Improving the Use of Commercial Building HVAC Systems for Electric Grid Ancillary Services

For Lawrence Berkeley National Laboratory

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Background and Research Introduction

Overview of Selected Work

Questions and Discussion
Current Electric Grid

Generation (Supply)

- Renewables: 18%
- Natural Gas: 31%
- Coal: 34%
- Nuclear: 16%

(EIA 2015)
Current Electric Grid

Consumption (Demand)

(EIA 2015)
Current Electric Grid

- Generation (Supply)
- Transmission (Wholesale)
- Distribution (Retail)
- Consumption (Demand)

Regional ISO/RTO

Utility
Current Electric Grid

- Generation (Supply)
- Transmission (Wholesale)
- Distribution (Retail)
- Consumption (Demand)

Regional ISO/RTO

Utility
Future Electric Grid

- Generation (Supply)
- Transmission (Wholesale)
- Distribution (Retail)
- Consumption (Demand)

Regional ISO/RTO

Utility
Ancillary Service Types

Regulation

Economic Max
Economic Min

Reg Up Capacity
Reg Down Capacity
Ancillary Service Types

Reserves

Economic Max
Economic Min
Reserve Capacity

Graphs showing power generation over time with different service types.
Future Electric Grid

- Generation (Supply)
- Transmission (Wholesale)
- Distribution (Retail)
- Consumption (Demand)

Regional ISO/RTO

Utility
Future Electric Grid with Demand Response

- Generation (Supply)
- Transmission (Wholesale)
- Distribution (Retail)
- Consumption (Demand)

Regional ISO/RTO
Utility
Demand Response (DR)
Ancillary Service Demand Response

Reserves
Ancillary Service Demand Response

Use Commercial Heating, Ventilating, and Air-conditioning (HVAC) Systems

1) Link electric consumption to thermal energy storage
Ancillary Service Demand Response

Use Commercial Heating, Ventilating, and Air-conditioning (HVAC) Systems

1) Link electric consumption to thermal energy storage
2) Compressors, fans, and pumps with variable speed drives (VSD)
Use Commercial Heating, Ventilating, and Air-conditioning (HVAC) Systems

1) Link electric consumption to thermal energy storage
2) Compressors, fans, and pumps with variable speed drives (VSD)
3) Building management systems (BMS) allow for individual building HVAC control and electric grid communication
Ancillary Service Demand Response

Research Questions

1) How do HVAC systems provide ancillary services?

2) Can buildings optimize a portfolio of ancillary services?

3) Is there a price for providing ancillary services?

4) Does HVAC ancillary service provision scale with other energy storage?
Research Questions

1) How do HVAC systems provide ancillary services?
   Dynamic Systems Modeling

2) Can buildings optimize a portfolio of ancillary services?
   Multi-market Optimization

3) Is there a price for providing ancillary services?
   Opportunity Cost Quantification

4) Does HVAC ancillary service provision scale with other energy storage?
   Quick ASDR Resource Estimation
Dynamic Systems Modeling

Goals

1) Consider a variable-air-volume (VAV) system
2) Analyze whole-system effects of providing reserve and regulation AS
3) Characterize successful and unsuccessful implementation strategies
Dynamic Systems Modeling

Method

1) Construct dynamic system model using Modelica
2) Simulate reserve and regulation provision with various strategies and loading
3) Process data in MATLAB to identify trends

Strategies
- Zone temperature
- Supply static pressure
- Supply air temperature
- Chilled water temperature

Intensities
- +/- 0 to 5 °C
- +/- 0 to 80%
- +/- 0 to 5 °C
- +/- 0 to 5 °C

Load Conditions
- Min to Design
Summary

1) Most effective reserve provision required zone airflow change
2) Most effective regulation provision required direct control of fan and chiller
3) Symmetric regulation does not impact zone temperature
4) Modelica demonstrated to be most appropriate modeling tool for future AS control development

Future

1) Advanced AS control development
2) Role of Modelica

This section based on (Blum and Norford 2014a, 2014b)
Ancillary Service Demand Response

Research Questions

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   Quick ASDR Resource Estimation
Multi-market Optimization

Electricity Markets

- Regional ISO/RTO
- Generation (Supply)
- Transmission (Wholesale)
- Distribution (Retail)
- Consumption (Demand)
- Utility

- Supply
- Wholesale
- Retail
- Demand
Multi-market Optimization

Electricity Markets

Wholesale Markets

Energy
Multi-market Optimization

Electricity Markets

Day-Ahead (24 hour) looks ahead to next day

Real-Time (5 min) responds to current conditions
## Electricity Markets

### Energy

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**LMP ($/MWh)**

### Wholesale Markets

- All generators get paid the LMP
- All load serving entities pay the LMP
Multi-market Optimization

