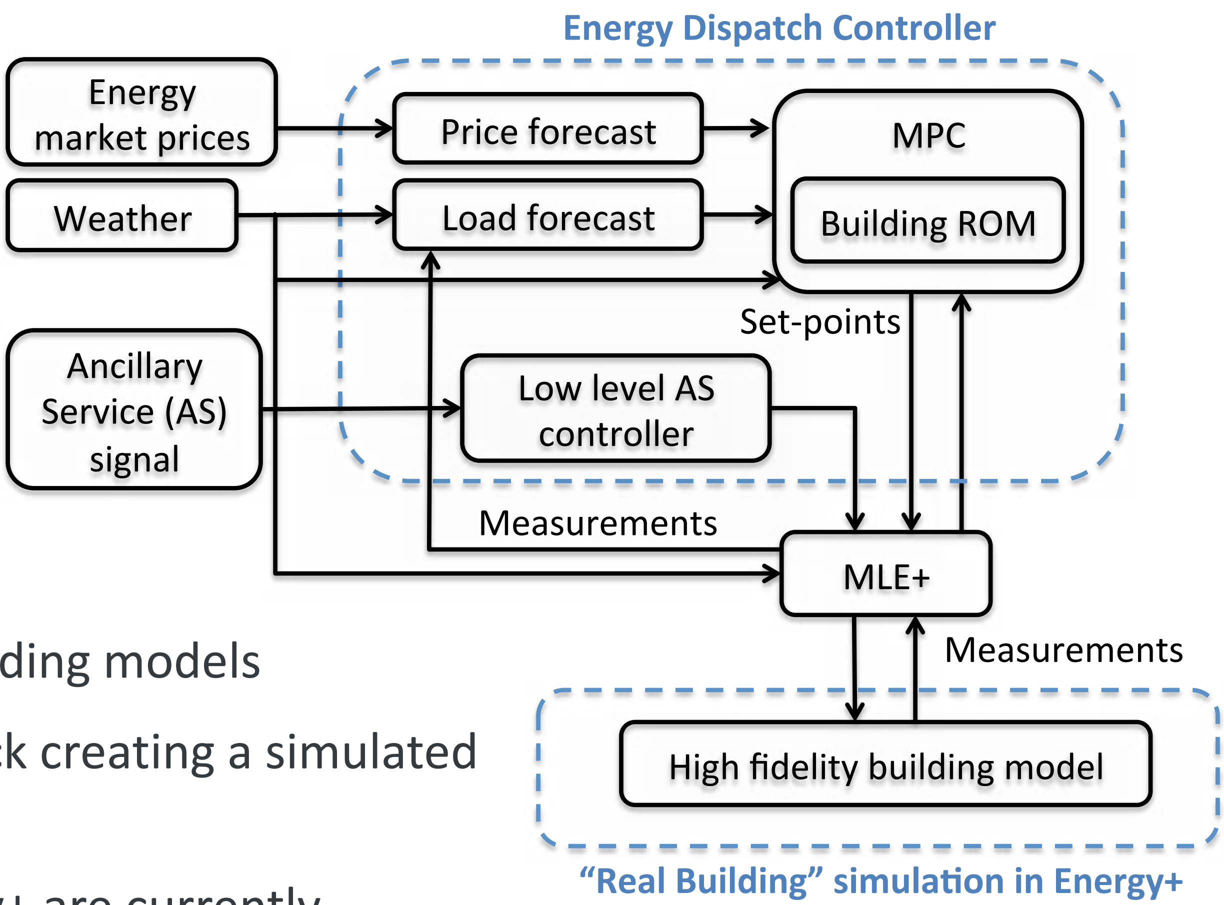
Accomplishments: GUI

Initial GUI interface under development
- **This shows snapshot of real-time viewer screen**



Accomplishments: Co-simulation environment to evaluate EDC

A co-simulation environment is needed to evaluate the EDC before it can be used in a real or other lab environment.



