A Multi-Scale Optimal Control Framework for Electricity Market Participation

Alexander Dowling, PhD

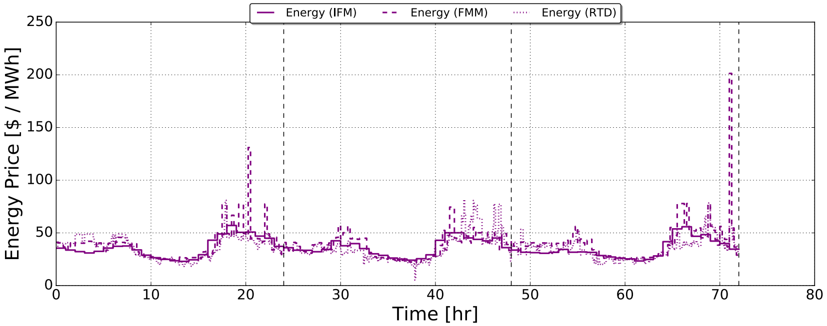
with **Prof. Victor Zavala**

Scalable Systems Laboratory

`zavalab.engr.wisc.edu`

Department of Chemical and Biological Engineering

University of Wisconsin-Madison



FERC Meeting: Increasing Market and Planning Efficiency through Improved Software

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

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Motivation: Economics of Industrial Systems Depend on Electricity Markets


Utility Scale Batteries


Commercial/Academic Campuses (District Heating, HVAC)


Aluminum Smelters


Solar Power Plants


Oil Refineries


Air Separation Systems

Key Questions:

Do market price signals sufficiently **incentivize** industrial partition?

Which markets/products are most promising for industrial participation?

How can industrial system **flexibility** be exploited through electricity markets participation?

How does **market design** impact industrial participation?

Presentation Outline

1. Overview of California Electricity Markets
2. Multi-Scale Optimal Control Framework
3. Case Study: Combined Heat and Power Utility System
4. Case Study: Battery Storage System
5. Conclusions and Future Work