Electricity Markets

Energy

- MWh $ $
- MWh $ 
- MWh $ 

LMP ($/MWh)

Wholesale Markets

(PJM 2016)
Multi-market Optimization

Electricity Markets

Ancillary Service

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Wholesale Markets
Multi-market Optimization

Electricity Markets

Ancillary Service

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ASMP ($/MW)

Wholesale Markets

All generators providing AS get paid the ASMP

Graph: Wholesale Markets over time (PJM 2016)
Multi-market Optimization

Electricity Markets

Wholesale Markets

Retail Markets
Multi-market Optimization

Electricity Markets

Day-Ahead (24 hours) Energy & Ancillary Service

Wholesale Markets
Concentrate on multi-zone VAV systems and multi-market Optimization

**Energy or Energy Price Optimization (E-market)**

- Li et al. 2015 – 2 hour planning horizon
- Henze et al. 2004 – 24 hour planning horizon, 4 decision periods
- Greensfelder et al. 2011 – 24 hour planning horizon, 6 decision periods

**Multi-market Optimization**

- Vrettos et al. 2014 – 48 hour planning horizon, LMP + Regulation pricing (EL-market)
  - aggregator of independent single-zone buildings
- Pavlak et al. 2014 – 24 hour planning horizon, LMP + Regulation pricing (EL-market)
  - VAV systems approximated as single-zone
  - perturbation approach, optimization time ~ 1-6 hours on 12-core CPU
Multi-market Optimization

Goals

1) Formulate multi-zone VAV system 24-hour multi-market (ELR) optimization
2) Solve 24-hour E-market optimization and improve optimization time
3) Solve 24-hour ELR-market optimization
Formulate ELR-market optimization problem

Minimize: Daily (Energy Cost – Regulation Revenue – Reserve Revenue)

Subject to: Zone Temperature physics
Zone Thermal Comfort
Zone Heat/Cool Limits
System Capacity Limits
Dispatched Reserve Zone Temperature physics
Dispatched Reserve Zone Thermal Comfort
Dispatched Reserve Zone Heat/Cool Limits

And calculate: HVAC Energy
Dispatched Reserve HVAC Energy
Regulation Capacity
Reserve Capacity

Primary Problem
Secondary Problem
Multi-market Optimization

Method

1) Formulate ELR-market optimization problem
2) Develop zone temperature physics model

Multi-zone iCRTF (Armstrong et al. 2006, Gayeski 2011)

Linear combination of current and past:
Zone temperatures
Zone HVAC heat rates
Adjacent zone temperatures
Exogenous load variables

DOE Commercial Reference Buildings

6-Zone
18-Zone
Multi-market Optimization

Method

1) Formulate ELR-market optimization problem
2) Develop zone temperature physics model
3) Develop multi-zone VAV system model

Previously established models for:

- Zone airflow (Energy balance)
- Supply fan airflow (Mass Balance)
- Return air temperature (Energy balance)
- Mixed air temperature (Energy balance)
- Coil cooling load (Energy balance)
- Chiller power (E+ EIR Chiller)
- Fan power (VSD SP Control Fan)
- Total HVAC power (Englander and Norford 1992)
Multi-market Optimization

Method

1) Formulate ELR-market optimization problem
2) Develop zone temperature physics model
3) Develop multi-zone VAV system model
4) Implement and solve in MATLAB

**Computer:**
Windows 7 x64
2-core Intel® Core™ i5-4200U CPU, 2.30 GHz
8 GB Physical RAM
MATLAB 2013a x86

**Solver:**
Fmincon w/ Sequential Quadratic Programming (SQP)

**24-Hour Optimization Time:**
E-market: 5-zone ~ 30 s, 18-zone ~ 5-20 min
ELR-market: 5-zone ~ 2-6 min, 18-zone ~ 1-4 hours

Multi-market Optimization

Results – ELR-market Optimization, 18-zone

3-Day Operating Costs:
- Energy: $118.57
- Regulation: -$52.52
- Reserve: -$27.21

Multi-market Optimization

Results – ELR-market Optimization, 18-zone

Multi-market Optimization

Summary

1) Successful 24-hour ELR-market optimization for 18-zone VAV system
2) HVAC systems can be incentivized to provide a portfolio of services with exposure to ancillary service market prices
3) Relatively high retail prices limit the incentives provided by wholesale market prices

Future

1) Latent energy
2) Regulation limit determination
3) Experimental implementation and validation

This section based on (Blum et al. 2016a)
Ancillary Service Demand Response

Research Questions

1) How do HVAC systems provide ancillary services?

   Dynamic Systems Modeling

2) Can buildings optimize a portfolio of ancillary services?

   Multi-market Optimization

3) Is there a price for providing ancillary services?

   Opportunity Cost Quantification

4) Does HVAC ancillary service provision scale with other energy storage?

