Dynamic Analysis and Optimal Control of Energy Utilization in Residential Buildings

Michael Baldea

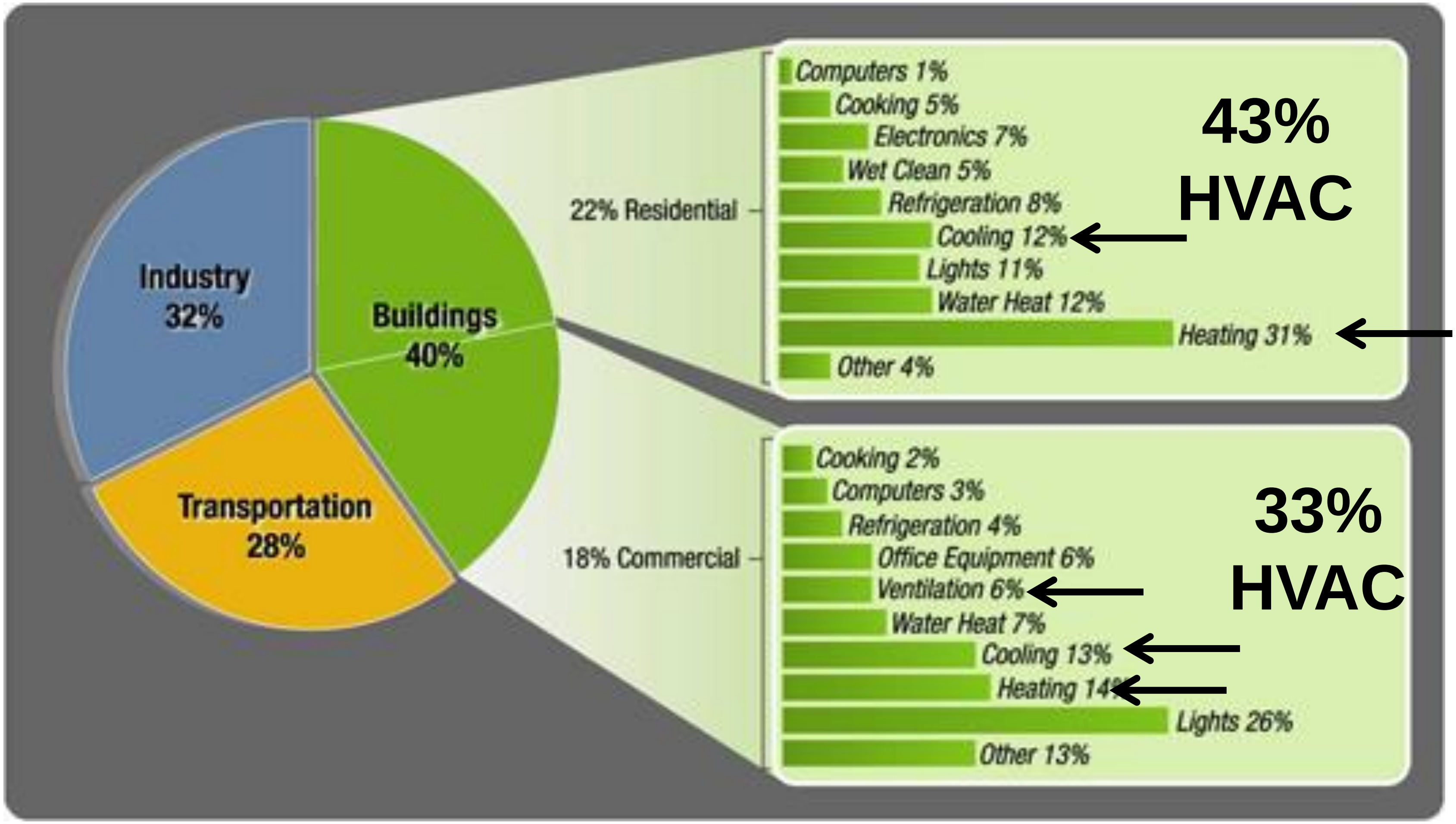
McKetta Department of Chemical Engineering

The University of Texas at Austin

CNAM, Paris, March 20, 2014

Motivation

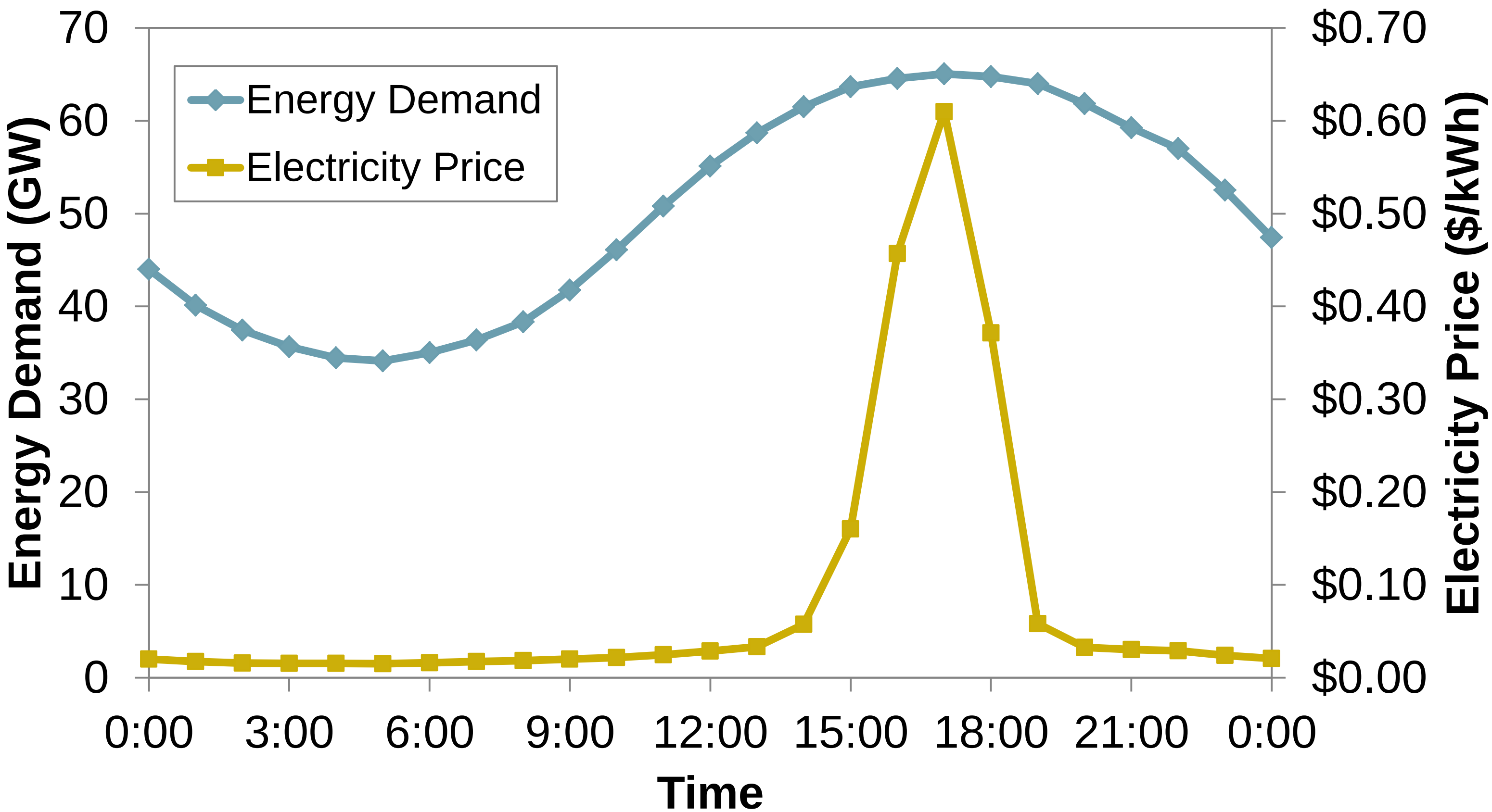
- Total US primary energy: 97 x 10^{15} BTU



Source: EIA (2008)

The Peak Energy Problem

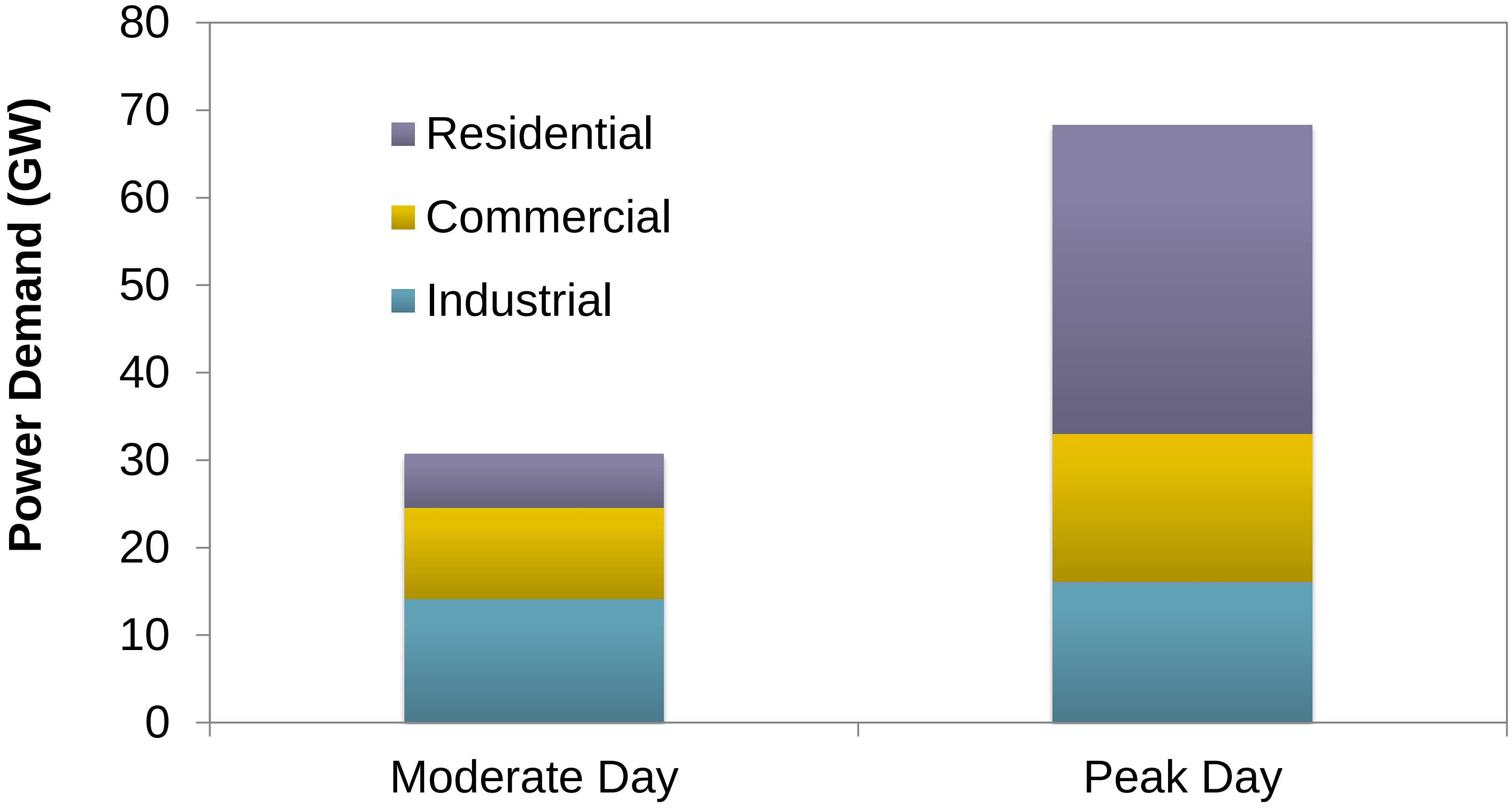
- Demand of buildings fluctuates heavily
- Peak demand → high cost