California ISO (CAISO) Electricity Markets

Day-Ahead Market

Integrated Forward Market

Energy & Ancillary Services

1 hour intervals

Real-Time Market

Fifteen Minute Market

Energy & Ancillary Services

15 minute intervals

Real-Time Dispatch

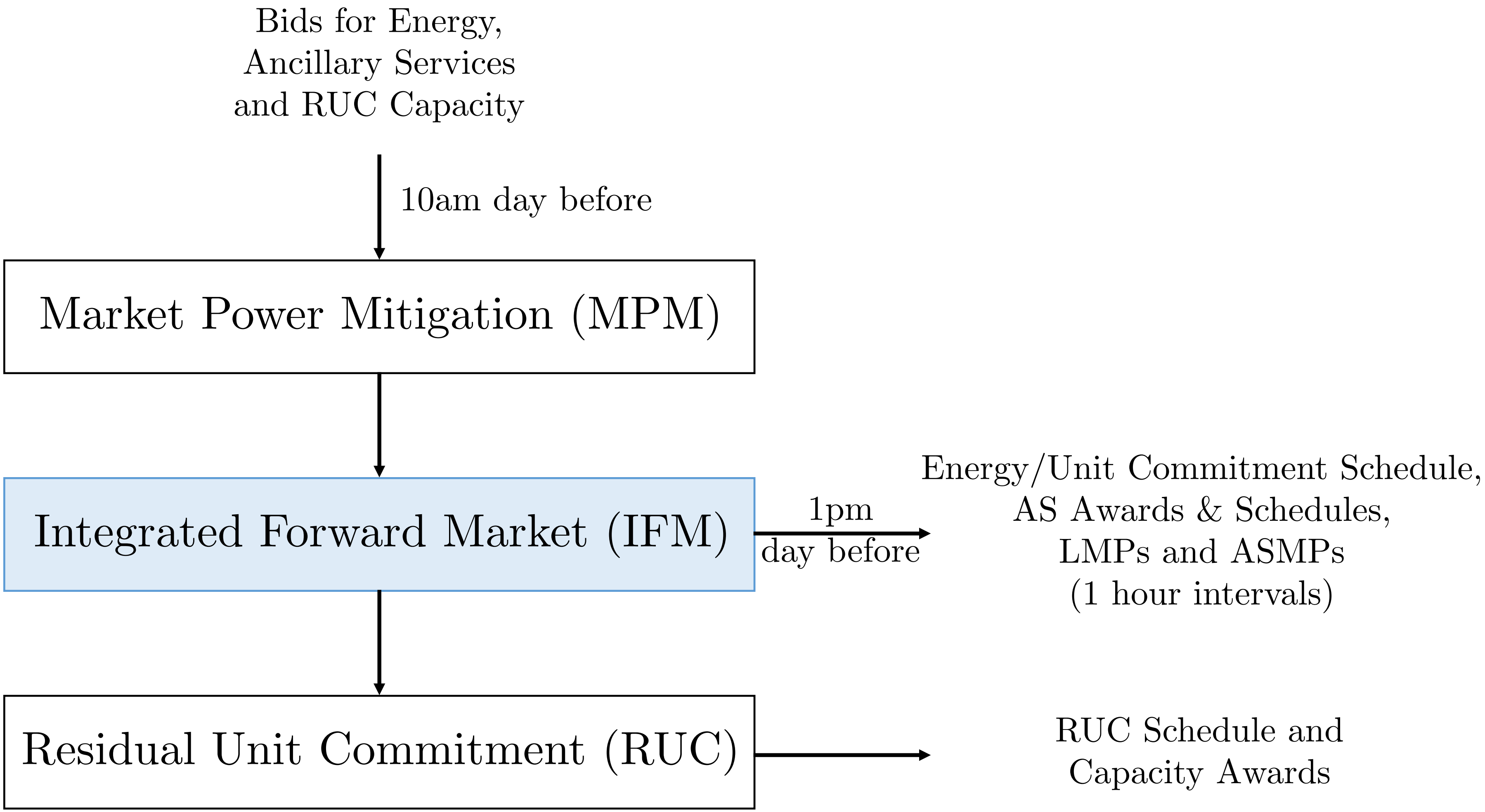
Energy

5 minute intervals

Ancillary Services:

- Regulation Up/Down
- Non-Spinning/Spinning Reserves

Day-Ahead Market Structure



Bids for Energy,
Ancillary Services
and RUC Capacity

10am day before

Market Power Mitigation (MPM)

Integrated Forward Market (IFM)