- Runs against Energy+ building models
- Energy+ provides feedback creating a simulated building
- Note: the EDC and Energy+ are currently running separately. We are working towards co-simulation environment.

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

- This is the project's first year and was not reviewed last year.

Collaborations & Partners

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

Thanks to our team:

Zhiwen.Ma@nrel.gov
Annabelle.Pratt@nrel.gov
Yashen.Lin@nrel.gov
dustin.mclarty@wsu.edu
William.Livingood@nrel.gov
Luigi.Gentile.Polese@nrel.gov
Brian.Ball@nrel.gov
Jereme.Haack@pnnl.gov
gregor.henze@colorado.edu

Remaining Challenges and Barriers

- The optimization problem in the MPC is a complicated one.
  - We are using a commercial solver, Gurobi, but are looking into ways of simplifying the problem so that we can use an open source solver.
- Extracting reduced-order models – exploring 2 options:
  - Off-line: calibrate the models for different typical buildings off-line, and prepare a building model database for the EDC.
  - On-line: for a given building structure, automatically run Energy+ simulations for system identification and obtain the reduced-order model.
- Energy+ model
  - Building model – initial test on DOE reference large office building in DC
    - Reheat coil for summer to knock-out humidity -> year-round thermal load
  - Fuel cell model
    - Current model(s) needs calibrations
  - Fuel cell integration into the building - electric is simple
    - Thermal side: connected to the hot water loop
    - Challenge: no bypass for excess heat in the fuel cell module, need to find water to handle excess heat

Proposed Future Work

- EDC & optimization algorithms
  - continue initial evaluation of large office in DC
  - Make improvements to reduce fix cycling and other negative behavior
  - Complete initial forecasting work
  - Work on methods for extracting ROM
  - Verify code runs on 2 different OS (FY17 Annual Milestone)
- Co-simulation environment
  - Complete connections needed for feedback loop
  - Calibrate/create fuel cell models for Energy+
- GUI
  - Complete initial interface
  - Stakeholder review of GUI and gather feedback (FY17 GNG)
- Building design
  - Complete initial set of use cases
  - Integrate OpenStudio building design interface into GUI (FY17/18)
- Communications backbone
  - Map out VOLTTRON agents needed for demonstration and future compatibility
- FY18
  - Evaluation and iterative refinements of EDC, integration of EDC with Planning Tool, continued work on communications backbone

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

First Year Progress (FY17)

- In first year most development is for the energy dispatch controller
  - Initial formulation of the MPC algorithms
  - Initial formulation for forecasting
  - Working on two methods for extracting reduced-order models
- Functional GUI interface
- Building design module
- Co-simulation environment

FY18

- Evaluation and testing of EDC -> Refinements of EDC
- Integration of EDC into Planning Tool with initial evaluation
- Communications backbone work begins in earnest

Technical Back-Up Slides

Approach – What is model predictive control (MPC)?

- Examples of controllable elements →
- Hierarchical **Model Predictive Control (MPC)** approach for real-time supervisory dispatch optimization will:
  - Manage building devices and loads
  - Gather data from the building (sensory), weather, grid markets
  - Satisfy device or user constraints
- Elements of forecasting and planning of demand and operation to maximize benefits

Generation	
Dispatchable	Non-dispatchable
• Fuel cells • Back-up diesel generator • (micro) CHP	• PV (curtailable) • Wind
Interruptible Loads	
With Storage	No storage
• Thermal mass of building • thermal storage: HVAC; water heater; refrigerator/freezer • chemical storage: stationary battery storage and electric vehicles	• Clothes dryer heating element • Dishwasher • Pool pump
Non-interruptible loads	
• Critical appliances, e.g., for medical support • Clothes washer (can control the start time)	

Accomplishments: Optimization problem formulation

Initial formulation of the MPC algorithm is complete

- **Decision variables:** set-points for zone temperature, fuel cell electrical and thermal generation, battery power, thermal storage operation
- **Objectives:** minimize electricity bill + natural gas bill - ancillary services payment + others (emission, comfort, etc.)
- **Constraints:** model predictive constraints, equipment constraints
- **Problem formulation:**