   Quick ASDR Resource Estimation
Opportunity Cost Quantification

Literature

Wholesale Markets
Opportunity Cost Quantification

Literature

Ancillary Service

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Wholesale Markets
### Literature

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Opportunity Cost Quantification

Opportunity Costs

Ancillary Service

- MW $ 
- MW $ 
- MW $ 
- MW $ 

Wholesale Markets

Offer Cost = Operating Cost + **Lost Opportunity Cost**

Additional fuel and efficiency loss

Forgone profit from energy market

(65-75% Hummon et al. 2013)

$/MWh

LMP

$/MWh

Energy Offer Curve

MWh

Economic Max Dispatch
Opportunity Cost Quantification

Opportunity Costs

Ancillary Service

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Wholesale Markets

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Offer Cost = Operating Cost + Lost Opportunity Cost

- Additional fuel and efficiency loss
- Forgone profit from energy market

(65-75% Hummon et al. 2013)

LMP

$/MWh

Energy Offer Curve

MWh

Economic Max Dispatch
Ancillary Service Types

Regulation

- Economic Max
- Economic Min
- Capacity

Graphs:
- Net Load (GW) vs. Time (hr)
- Generation (MW) vs. Time (hr)

He2 Reg Up Capacity
He2 Reg Down Capacity
Ancillary Service Types

Reserves

Economic Max

Economic Min

Reserves

HE2 Reserve

Capacity
Opportunity Cost Quantification

Opportunity Costs

Ancillary Service
- MW $ $
- MW $ $
- MW $ $
- MW $ $

Wholesale Markets

Offer Cost = Operating Cost + Lost Opportunity Cost

Additional fuel and efficiency loss
Forgone profit from energy market

(65-75%) $/MWh

LMP

$/MWh

Energy Offer Curve

Economic Max Dispatch

MWh
Opportunity Cost Quantification

Opportunity Costs

Ancillary Service

- MW $ 
- MW $ 
- MW $ 
- MW $ 

Wholesale Markets

- MW $ 
- MW $ 
- MW $ 

Offer Cost = Operating Cost + Lost Opportunity Cost

Additional fuel and efficiency loss

Forgone profit from energy market

(65-75%) LMP

$/MWh

Energy Offer Curve

AS Alternative Dispatch

Economic Max Dispatch

MWh
Opportunity Cost Quantification

Opportunity Costs

Ancillary Service

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Wholesale Markets

$\text{Offer Cost} = \text{Operating Cost} + \text{Lost Opportunity Cost}$

- Additional fuel and efficiency loss
- Forgone profit from energy market

(65-75%)

$/\text{MWh}$

$LMP$

$/\text{MWh}$

AS Alternative Dispatch

Economic Max Dispatch

MWh

Opportunity Cost

Energy Offer Curve
Opportunity Cost Quantification

Goals

1) Develop method for HVAC opportunity cost quantification
2) Produce opportunity cost bid curves for a given hour
3) Compare to ASMP
Method

1) Define HVAC opportunity costs

Generator: Decreased energy profits due to capacity used as ancillary service rather than sold into energy market.

\[ \text{LOC} = \text{Profit with economic max} - \text{Profit with AS adjustment} \]

HVAC: Increased energy costs due to operating trajectories used for ancillary service rather than an economic minimum.

\[ \text{HVAC LOC} = \text{Cost with AS adjustment} - \text{Cost of economic baseline} \]
Opportunity Cost Quantification

Method

1) Define HVAC opportunity costs
Opportunity Cost Quantification

Method

1) Define HVAC opportunity costs

---

Method

1) Define HVAC opportunity costs
Method

1) Define HVAC opportunity costs

2) Develop calculation procedure
   
i) Calculate 24-hour economic baseline schedule by solving E-market optimization problem
   
ii) Choose AS adjustment for hour

iii) Calculate AS alternative schedule by solving modified E-market optimization problem

iv) Calculate HVAC LOC by difference in daily cost
Opportunity Cost Quantification

Method

1) Define HVAC opportunity costs
2) Develop calculation procedure
3) Implement in MATLAB using E-market optimization

(PJM 2013)
Opportunity Cost Quantification

Results – Single-Zone with Heat Pump

Opportunity Cost Quantification

Summary

1) Developed method for HVAC opportunity cost quantification
2) HVAC opportunity costs are comparable to ancillary service market prices

Future

1) Multi-zone buildings
2) Market integration
3) Experimental validation

This section based on (Blum et al. 2016b)
Ancillary Service Demand Response

Research Questions

1) How do HVAC systems provide ancillary services?
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3) Is there a price for providing ancillary services?
   Opportunity Cost Quantification

4) Does HVAC ancillary service provision scale with other energy storage?
   Quick ASDR Resource Estimation
Questions?

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