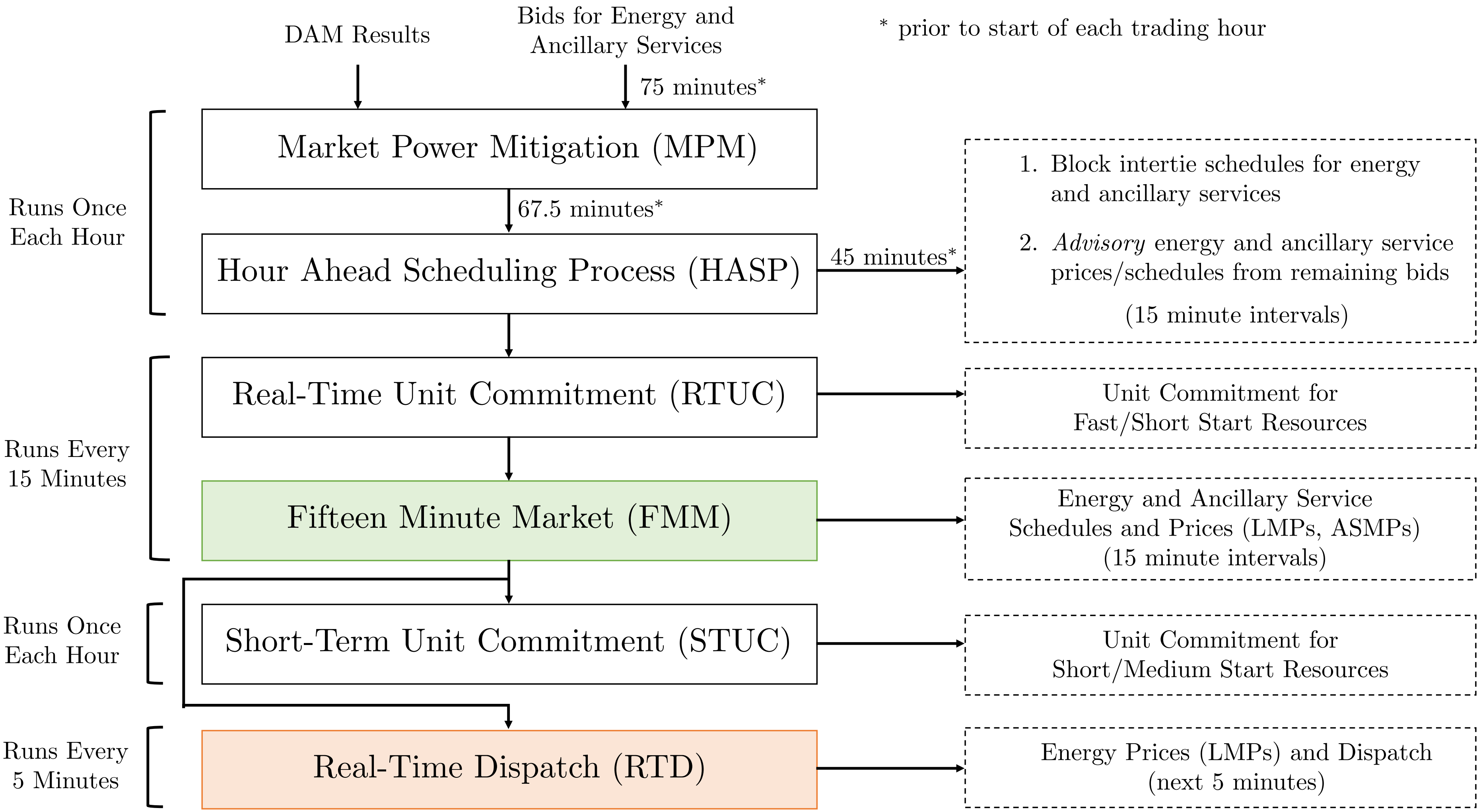
1pm
day before

Energy/Unit Commitment Schedule,
AS Awards & Schedules,
LMPs and ASMPs
(1 hour intervals)

Residual Unit Commitment (RUC)

RUC Schedule and
Capacity Awards

Real-Time Market Structure



DAM Results

Bids for Energy and Ancillary Services

75 minutes*

* prior to start of each trading hour

Runs Once Each Hour

Market Power Mitigation (MPM)

67.5 minutes*

Hour Ahead Scheduling Process (HASP)

45 minutes*

1. Block intertie schedules for energy and ancillary services
2. *Advisory* energy and ancillary service prices/schedules from remaining bids

(15 minute intervals)

Runs Every 15 Minutes

Real-Time Unit Commitment (RTUC)

Unit Commitment for Fast/Short Start Resources

Fifteen Minute Market (FMM)

Energy and Ancillary Service Schedules and Prices (LMPs, ASMPs) (15 minute intervals)

Runs Once Each Hour

Short-Term Unit Commitment (STUC)