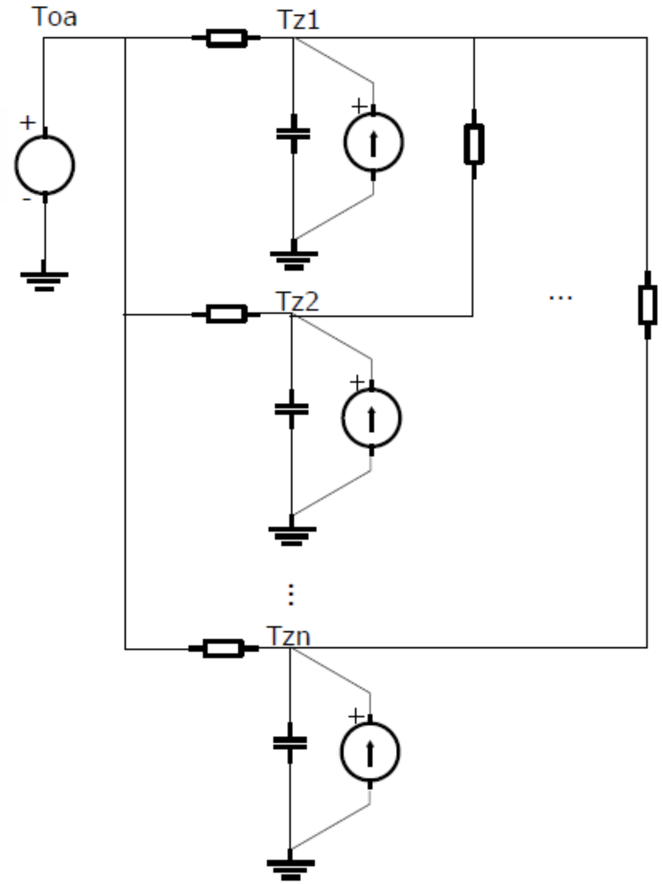
$$\min_{U_1,\cdots,U_n} \sum_i \alpha_i J_i$$

$$\begin{aligned} \text{s.t.} \quad X_{k+1} &= f(X_k, U_k, D_k),\ \forall k \in \{0,1,2,\cdots,N-1\} \\ g(X,U) &= 0 \\ h(X,U) &\leq 0 \end{aligned}$$

Accomplishments: Reduced-order building model

The MPC uses reduced-order models (ROM) to predict the behavior of the building with faster calculation times.

- We develop an equivalent circuit for different components and integrate them together to form the building model.
  - Zone thermal dynamics: example circuit diagram
  - Cooling mode: the supply air flow rate is controlled to maintain room temperature, and there is no heating.
  - Heating mode: the supply air temperature is controlled to maintain room temperature, and the supply air flow rate is fixed.
  - Other models include: cooling coil, chiller, fuel cell, boiler, battery, thermal storage, energy balance



Accomplishments: Preliminary results for EDC optimization

Simulation setup for preliminary results of EDC

- **Simulation:**
  - Testing on a simple building model of an auditorium
  - Single optimization runs, not closed loop simulations.
  - One 24 hour period, no feedback loop
- **Objective:**
  - minimize electricity cost + NG cost – AS payment
  - No weighting variables for some factors (i.e. thermal comfort)
- **Control variable:**
  - zone temperature set-point
  - fuel cell electric power and thermal output set-points
- **Assumptions:**
  - Constant incidental loads
  - Prices are fictitious for demonstration
  - HVAC system runs 24 hours, and temperature bounds are constant (71-73 F)
  - Cooling and heating modes are considered separately
- Schedule is changed every hour, the scheduling horizon is 24-hour.
- Problem can be solved in seconds, but has numerical issues in some cases.

Accomplishments: GUI - Software Architecture Draft