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FOUNDATIONS OF RESILIENT CYBER-PHYSICAL SYSTEMS

Aggregating buildings to provide Ancillary Services

Optimal contract design for provision of frequency regulation capacity

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The Electricity Spot Market in California

Day-ahead market (DAM)

- runs every day at noon (bids due before 10am)
- market clearing is the solution of a large optimization problem)
- awards hourly schedules (for both energy and **Ancillary Services (AS)**)

→

Real-time market (RTM)

- Hour-ahead scheduling process (HASP)
- Fifteen-minute market (FMM)
- bids due >75 min before settling period begins
- ISO procures additional resources based on new forecast

→

Real-time dispatch (RTD)

- ISO sends dispatch signals to resources
- 5-minute dispatch intervals for energy providing resources
- 4-second intervals for regulation up/down

* Ancillary services (traditionally provided by generators):
  * Non-spinning reserves, Spinning reserves
  * **Regulation Up, Regulation Down**

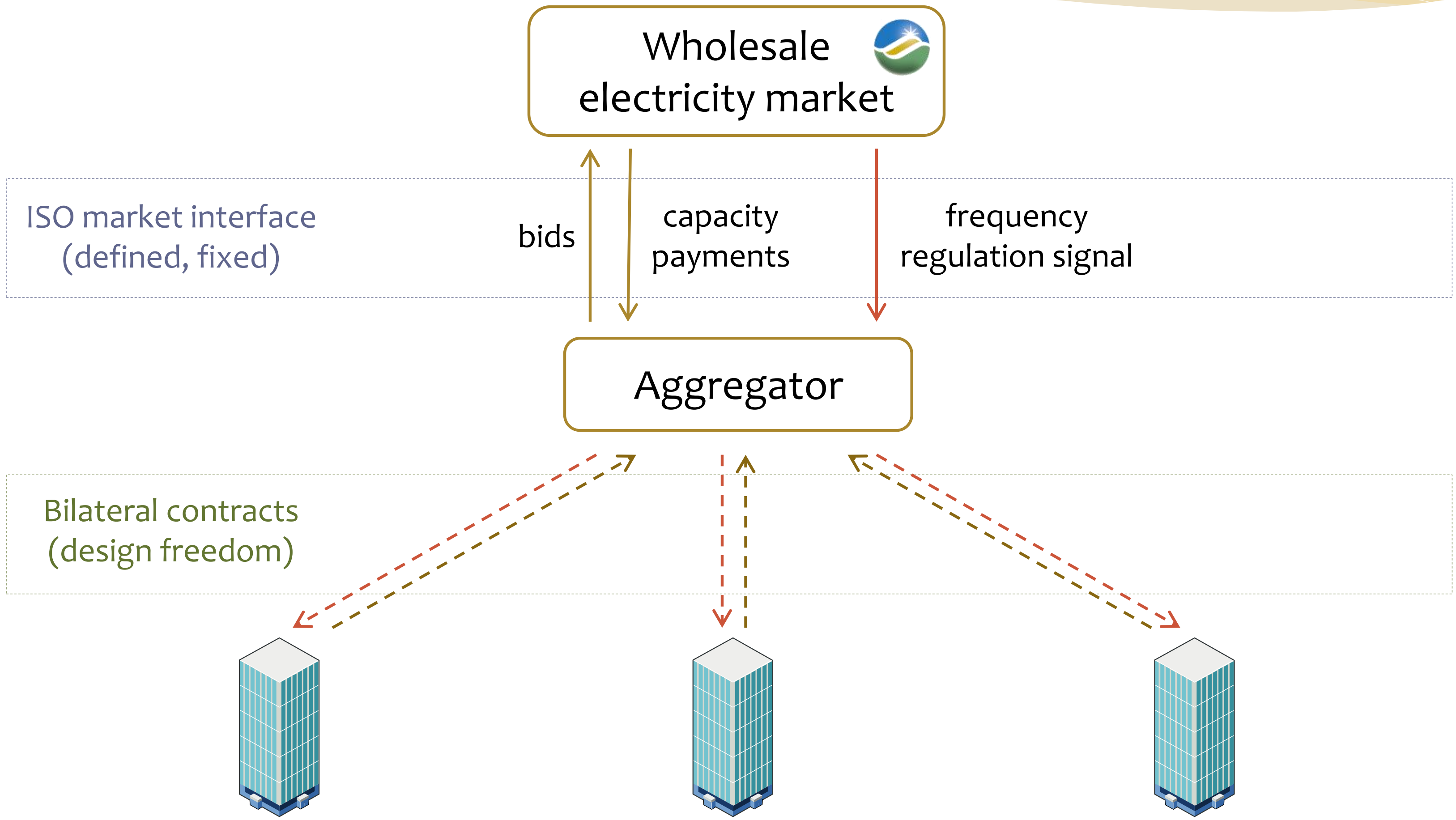
CAISO Fifth Replacement FERC Electric Tariff (May 2014)