ERCOT demand and day ahead settlement point prices for June 25, 2012 from www.ercot.com

The Peak Energy Problem

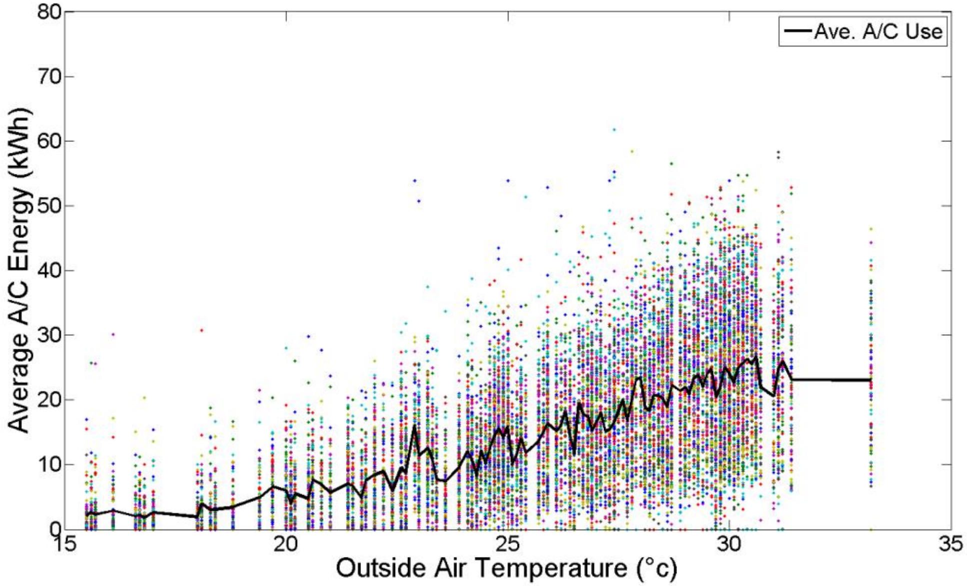
- Residential buildings are the primary culprits



Wattles, ERCOT Demand Response Overview & Status Report , 2011

Not All Homes are the Same

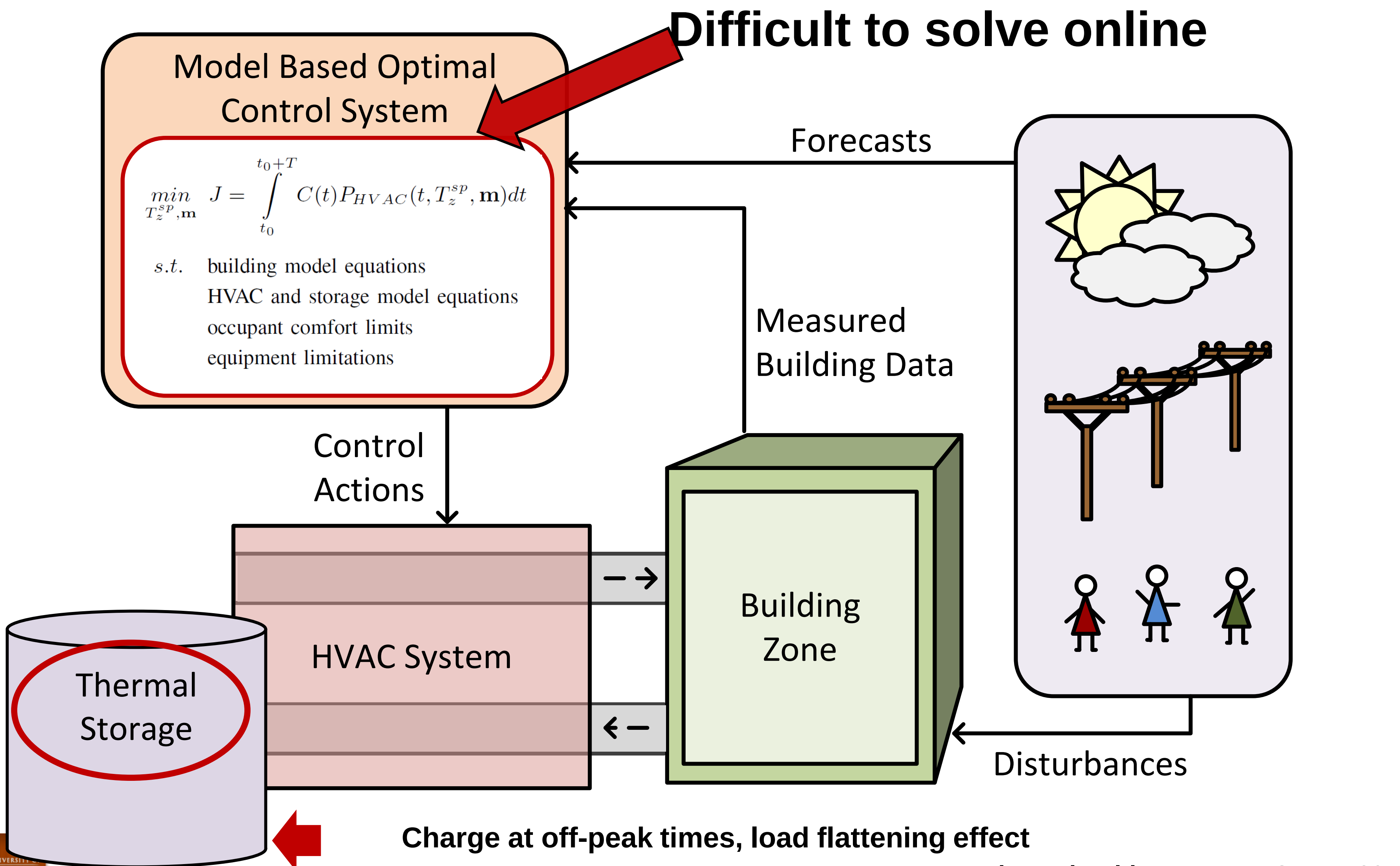
Pecan Street Research Institute: 88 monitored homes; smart meters and subcircuit monitoring used to record energy use with **one minute frequency**



- Big Data insight: variability in HVAC energy use increases as outside temperature increases
- Grid-level variability exacerbated
- Must coordinate generation and consumption on a large scale to achieve load leveling

Photo: Pecan Street Inc.; Data: K.X. Perez et al., Energy and Buildings, 2014, submitted.

Improved Thermal Management



Touretzky and Baldea, J. Proc. Contr., 2014

General Formulation

$$\min_{T_z^{sp},\mathbf{m}} \; J = \int_{t_0}^{t_0+T} C(t) P_{HVAC}(t, T_z^{sp}, \mathbf{m}) dt$$

(economic objective)

$s.t.$ building model equations
HVAC and storage model equations
occupant comfort limits
equipment limitations

Prediction horizon T = NM (N control intervals of time length M)

Decision Variables:

$T_z^{sp}(t)$ (zone temperature setpoint)

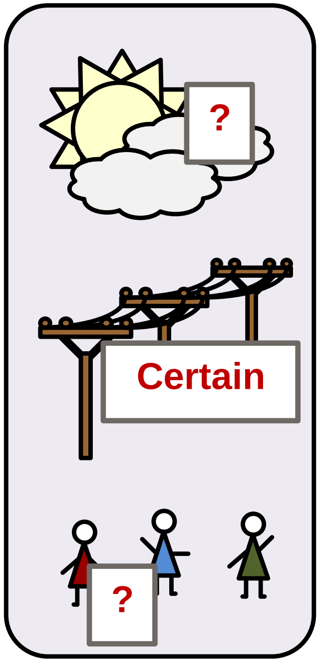
$\mathbf{m}(t) = [m_1 \ldots m_k] \in B^k$ (storage operating modes)

Touretzky and Baldea, J. Proc. Contr., 2014

Assumptions and Observations

$$\min_{T_z^{sp},\mathbf{m}} \; J = \int_{t_0}^{t_0+T} C(t) P_{HVAC}(t, T_z^{sp}, \mathbf{m})dt$$

$s.t.$ building model equations
HVAC and storage model equations
occupant comfort limits
equipment limitations



- Energy prices are known in advance

Touretzky and Baldea, J. Proc. Contr., 2014

Assumptions and Observations

$$\min_{T_z^{sp},\mathbf{m}} \quad J = \int_{t_0}^{t_0+T} C(t)P_{HVAC}(t, T_z^{sp}, \mathbf{m})dt$$

$$\begin{aligned} s.t. \quad & \text{building model equations} \\ & \text{HVAC and storage model equations} \\ & \text{occupant comfort limits} \\ & \text{equipment limitations} \end{aligned}$$

Shorter horizon with sufficient accuracy

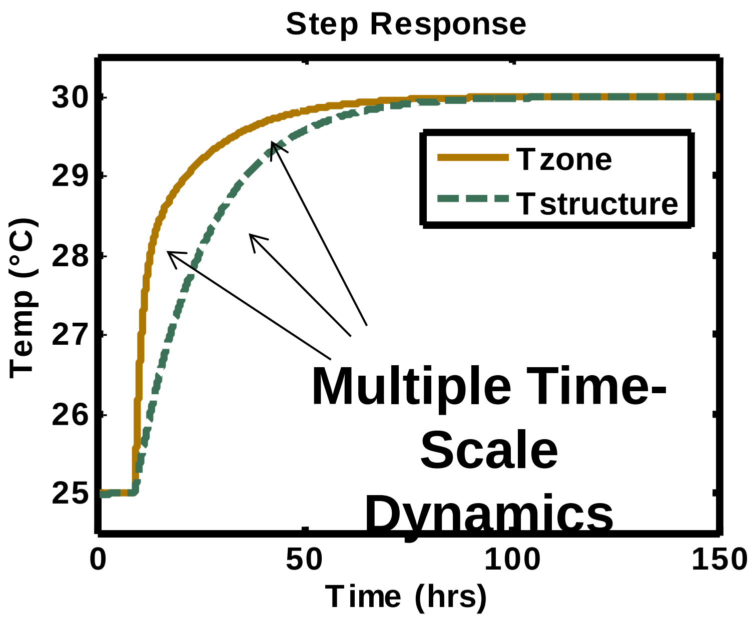
- Energy prices are known in advance
  - Schedule TES for energy price forecast horizon
  - Cost of TES charging relatively insensitive to disturbances

Touretzky and Baldea, J. Proc. Contr., 2014

Assumptions and Observations

Time scale separation

- TES dynamics similar to that of building structural elements
- TES utilization can be shaped at will
- Air dynamics are much faster