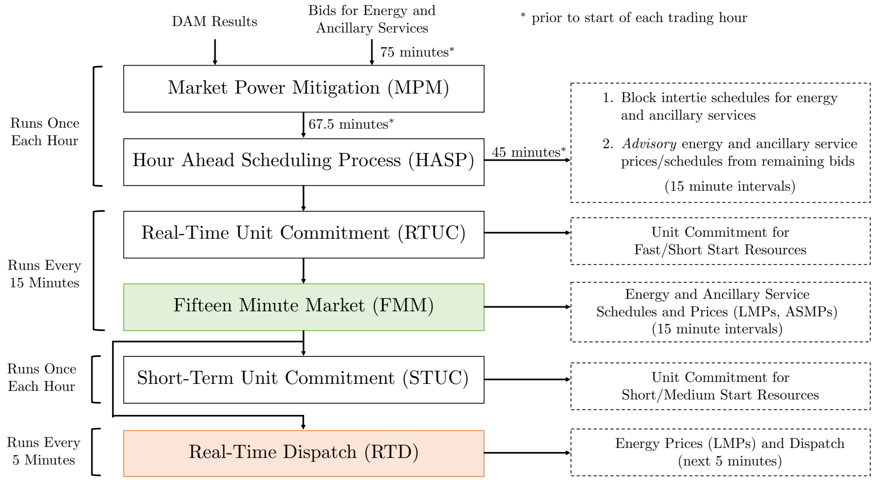
Unit Commitment for Short/Medium Start Resources

Runs Every 5 Minutes

Real-Time Dispatch (RTD)

Energy Prices (LMPs) and Dispatch (next 5 minutes)

Real-Time Market Timeline



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Unit Commitment for Short/Medium Start Resources

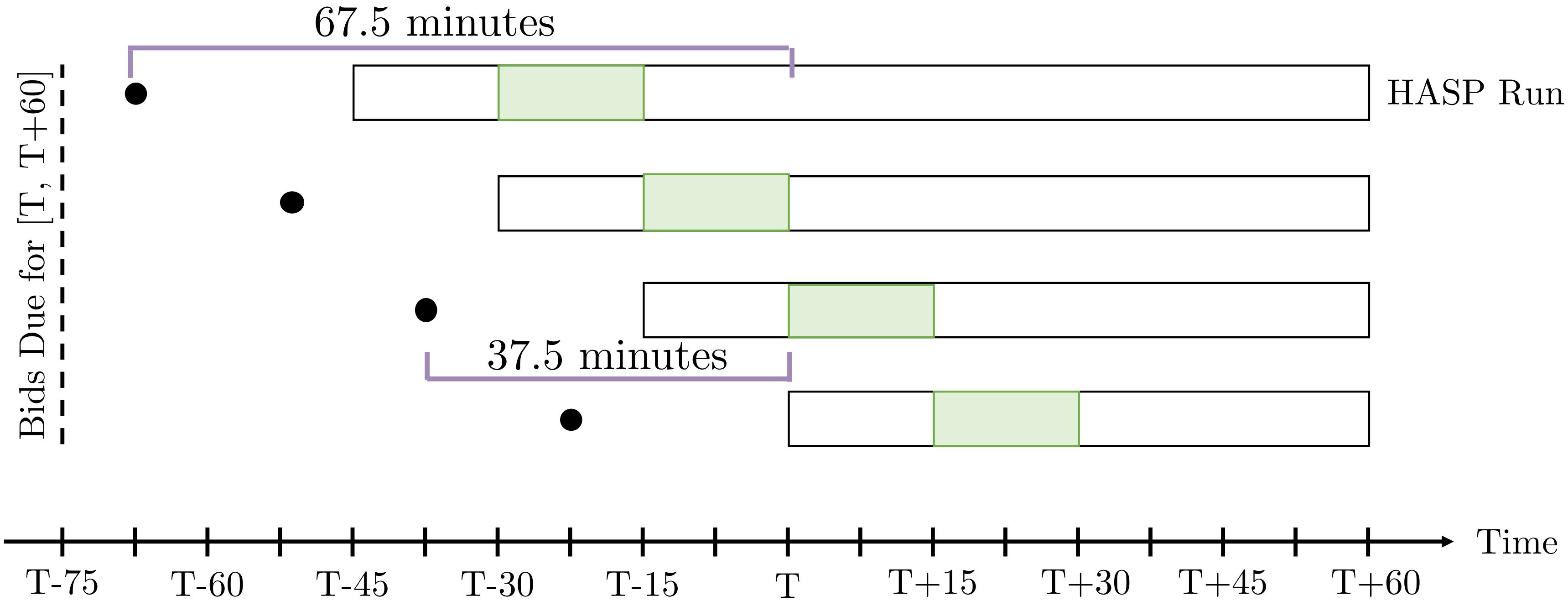
Runs Every 5 Minutes

Real-Time Dispatch (RTD)