Using Buildings to Provide Frequency Regulation Capacity

* Why buildings?
  * HVAC systems significant share of overall energy consumption (~30%)
  * thermal mass provides temporal flexibility in terms of cooling/heating
  * relatively fast actuation speeds (high ramp rates)
  * very low opportunity cost compared to conventional generators
* However:
  * Buildings too small to participate in the market by themselves
  * Aggregator can provide the interface - *if the incentives are right*

- TIAX Report for NTIS: (2002). Energy Consumption Characteristics of Commercial Building HVAC Systems Volume III: Energy Savings Potential (2002).
- Vrettos et al.: Robust Provision of Frequency Reserves by Office Building Aggregations (2014).
- Maasoumy et al.: Model Predictive Control Approach to Online Computation of Demand-Side Flexibility of Commercial Buildings HVAC Systems for Supply Following (2014).

Aggregating Buildings for Frequency Regulation



Robust Scheduling of Building HVAC for Providing Frequency Regulation Capacity

* Basic optimization problem for building b for **fixed regulation capacities** $\mathbf{r}^{\mathrm{b}\uparrow} = (r_0^{\mathrm{b}\uparrow}, \dots, r_N^{\mathrm{b}\uparrow})$ and $\mathbf{r}^{\mathrm{b}\downarrow} = (r_0^{\mathrm{b}\downarrow}, \dots, r_N^{\mathrm{b}\downarrow})$

$$\bar{\mathbf{u}}^{\mathrm{b}*}(\mathbf{r}^{\mathrm{b}\uparrow}, \mathbf{r}^{\mathrm{b}\downarrow}) = \arg\min \ \textstyle\sum_t c_t^{\mathrm{b}} u_t^{\mathrm{b}}$$

s.t.

$u_t^{\mathrm{b}} + w_t^{\mathrm{b}} \in \mathbb{U}_t^{\mathrm{b}}$	Input constraints
$y_t^{\mathrm{b}} \in \mathbb{Y}_t^{b}$	Comfort constraints
$x_{t+1}^{\mathrm{b}} = A^{\mathrm{b}} x_t^{\mathrm{b}} + B^{\mathrm{b}} u_t^{\mathrm{b}} + E^{\mathrm{b}} v_t^{\mathrm{b}} + R^{\mathrm{b}} w_t^{\mathrm{b}}$ $y_t^{\mathrm{b}} = C^{\mathrm{b}} x_t^{\mathrm{b}} + D^{\mathrm{b}} u_t^{\mathrm{b}} + F^{\mathrm{b}} v_t^{\mathrm{b}}$	System dynamics and output
$-r_t^{\mathrm{b}\uparrow} \leq w_t^{\mathrm{b}} \leq r_t^{\mathrm{b}\downarrow}$	Bounds on regulation signal

u : HVAC inputs (normalized)
y : zone temperatures
w : regulation signal
v : combined heating load
c : energy price

Robust Linear Program

Determining Optimal Sign-Up Rewards – Formulation as a Bilevel Optimization Problem

* Aggregator chooses contracted capacities, pays rewards R^{b}

$$(\bar{\mathbf{u}}^*, \mathbf{r}^{\uparrow *}, \mathbf{r}^{\downarrow *}, R^*) = \underset{\mathbf{u},\mathbf{r}^{\uparrow},\mathbf{r}^{\mathrm{b}\uparrow},\mathbf{r}^{\downarrow},\mathbf{r}^{\mathrm{b}\downarrow}R^{\mathrm{b}}}{\arg\max} \underbrace{\sum_t \rho_t^{\uparrow} r_t^{\uparrow} + \rho_t^{\downarrow} r_t^{\downarrow}}_{\text{Revenue (market)}} - \underbrace{\sum_{\mathrm{b}} R^{\mathrm{b}}}_{\text{Total rewards}}$$

s.t.