Use a composite fast/slow control strategy

Touretzky and Baldea, J. Proc. Contr., 2014

Hierarchical Control Structure

Control Tier	Control Objectives
Slow M	**Integer decisions $m(t)$ present**

hours

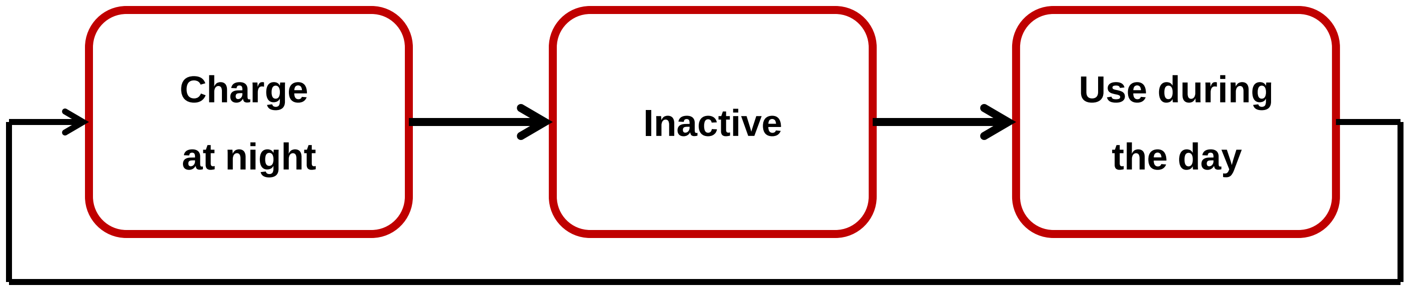
minutes

seconds

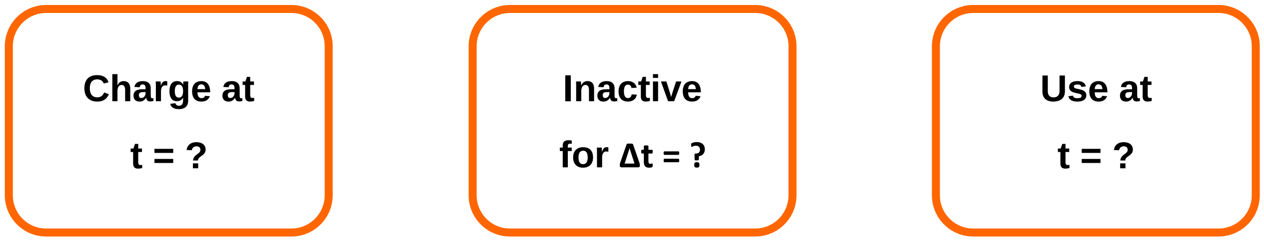
Baldea and Touretzky, Sys. Contr. Lett, 2013, J. Proc. Contr., 2014; J. Proc. Contr., submitted

Continuous Reformulation of Slow MPC

- Principle:
  - Exploit cyclical nature of mode transitions – *establish event order offline*



  - Emulate hybrid control
    - *decide timing of ordered events with known sequence*



Continuous-Time Formulation of Slow MPC

n mode transitions, $\mathbf{m}(t) = [m_1 \ldots m_k] \in B^k$

Schedule: $S = (s_1 \rightarrow s_2 \rightarrow \ldots \rightarrow s_n \rightarrow s_1)$

Select continuous start time t_i of events: $s_i = m_j$

Slow (scheduling) MPC

$$\min_{T_z^{sp}, t_1, \ldots, t_n} J = \int_0^{24} C(t) P_{HVAC}(t, T_z^{sp}, S) dt$$

$s.t.$ building model equations

occupant comfort limits

TES model equations

TES equipment limitations

$\sum_{i=1}^{n}(t_i) = 24$

Fast MPC

$$\min_{T_z^{sp}} J = \int_{t_0}^{t_0+T} C(t) P_{HVAC}(t, T_z^{sp}, S) dt$$

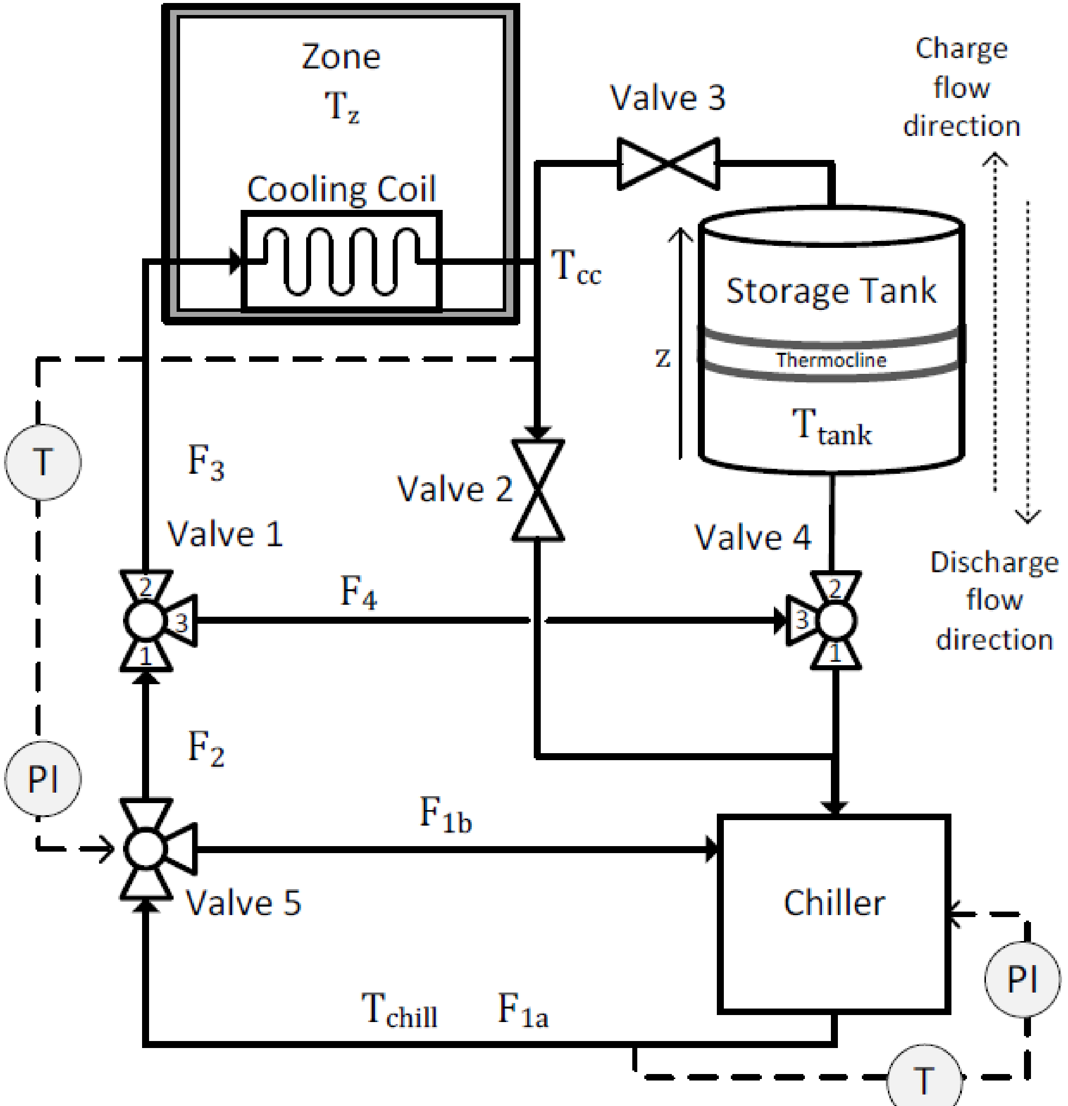
$s.t.$ building model equations

occupant comfort limits

Touretzky and Baldea, J. Proc. Contr., 2014

Case Study: UT Thermal Façade Lab

Single zone test buildings with thermal storage

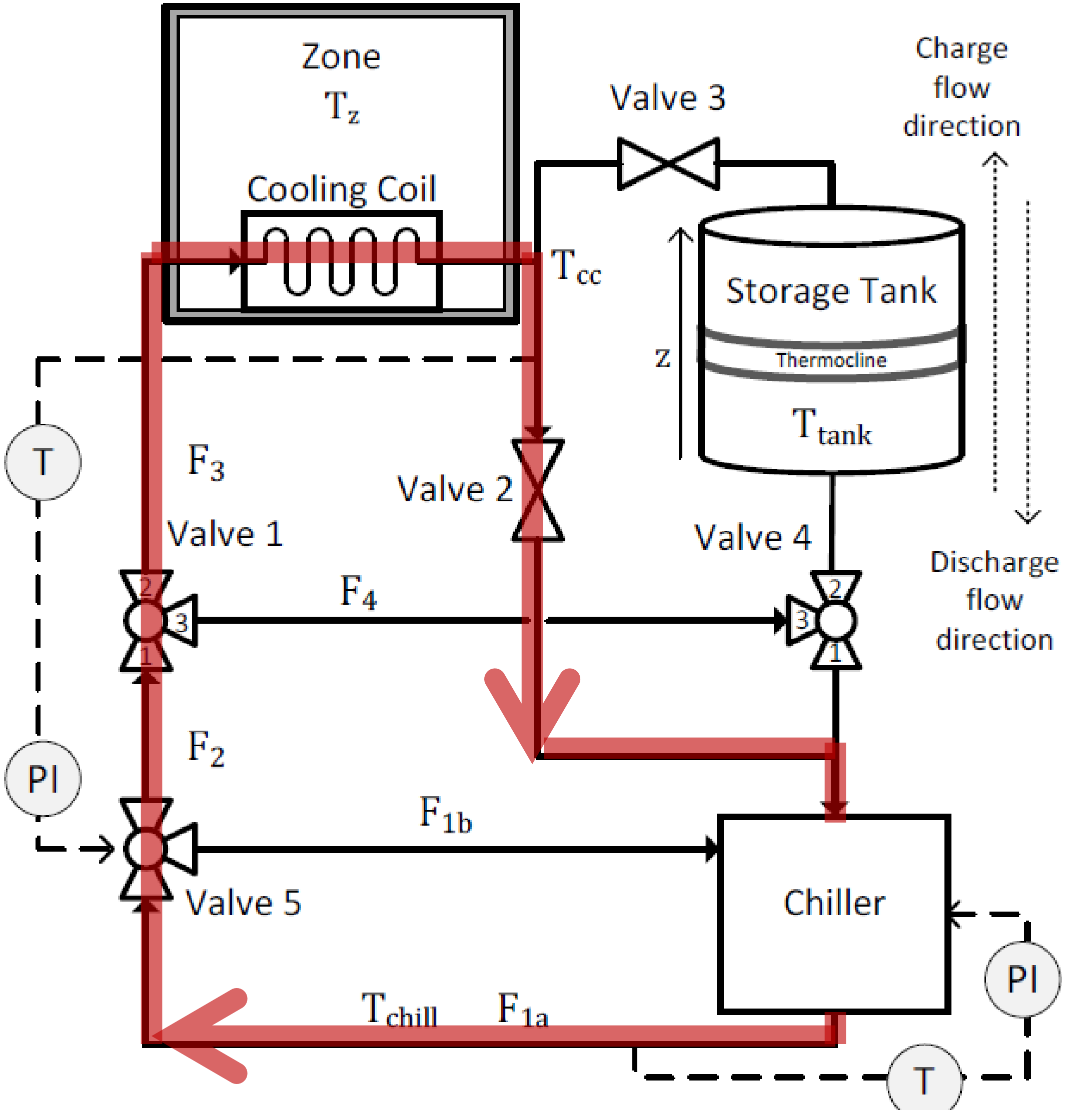


Touretzky and Baldea, J. Proc. Contr., 2014

Case Study: UT Thermal Façade Lab

Operating Modes:

m_1 – Inactive



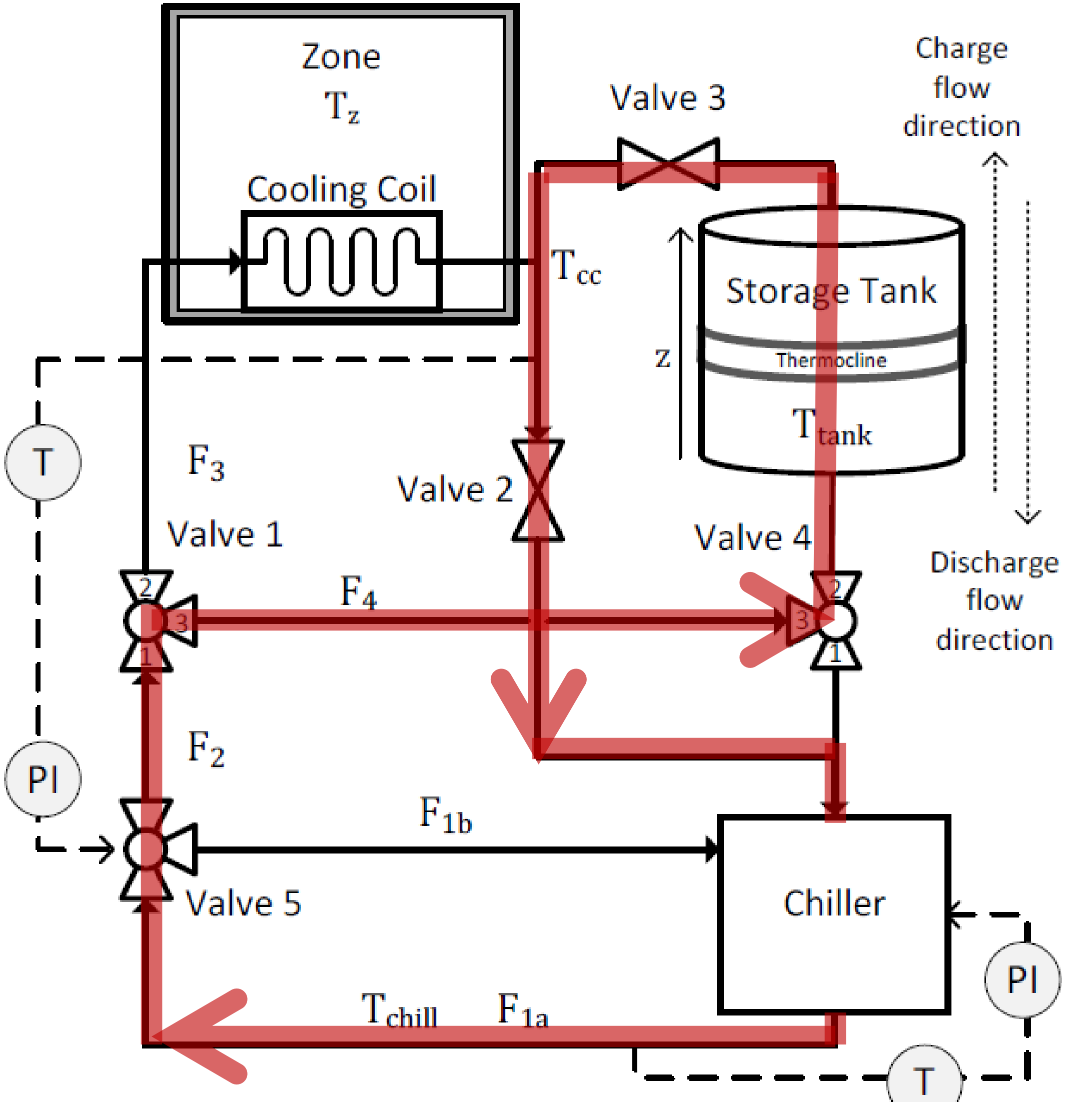
Touretzky and Baldea, J. Proc. Contr., 2014

Case Study: UT Thermal Façade Lab

Operating Modes:

m_1 – Inactive

m_2 – Charge



Touretzky and Baldea, J. Proc. Contr., 2014

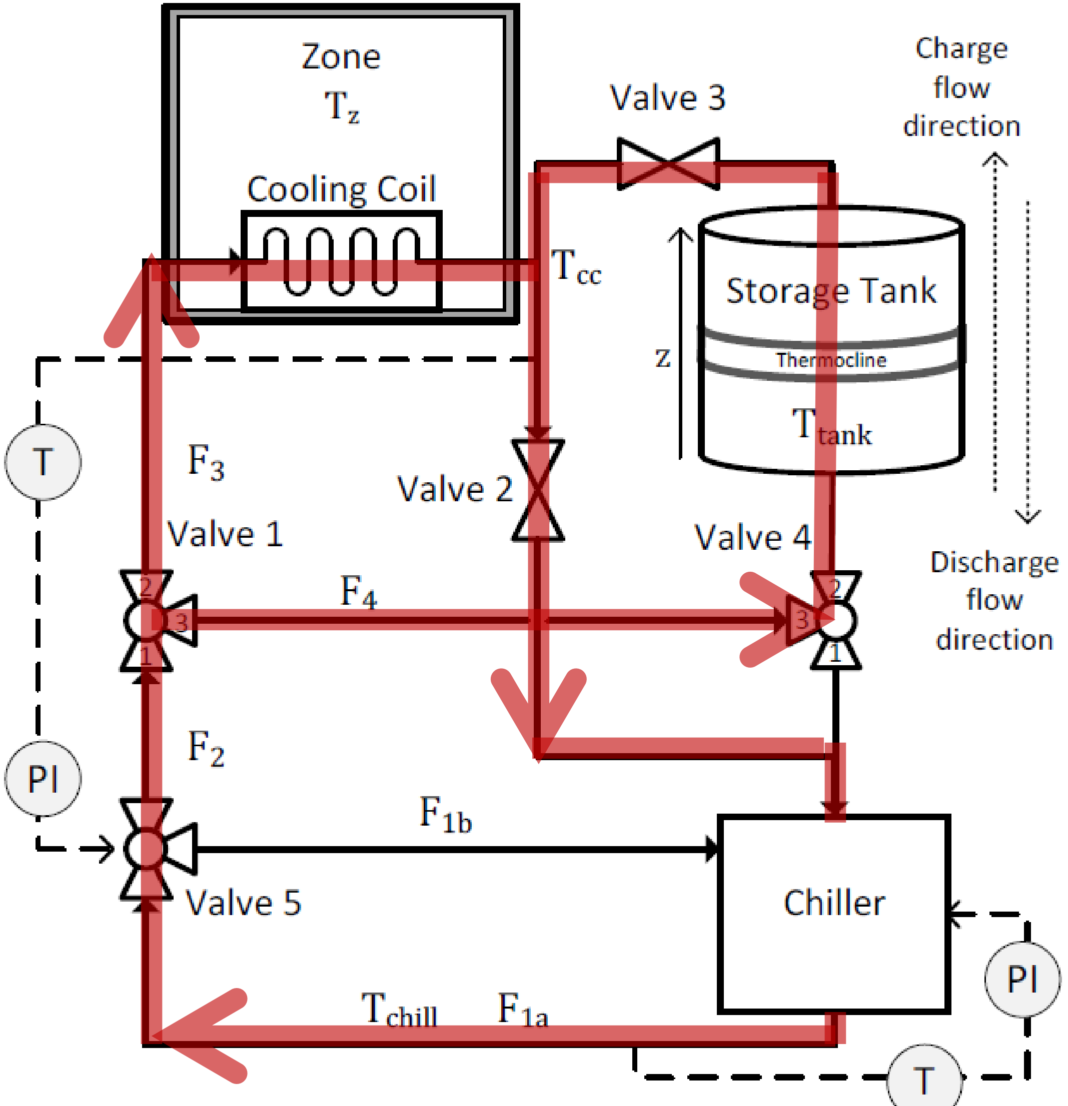
Case Study: UT Thermal Façade Lab

Operating Modes:

m_1 – Inactive

m_2 – Charge

m_3 – Charge and Cool



Touretzky and Baldea, J. Proc. Contr., 2014

Case Study: UT Thermal Façade Lab

Operating Modes:

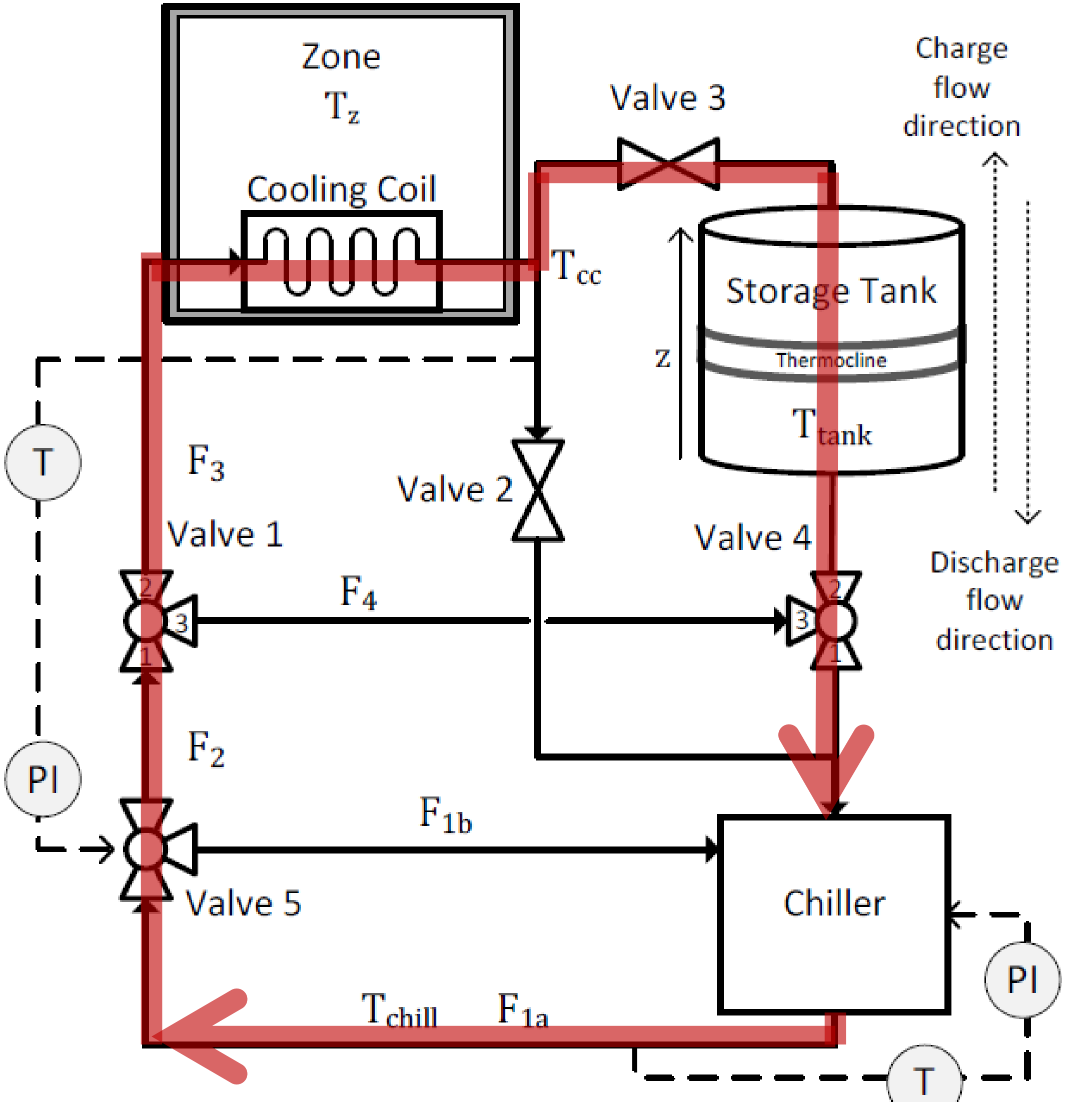
m_1 – Inactive

m_2 – Charge

m_3 – Charge and Cool

m_4 – Discharge (chiller off)