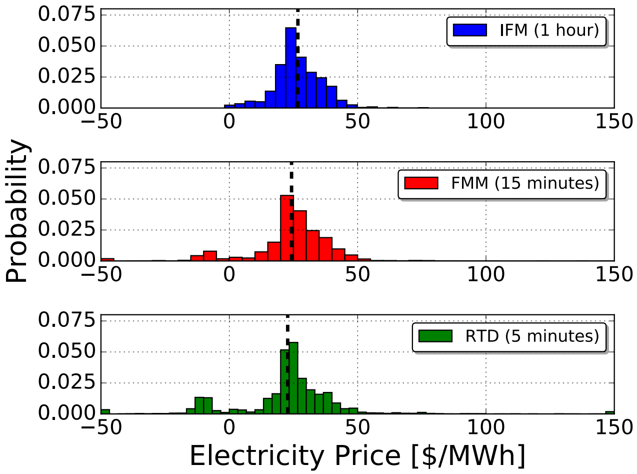
Energy Prices (LMPs) and Dispatch (next 5 minutes)

Real-Time Unit Commitment (RTUC) runs are used to clear the

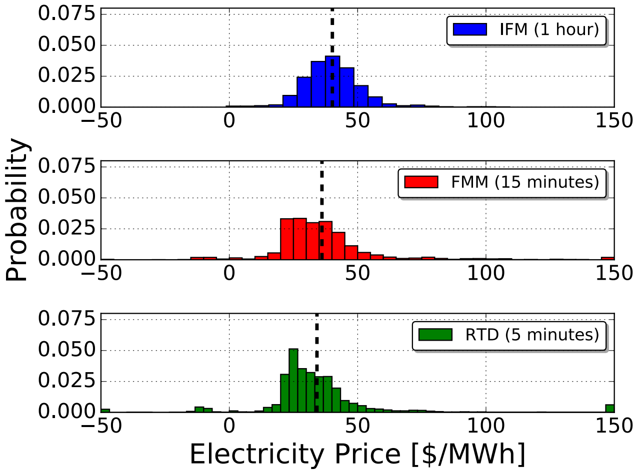
1. Fifteen Minute Market
2. Hour Ahead Scheduling Process