Capacity adequacy:

$$\sum_{\mathrm{b}} r_t^{\mathrm{b}\uparrow} \geq r_t^{\uparrow}$$

$$\sum_{\mathrm{b}} r_t^{\mathrm{b}\downarrow} \geq r_t^{\downarrow}$$

Non-negativity:

$$r_t^{\uparrow},\ r_t^{\downarrow},\ r_t^{\mathrm{b}\uparrow},\ r_t^{\mathrm{b}\downarrow} \geq 0$$

Optimality:

$$\bar{\mathbf{u}}^{\mathrm{b}} = \bar{\mathbf{u}}^{\mathrm{b}*}(\mathbf{r}^{\mathrm{b}\uparrow}, \mathbf{r}^{\mathrm{b}\downarrow})$$

Individual Rationality:

$$\sum_t c_t^{\mathrm{b}} u_t^{\mathrm{b}} - R^{\mathrm{b}} \leq \sum_t c_t^{\mathrm{b}} u_t^{\mathrm{b}*}(0,0)$$

$\rho^{\uparrow}$: regulation up capacity price

$\rho^{\downarrow}$: regulation down capacity price

R^{b} : sign-up reward for building b

Linear Bilevel Program – cast as Mixed Integer Linear Program

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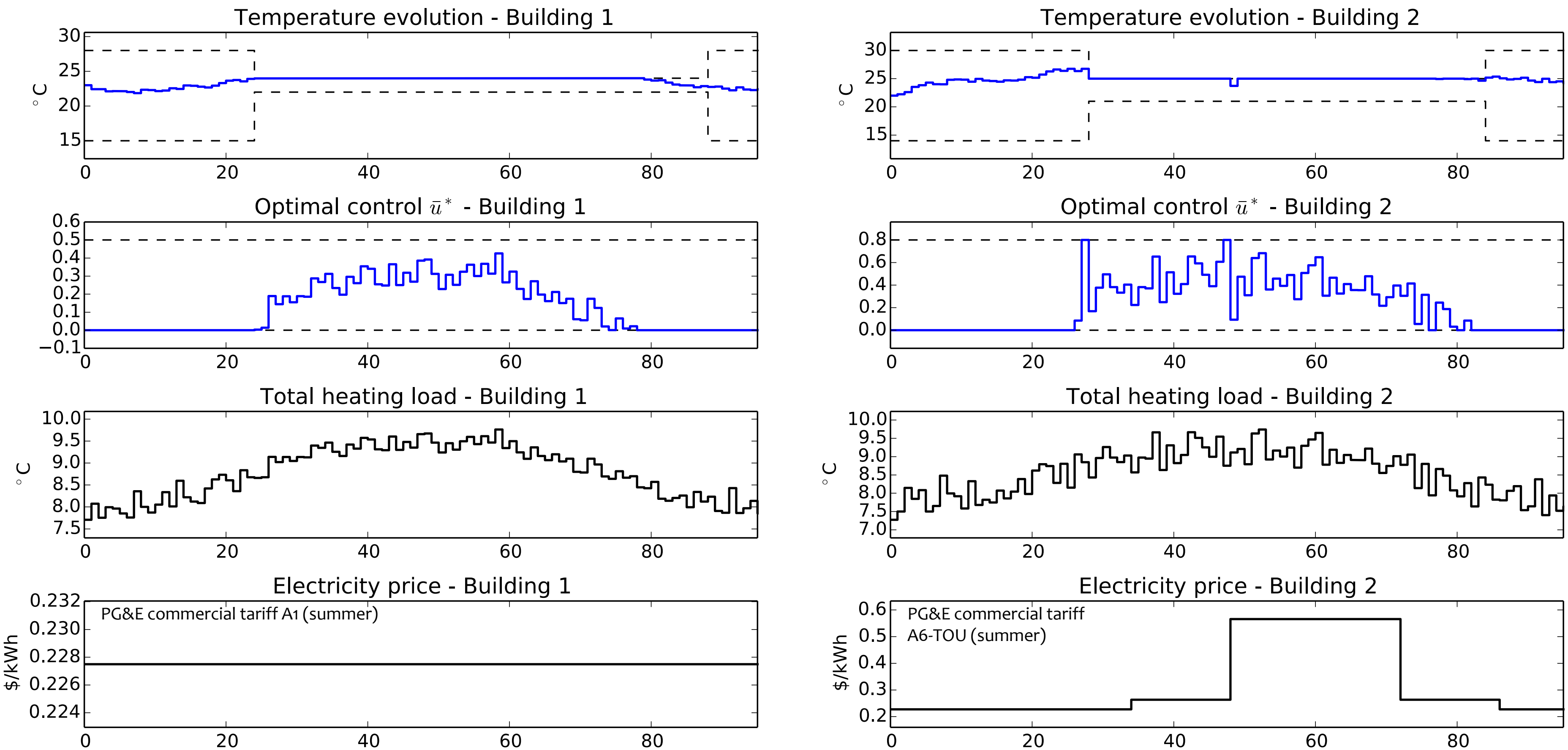
Simulation Results: Outside Option (no contract)