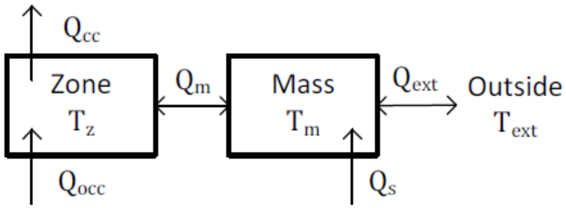
$$\mathbf{m} = [m_1\, m_2\, m_3\, m_4]$$



Touretzky and Baldea, J. Proc. Contr., 2014

Case Study: UT Thermal Façade Lab

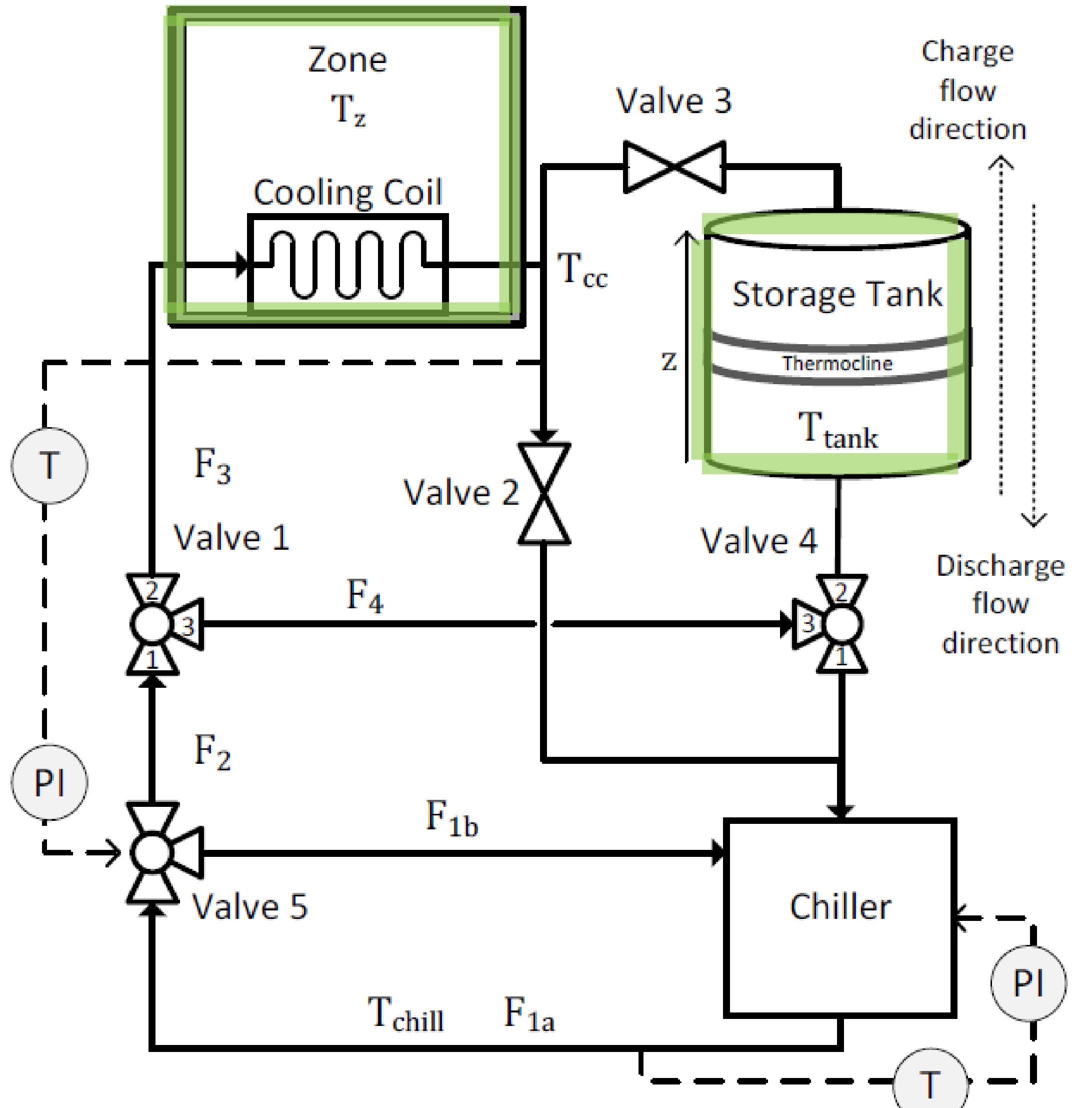
Building Model:



- Lumped model
- Single thermal mass represents entire structure

TES Model:

- Reverse flow direction
- Discretized PDE



Touretzky and Baldea, J. Proc. Contr., 2014

Case Study: Slow MPC

(charge) **(discharge)**

$$S = (m_1 \rightarrow m_2 \rightarrow m_1 \rightarrow m_4 \rightarrow m_1)$$

$$\min_{T_z^{sp}, t_1, \ldots, t_5} \quad J = \int_0^{24} C(t) Q_{chill}^2(t, T_z^{sp}, S) dt$$

