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

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NREL
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Project ID # TV042

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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)
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

- 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

- 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)

MPC approach provides forecasts of load and predicted operation which allows participation in grid services.
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
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.
Accomplishments: Preliminary Results - Cooling, ancillary service compensation

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

**Temperature**

- $T$ (actual temperature)
- $T_{\text{ref}}$ (reference temperature)

**Ancillary Service**

- Ancillary service price

**Ancillary Service Price**

- Price: $0.05, 0.10$ per kWh

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NATIONAL RENEWABLE ENERGY LABORATORY
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 Graph](image1)

![Fuel Cell Graph](image2)

![Natural Gas Price Graph](image3)
Accomplishments: Preliminary Results - Heating, excess heating from FC

Excess heat from FC:

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

![Graphs showing temperature, fuel cell output, heating load, and natural gas price over time.](image-url)
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
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

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**Percent Error**

<table>
<thead>
<tr>
<th>Percent Error</th>
<th>Corrected Naïve</th>
<th>ARIMA</th>
<th>Neural Network</th>
<th>Surface Fit</th>
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<td>14</td>
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</tbody>
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**Forecast Horizon (hours)**

0 2 4 6 8 10 12 14 16 18 20 22 24

*Courtesy WSU*
Accomplishments: GUI

Initial GUI interface under development

• This shows snapshot of real-time viewer screen

![Electric Dispatch and Heating Dispatch graphs with various components and controls.](image)
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

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Remaining Challenges and Barriers

• The optimization problem in the MPC is a complicated one.
  o 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:
  o Off-line: calibrate the models for different typical buildings off-line, and prepare a
    building model database for the EDC.
  o On-line: for a given building structure, automatically run Energy+ simulations for
    system identification and obtain the reduced-order model.

• Energy+ model
  o Building model – initial test on DOE reference large office building in DC
    – Reheat coil for summer to knock-out humidity -> year-round thermal load
  o Fuel cell model
    – Current model(s) needs calibrations
  o 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
  o Initial formulation of the MPC algorithms
  o Initial formulation for forecasting
  o 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

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<thead>
<tr>
<th>Generation</th>
<th>Dispatchable</th>
<th>Non-dispatchable</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>• PV (curtailable)</td>
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<tr>
<td></td>
<td></td>
<td>• Wind</td>
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<tr>
<td>Fuel cells</td>
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<tr>
<td>Back-up diesel generator</td>
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<tr>
<td>(micro) CHP</td>
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<table>
<thead>
<tr>
<th>Interruptible Loads</th>
<th>With Storage</th>
<th>No storage</th>
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<tbody>
<tr>
<td></td>
<td>• Thermal mass of building</td>
<td>• Clothes dryer heating element</td>
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<tr>
<td></td>
<td>• thermal storage: HVAC;</td>
<td>• Dishwasher</td>
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<tr>
<td></td>
<td>water heater;</td>
<td>• Pool pump</td>
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<td></td>
<td>refrigerator/freezer</td>
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<tr>
<td></td>
<td>• chemical storage: stationary battery storage and electric vehicles</td>
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</tbody>
</table>

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<table>
<thead>
<tr>
<th>Non-interruptible loads</th>
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<tbody>
<tr>
<td>• Critical appliances, e.g., for medical support</td>
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<tr>
<td>• Clothes washer (can control the start time)</td>
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</tbody>
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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**:

\[
\begin{align*}
\min_{U_1, \ldots, U_n} \sum_i \alpha_i J_i \\
\text{s.t.} \quad X_{k+1} &= f(X_k, U_k, D_k), \forall k \in \{0, 1, 2, \ldots, N - 1\} \\
g(X, U) &= 0 \\
h(X, U) &\leq 0
\end{align*}
\]
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:**
  - 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

Internet

Setup Layer (GUI) Common

Function Layer (Computation/Control Engine)

Presentation Layer (GUI)

- Weather
- Start Screen
- Ancillary Market
- Energy Dispatch Controller
- Component Control Schedule
- Building Design (Real/Proposed)
- Utility Parameters
- Economic Parameters
- Planning Tool
- Setup Inputs
- Energy + Engine
- Reduced Order Model
- Building Model
- MPC
- Detailed Results
- Utility Constraints
- Simulation Calibration
- Component Sizing Constraints
- Sensor
- Realtime Viewer
- Actuator
- Annualized results