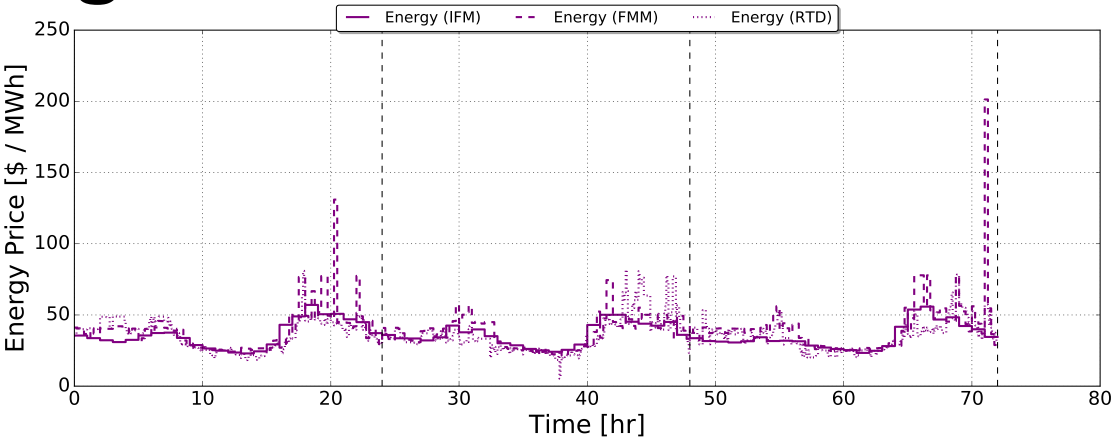
Multi-Scale Price Signals

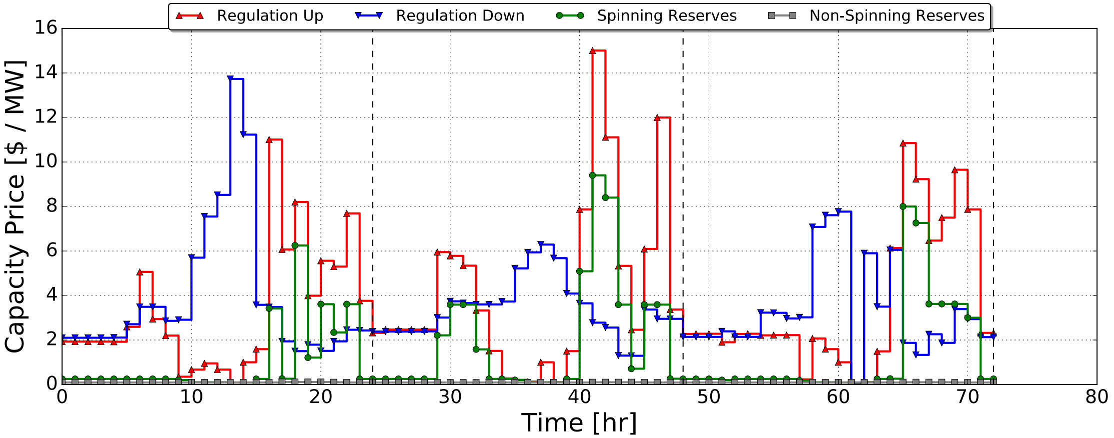


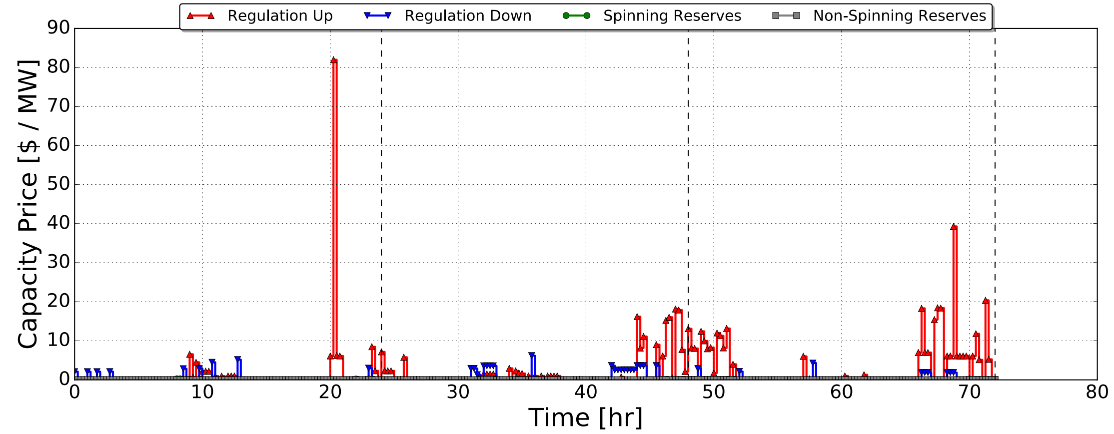
1pm to 3pm



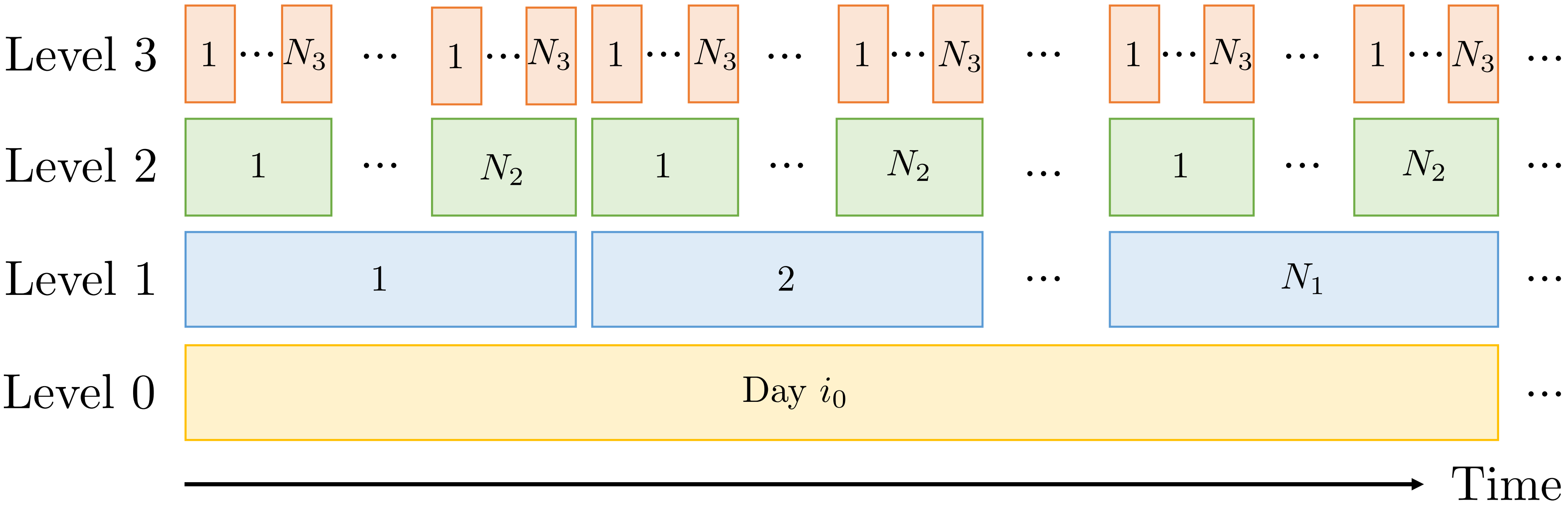
5pm to 7pm







Multi-Scale Mathematical Model



$$\mathcal{T}_\ell := \{1, ..., N_\ell\} \text{ for } \ell \in \mathcal{L} := \{3,2,1,0\}, \qquad \mathcal{M} := \{3,2,1\} \subset \mathcal{L}$$

$$\begin{aligned}
\mathcal{T}_3^* &:= \mathcal{T}_3 \times \mathcal{T}_2 \times \mathcal{T}_1 \times \mathcal{T}_0 \\
&= \{(1,1,1,1),(2,1,1,1),...,(N_3,1,1,1),(N_3,2,1,1), \\
&\quad ...,(N_3,N_2,1,1),...,(N_3,N_2,N_1,N_0)\} \\
\mathcal{T}_2^* &:= \mathcal{T}_2 \times \mathcal{T}_1 \times \mathcal{T}_0 \\