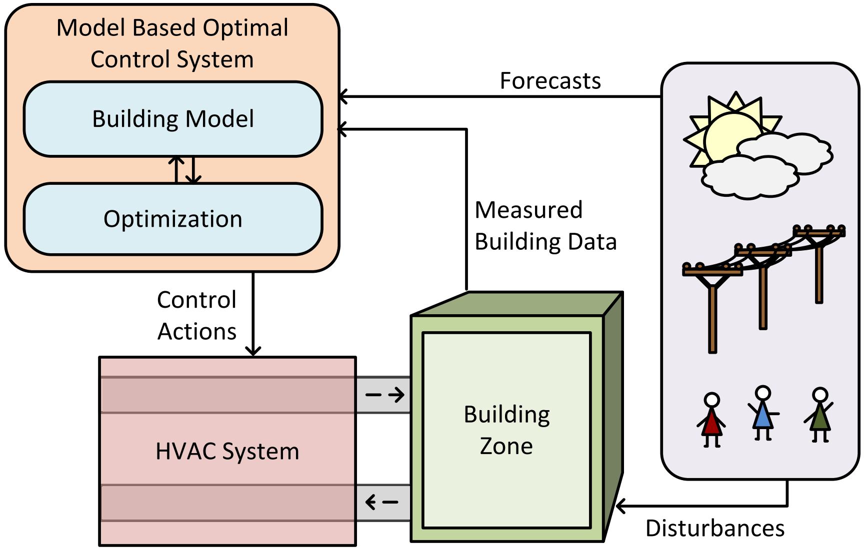
$s.t.$ building model equations

$$297 < T_z^{sp} < 302$$

$$295 < T_z < 305$$

$$T_{cc} < 285$$

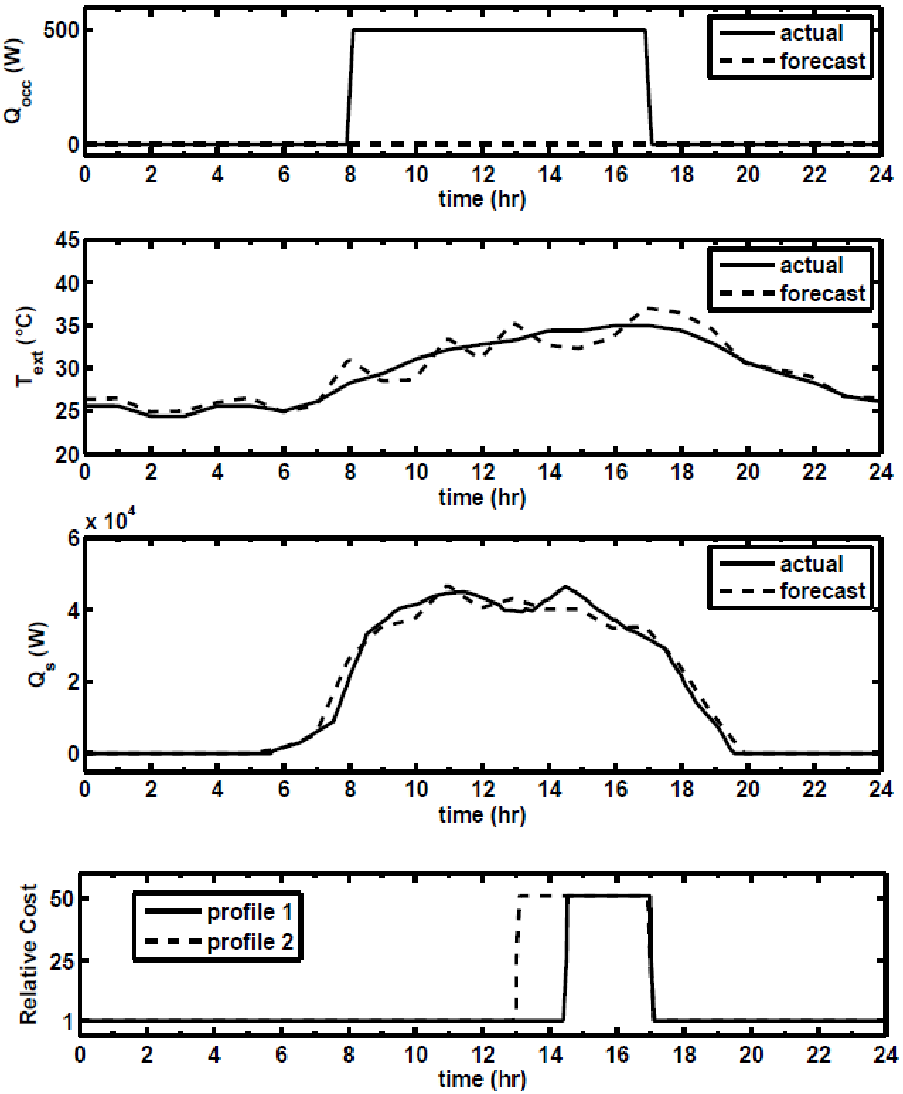
$$\sum_{i=1}^{5} t_i = 24$$



Touretzky and Baldea, J. Proc. Contr., 2014

Case Study: Disturbances

- Occupants
- Outside air temperature
- Solar radiation
- **Cost**

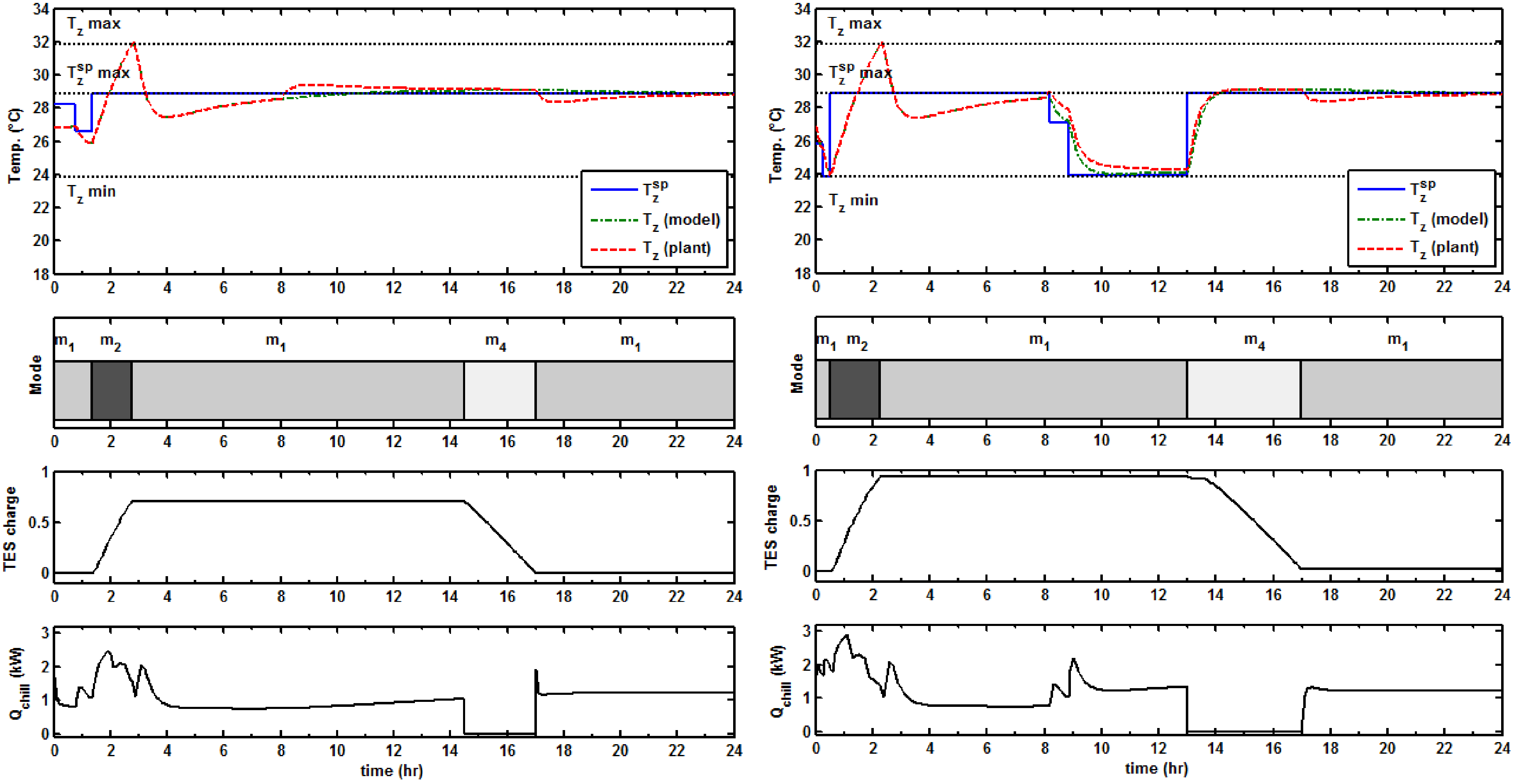


"forecast" provided to the optimization model vs. "actual" incurred by the plant

Case Study: Results

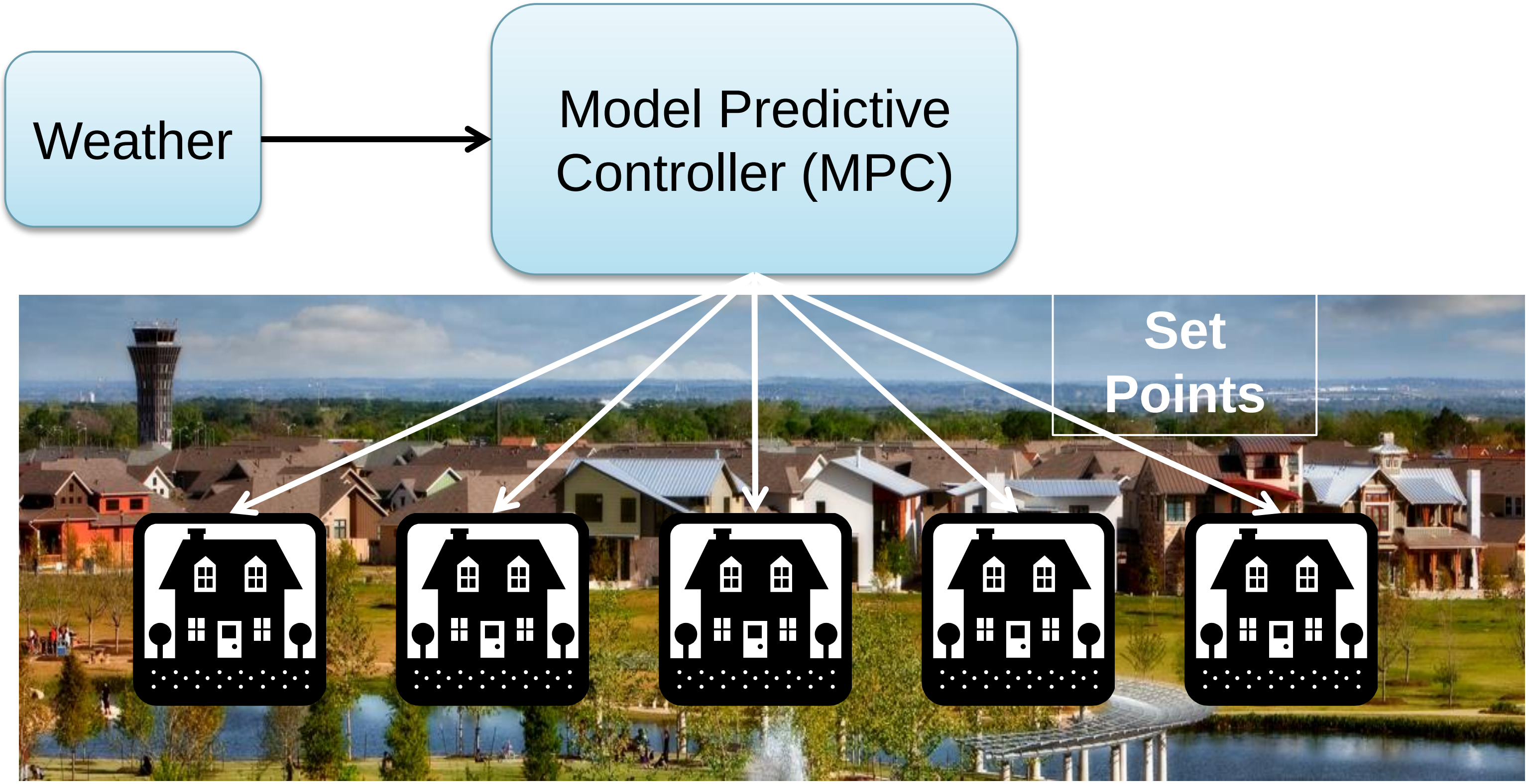
Cost profile 1: sufficient storage

Cost profile 2: insufficient storage



Touretzky and Baldea, J. Proc. Contr., 2014

Extension to Neighborhood Level



"Budget" scenario:

- Time-series models identified from smart meter data
- No dedicated thermal storage (use walls)
- No local optimization- set thermostat setpoint centrally

Minimum Peak Model Predictive Control

$$J = \min_{T} z$$ **Minimize Peak Value**

Subject to

$$z \geq \sum_{i=1}^{N} y_{i,j} \qquad \forall j$$

i **= index for homes**

j **= index for time**

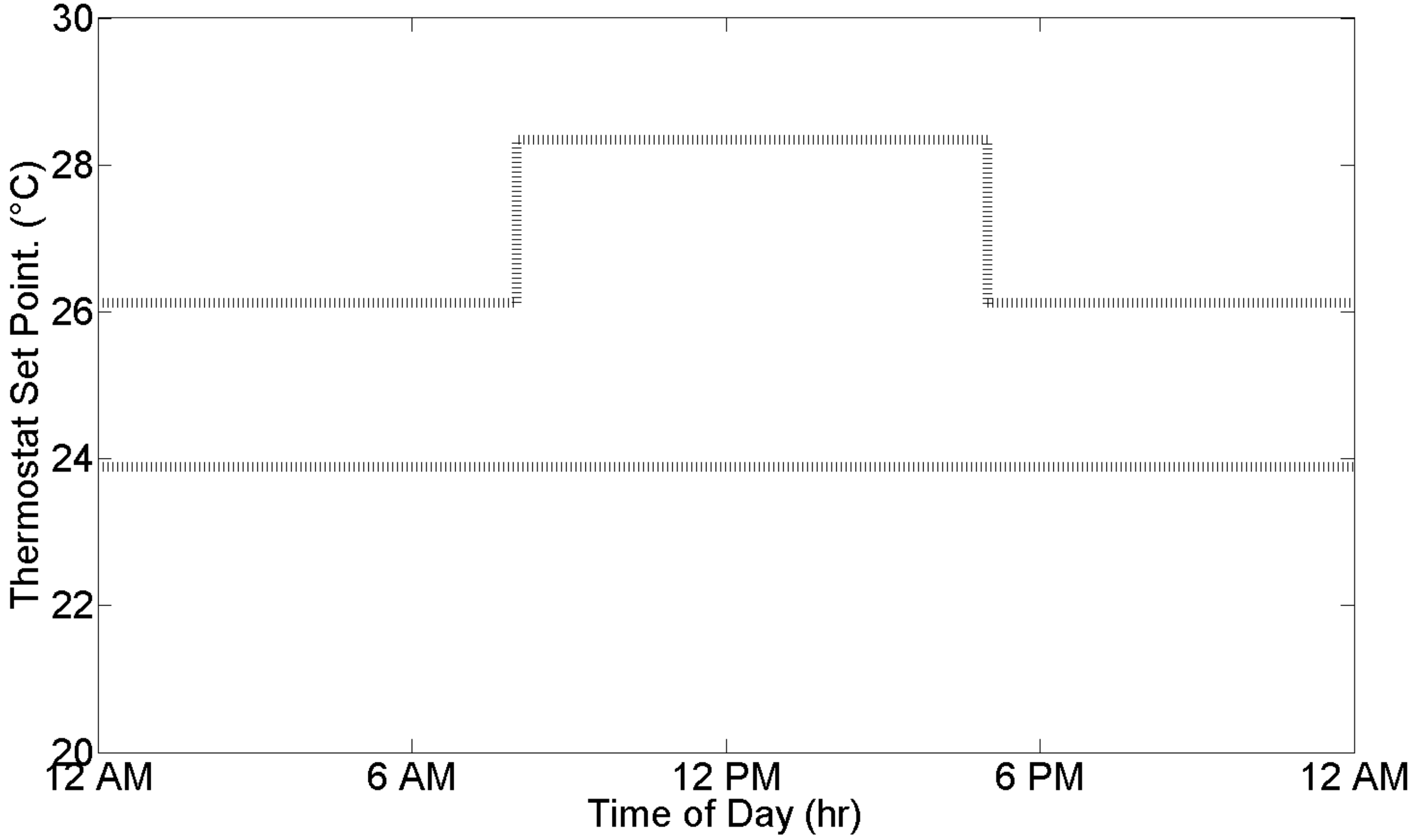
$$y_{i,j} = f\left(y_{i,j-1}, T_{i,j-2:j}, DBT_{j-2:j}, j\right) \qquad \forall i, j$$ **Predicted Value**