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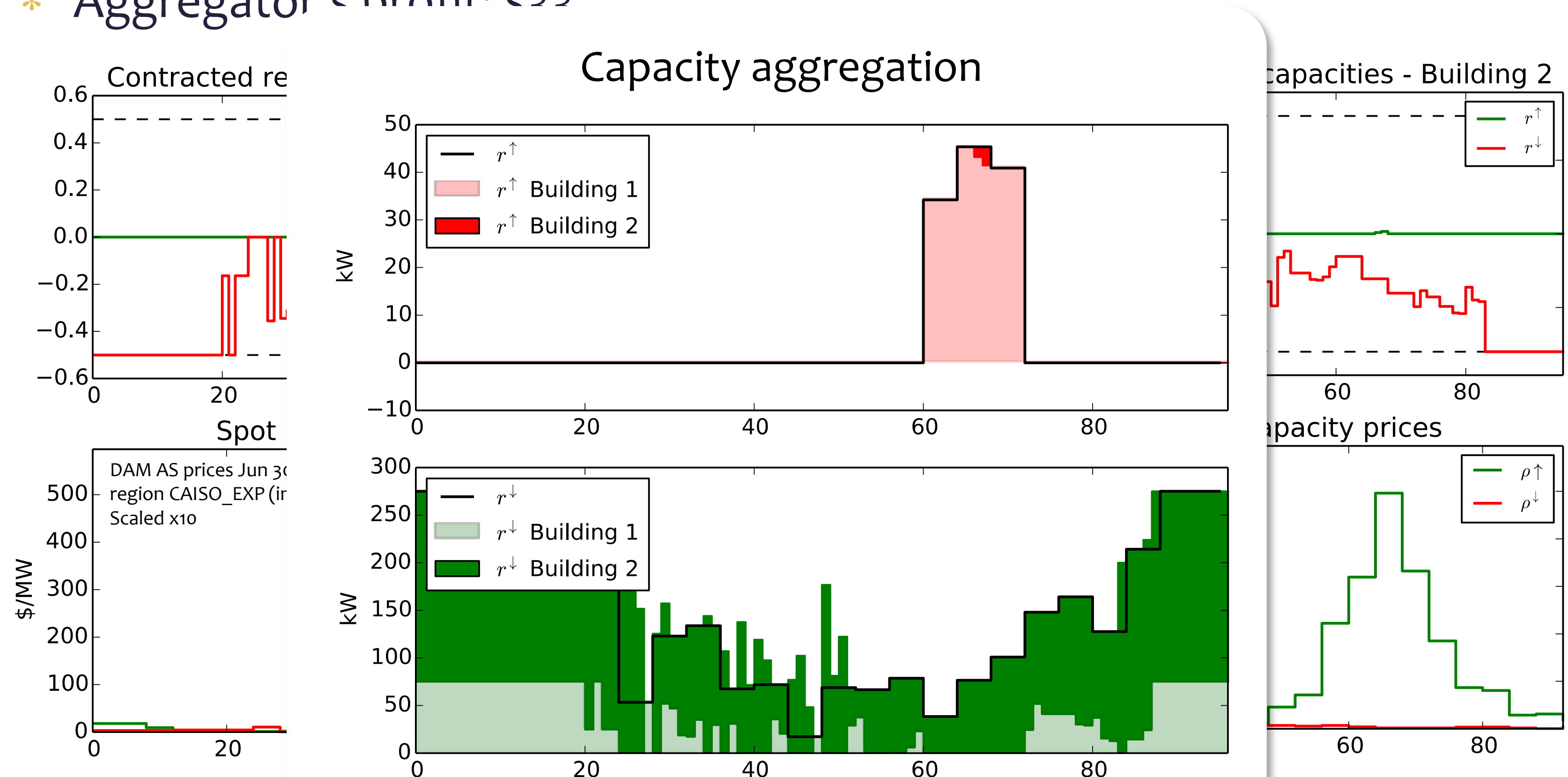
Simulation Results: Optimal Contracts