\mathcal{T}_1^* &:= \mathcal{T}_1 \times \mathcal{T}_0 \\
\mathcal{T}_0^* &= \mathcal{T}_0
\end{aligned}$$

$$\begin{aligned}
t_3^*(t) &= (i_3, i_2, i_1, i_0) \in \mathcal{T}_3^* \\
t_2^*(t) &= (i_2, i_1, i_0) \in \mathcal{T}_2^* \\
t_1^*(t) &= (i_1, i_0) \in \mathcal{T}_1^* \\
t_0^*(t) &= i_0 \in \mathcal{T}_0^*
\end{aligned}$$

Generalized Model

$$\mathcal{A} := \{s, n, r^+, r^-\}, \quad \ell \in \mathcal{M}$$

Net Energy $$0 \le \underline{E}_{t_\ell^*(t)}, \bar{E}_{t_\ell^*(t)} \le 1, \quad t_\ell^*(t) \in \mathcal{T}_\ell^*,$$

$$E_{t_3^*(t)} = \sum_{\ell \in \mathcal{M}} \left(\bar{E}_{t_\ell^*(t)} - \underline{E}_{t_\ell^*(t)} + \hat{E}_{t_\ell^*(t)} \right), \quad t_3^*(t) \in \mathcal{T}_3^*.$$