$$0 \leq y_{i,j} \leq maxLoad_i \qquad \forall i, j$$ **Equipment Constraints**

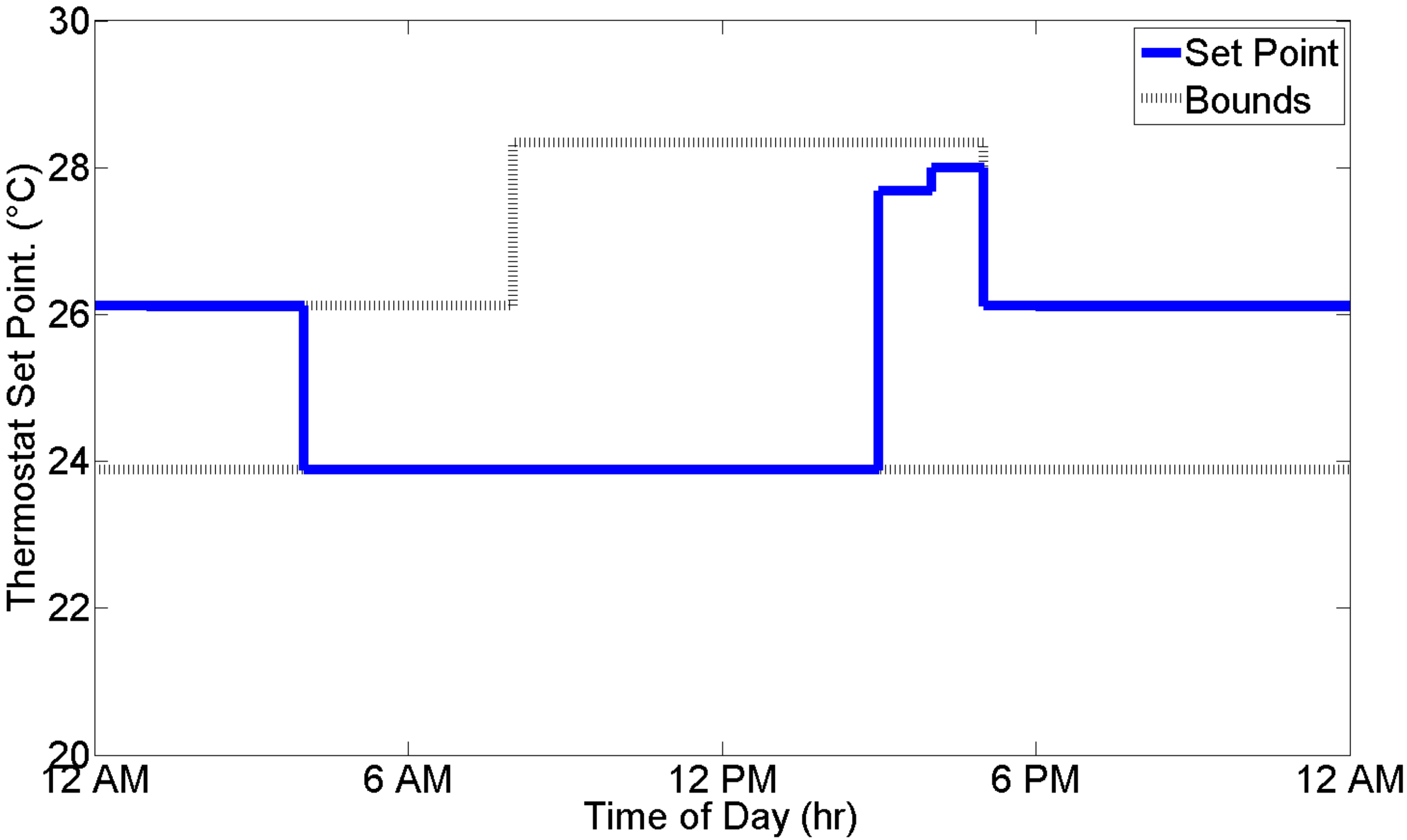
$$lb_{i,j} \leq T_{i,j} \leq ub_{i,j} \qquad \forall i, j$$ **Comfort Constraints**

Cole *et al*., *Appl. Energ.*, 2014, under review, Perez et al., ACEEE Meeting, submitted

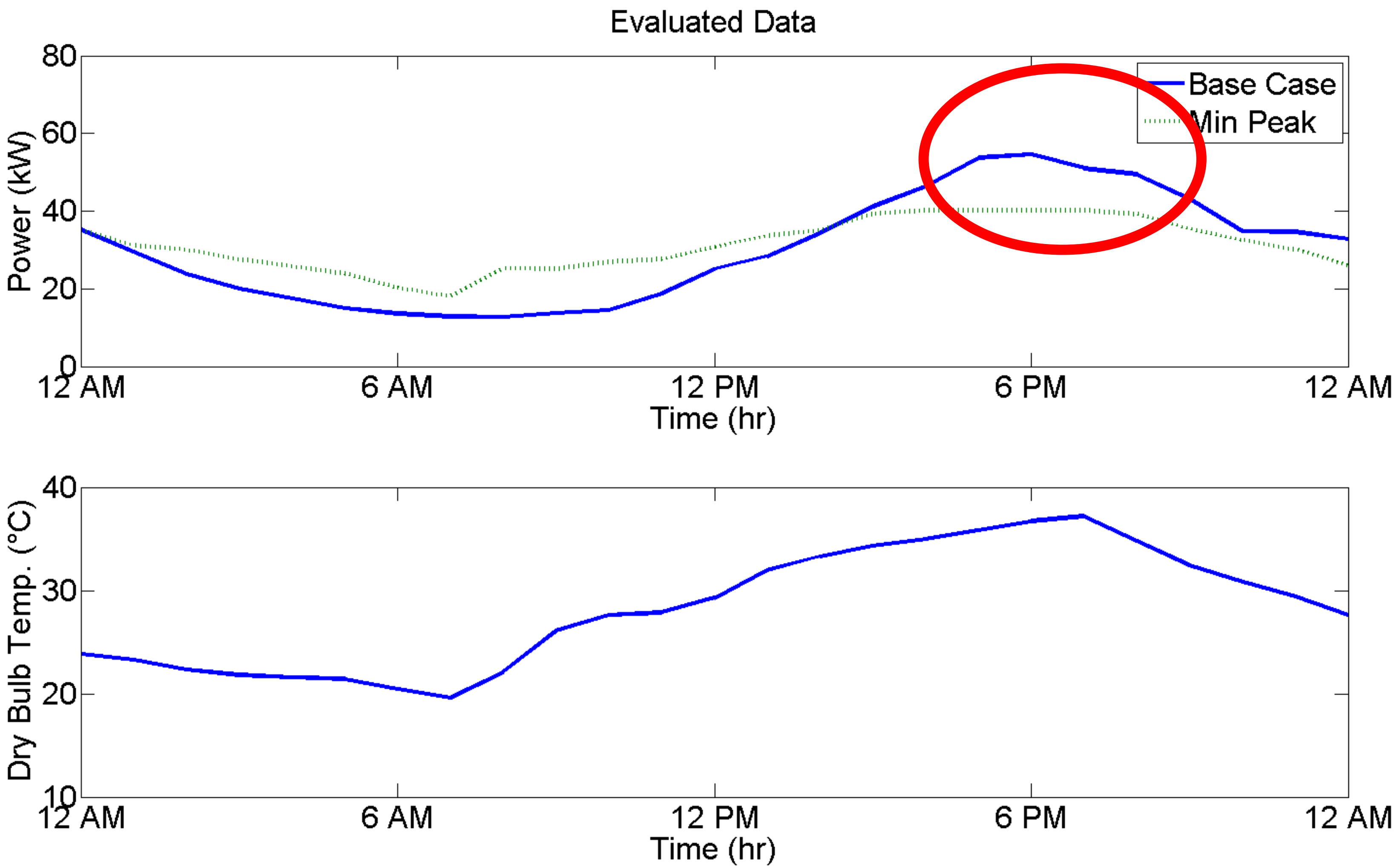
Thermostat Setpoint Boundary Constraints



Sample Home Control



Peak Minimization (41 homes)



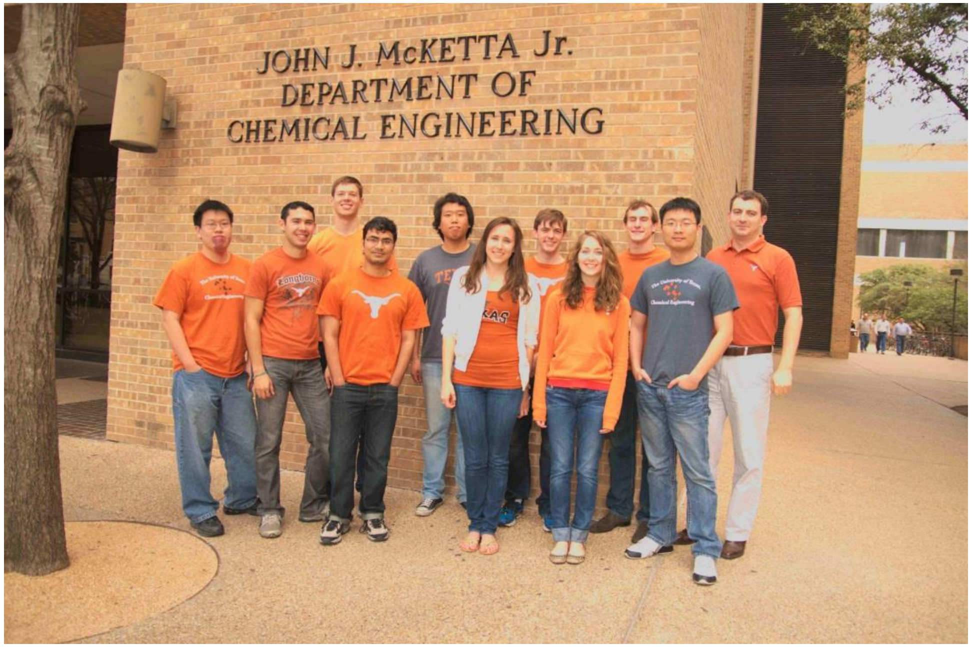
Perez et al., ACEEE Meeting, submitted

Conclusions

- Variability in residential energy consumption has strong impact on grid
- Effective solutions for large-scale load leveling
  - Storage: dedicated media (tank) or structural
  - Predictive control strategy (centralized/decentralized)
  - Models: first principles vs. data driven (smart meter)

- Future work:
  - Centralized storage
  - Decentralized control/communication

Acknowledgements



National Science Foundation
WHERE DISCOVERIES BEGIN

ACS PRF

U.S. DEPARTMENT OF ENERGY

ABB

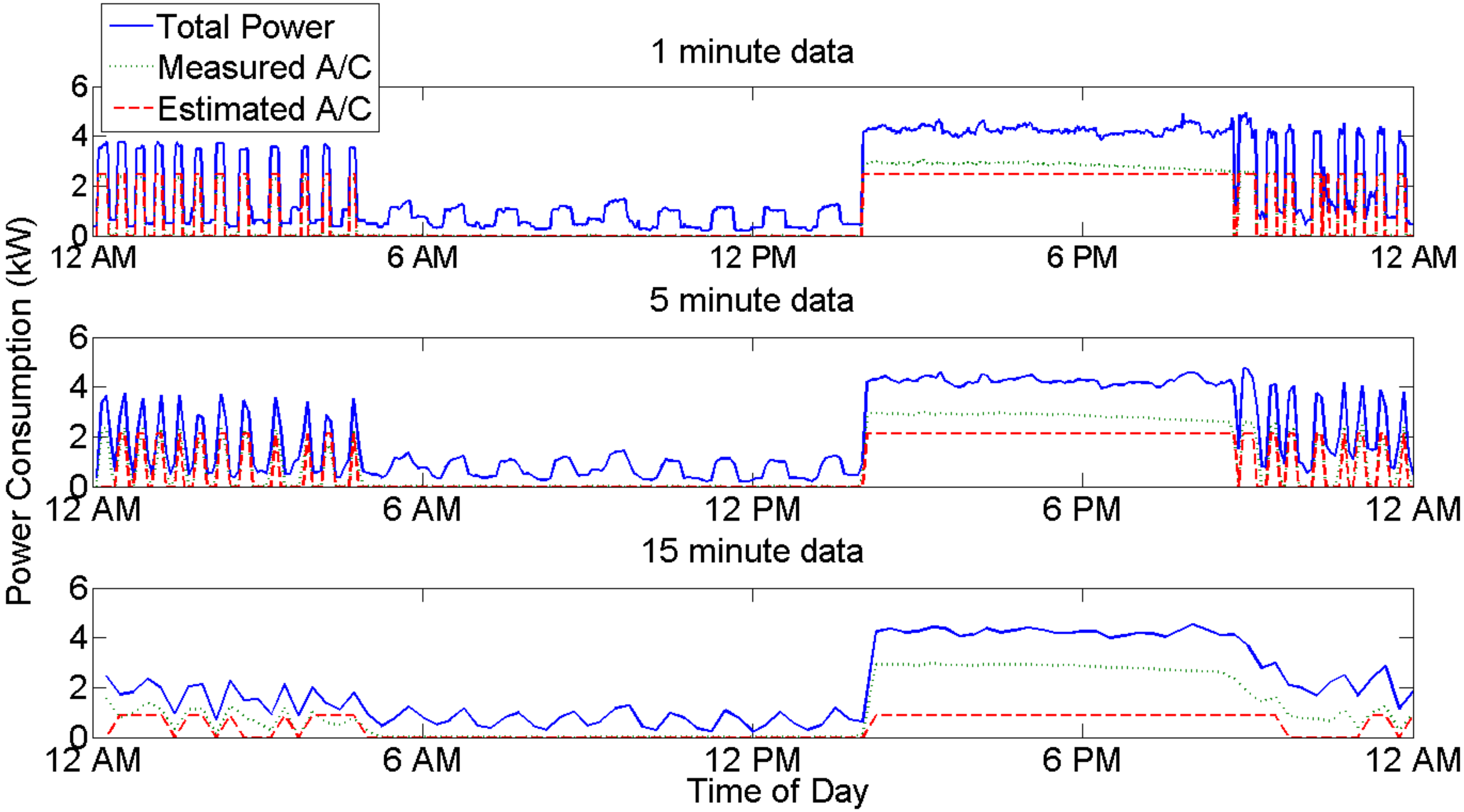
Center for Operator Performance
An Industry/University Center for Excellence