* Aggregator's profit: $33



Sign-u ... ward: $0.9

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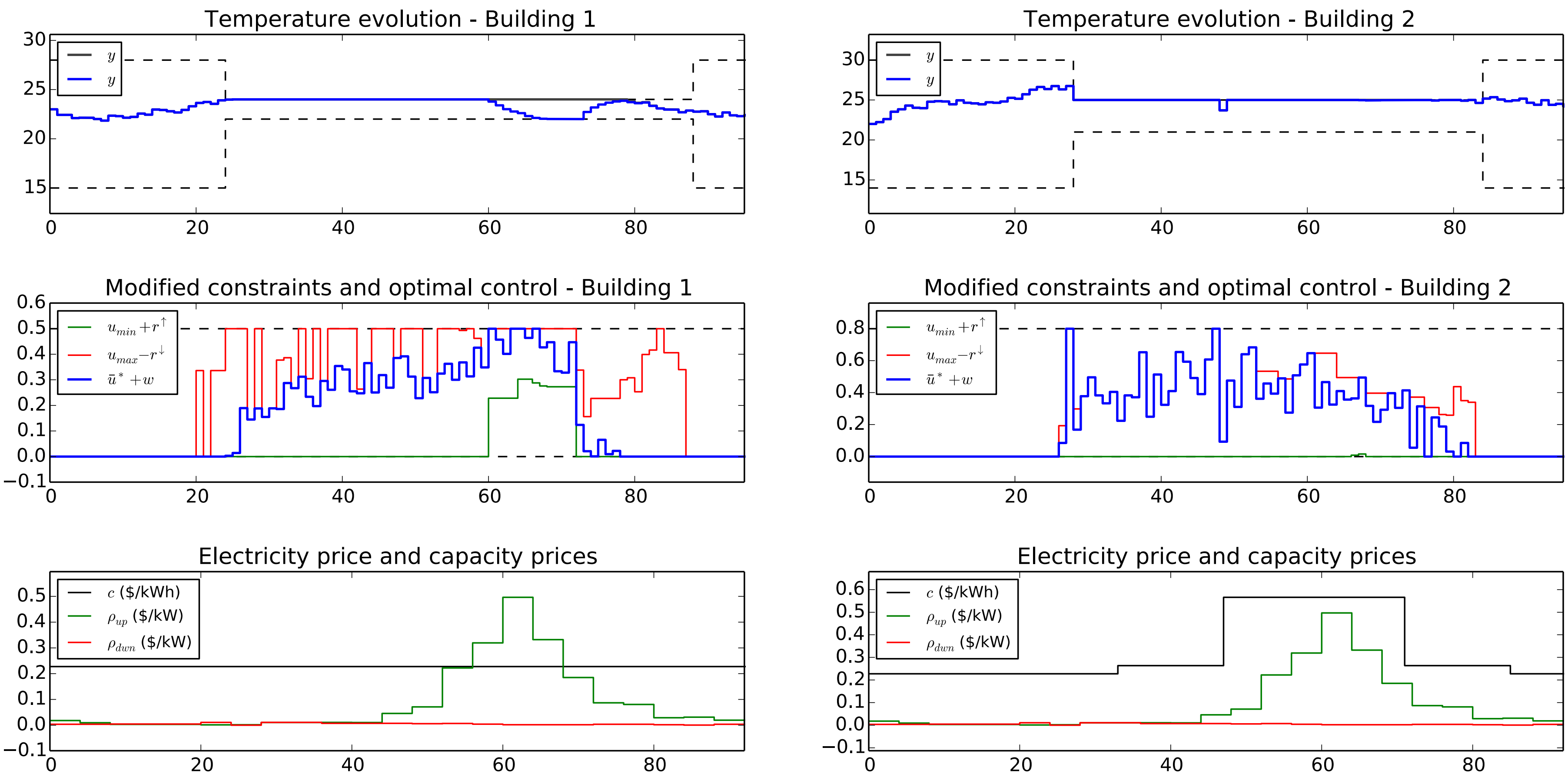
Simulation Results: Optimal Control

* Nominal case (w=0)