CORNING

DOW

EMERSON

5-Minute Data



K. X. Perez, et al. "Nonintrusive Disaggregation of Residential Air-Conditioning Loads from Smart Meter Data," ***Energy & Build.*****,2014.**

Source: Pecan Street Research Institute

Model Form

$$y(k) = ay(k-1) + \sum_{i=0}^{2}\left[b_i DBT(k-i) + c_i T(k-i)\right]$$
$$+d\left[DBT(k)\right]^2 + fDBT(k)\cdot T(k) + h_k$$

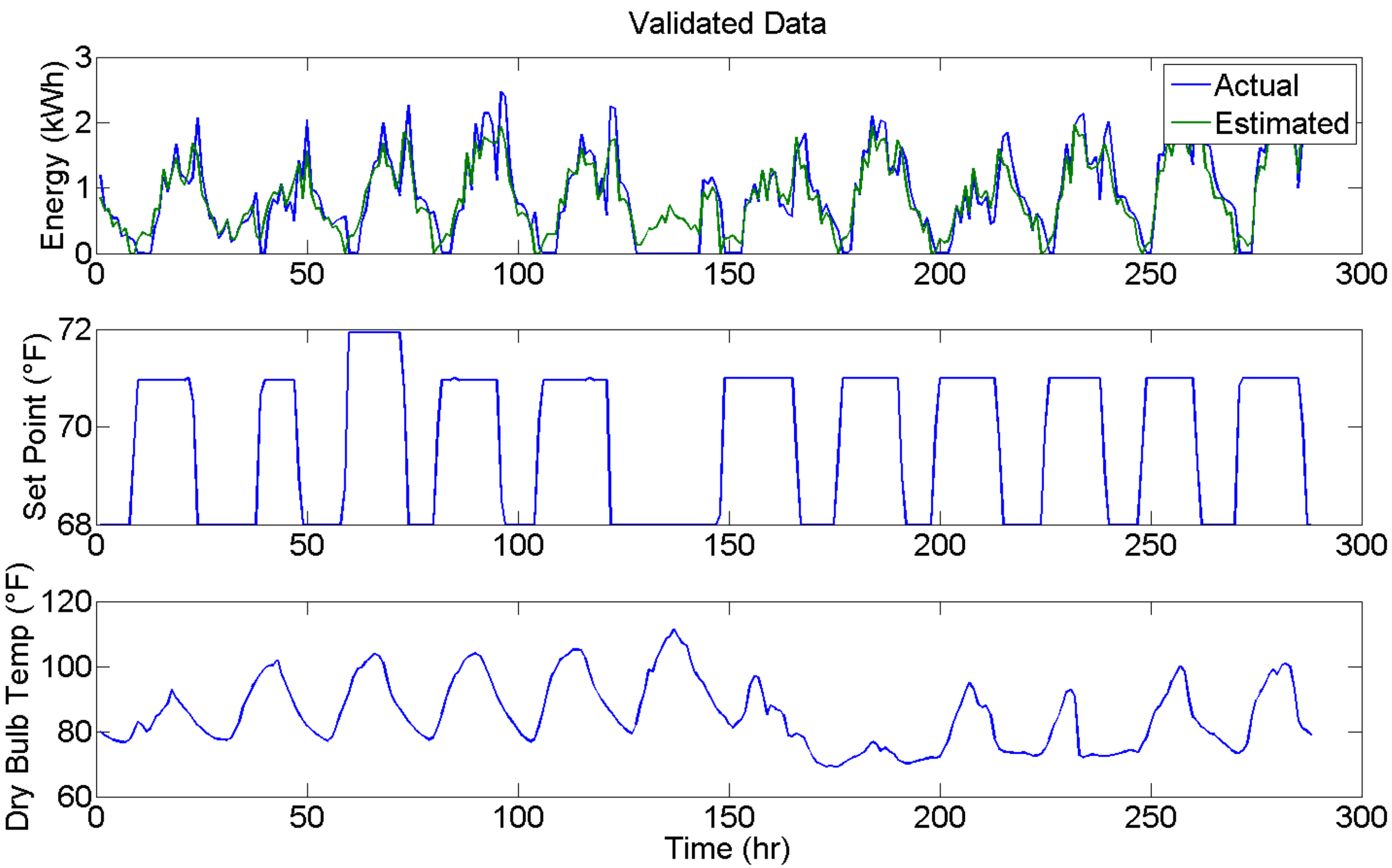
y = A/C Electricity Use

T = Thermostat Set Point

DBT = Outdoor Dry Bulb Temperature

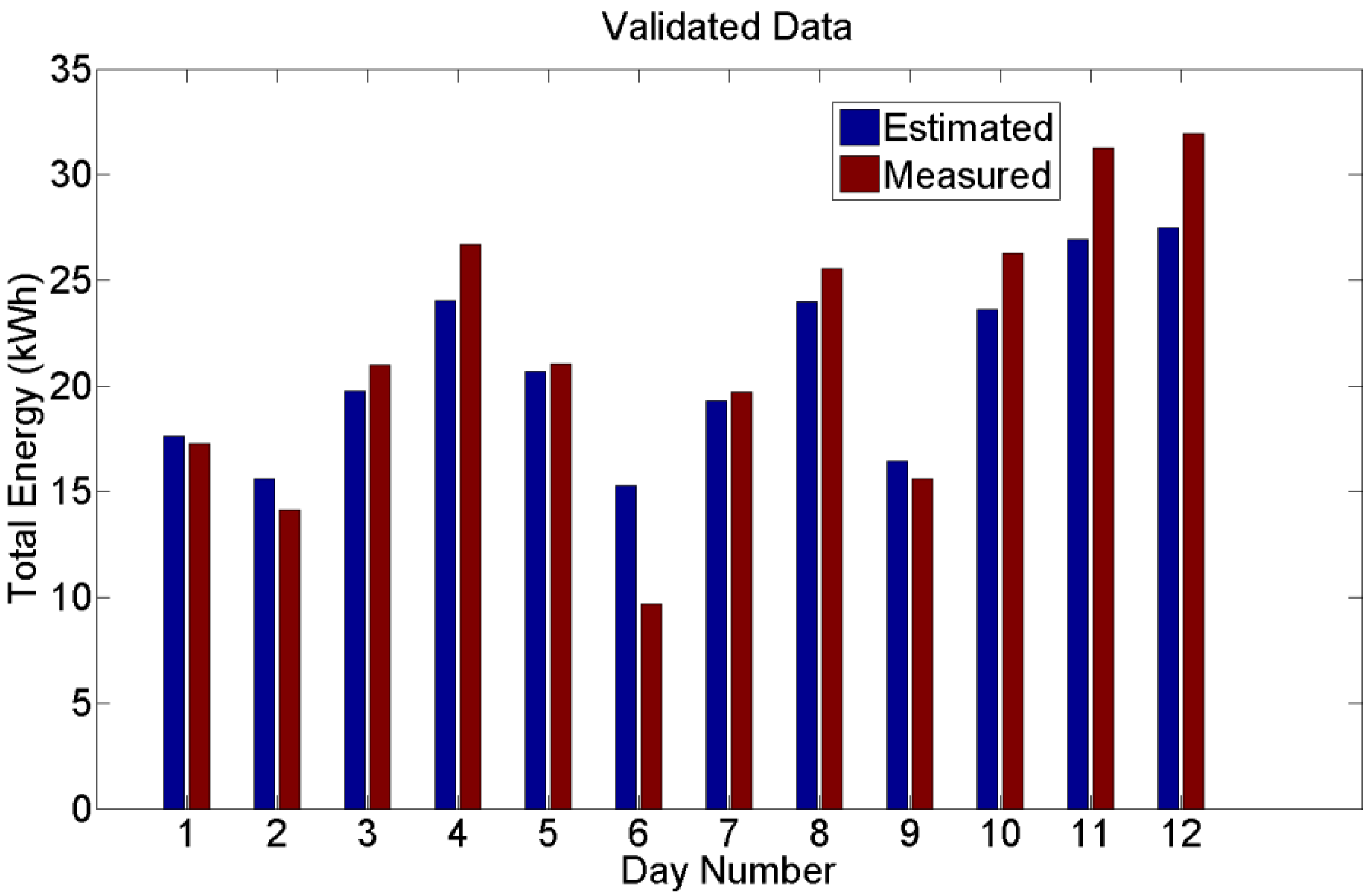
W. J. Cole, K. M. Powell, E. T. Hale, and T. F. Edgar, "Reduced-order residential home modeling for model predictive control," ***Energy Build.*****, Jun. 2013.**

Model Results



Source: Pecan Street Research Institute

Daily Results



Perez et al., Energy and Buildings, submitted

Overall Results

		Total A/C Energy (kWh)			A/C Power Peak (kW)			Average Set Point Temp (°C)	
Day	Max Temp (°C)	Base Case	Min Peak	Savings	Base Case	Min Peak	Savings	Base Case	Min Peak
1	37.02	768.81	689.91	10.3%	58.38	39.98	31.5%	25.02	24.67
2	33.00	721.13	744.34	-3.2%	54.55	40.21	26.3%	25.02	24.74
3	37.20	685.33	692.10	-1.0%	54.62	39.77	27.2%	25.02	24.72
4	35.72	691.77	689.61	0.3%	50.98	39.67	22.2%	25.02	24.72
5	35.67	690.11	683.30	1.0%	54.37	38.90	28.5%	25.00	24.73
6	39.12	746.48	687.18	7.9%	58.55	39.89	31.9%	24.91	24.72
7	33.28	683.97	730.64	-6.8%	54.22	40.34	25.6%	24.92	24.66
8	35.05	685.21	702.33	-2.5%	53.33	40.23	24.6%	25.19	24.69
9	34.27	725.39	685.02	5.6%	58.55	39.36	32.8%	25.34	24.73
10	37.27	729.98	702.97	3.7%	56.09	40.31	28.1%	25.36	24.72
11	35.03	702.43	697.64	0.7%	53.47	39.82	25.5%	25.35	24.71

Perez et al., ACEEE Meeting, submitted