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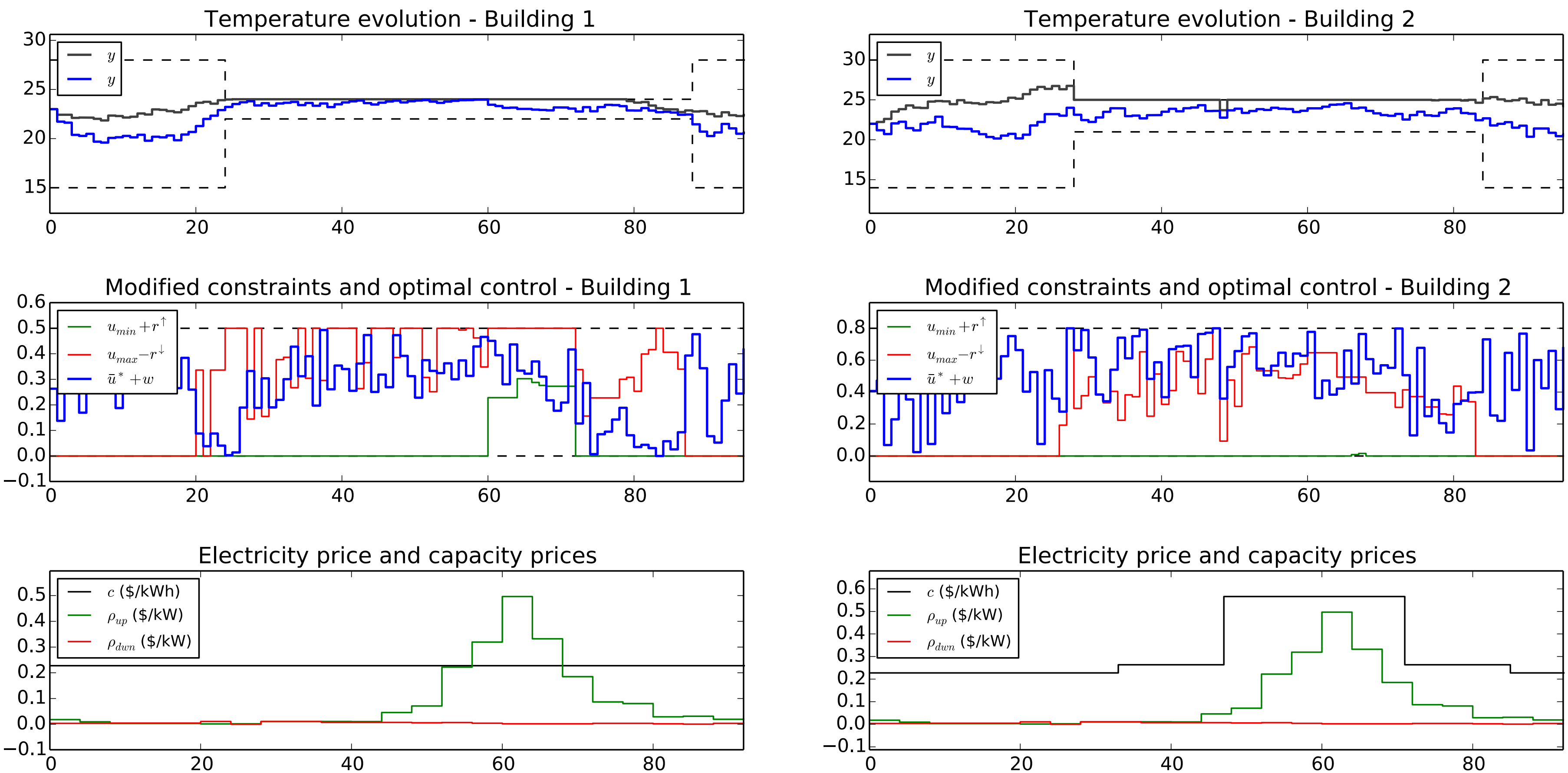
Simulation Results: Optimal Control

- w random (uniform)



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Conclusion and Future Work

Conclusion

* Formulated aggregator's optimal contract design problem
* Developed MILP-based solution framework
  * can easily incorporate additional constraints and objectives (e.g. energy limits, savings requirements)

Future work

* Extension to bilinear building models
* Account for uncertainty in predictions
* Feasibility study based on comprehensive CAISO price data
* Interface considerations: does a simple generic model suffice?
* Include performance payments ("mileage")

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