Ancillary Services

$$0 \le s_{t_\ell^*(t)}, n_{t_\ell^*(t)} \le 1, \quad \ell \in \mathcal{M}, \quad t_\ell^*(t) \in \mathcal{T}_\ell^*,$$

$$0 \le r^+_{t_\ell^*(t)} \le \rho_+^{max}, \quad \ell \in \mathcal{M}, \quad t_\ell^*(t) \in \mathcal{T}_\ell^*,$$

$$0 \le r^-_{t_\ell^*(t)} \le \rho_-^{max}, \quad \ell \in \mathcal{M}, \quad t_\ell^*(t) \in \mathcal{T}_\ell^*.$$

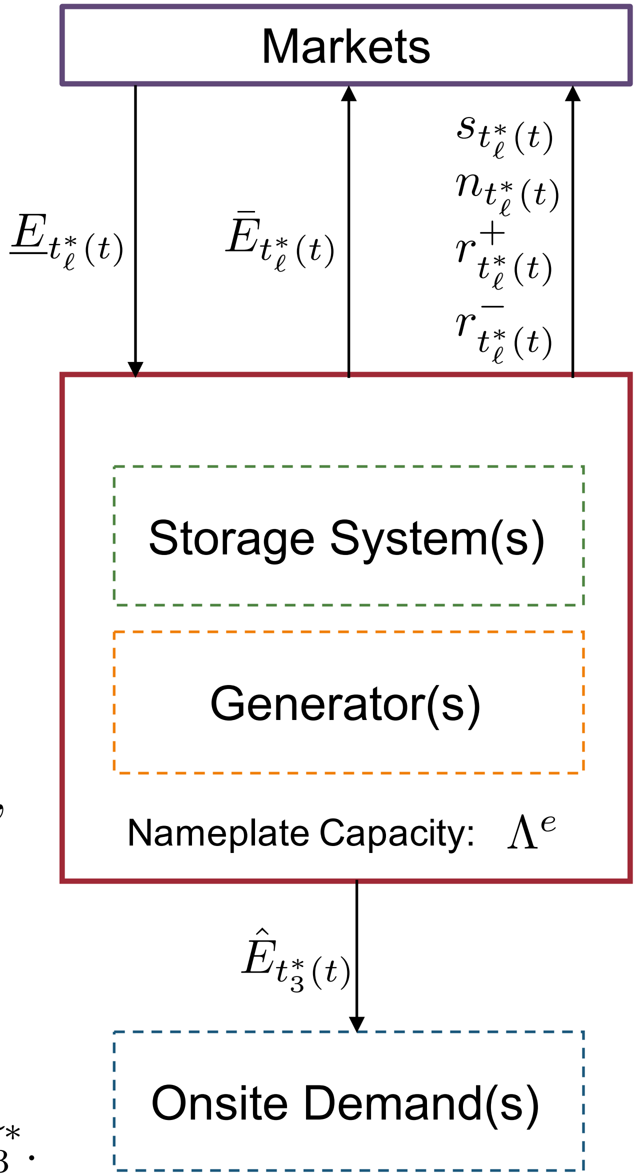
Energy and Ancillary Service Revenues

$$R_E = \Lambda^e \sum_{t \in \mathcal{T}^*} \sum_{\ell \in \mathcal{M}} \Delta t_\ell \, \pi^{energy}_{t_\ell^*(t)} \left(\bar{E}_{t_\ell^*(t)} - (1 + \epsilon) \, \underline{E}_{t_\ell^*(t)} \right),$$

$$R_{AS} = \Lambda^e \sum_{a \in \mathcal{A}} \sum_{t \in \mathcal{T}^*} \sum_{\ell \in \mathcal{M}} \left(\pi^{AS}_{a, t_\ell^*(t)} a_{t_\ell^*(t)} \right).$$

Ramping Limits

$$-\rho_{elec} \, \Delta t_3 \le E_{t_3^*(t)} - E_{t_3^*(t-1)} \le \rho_{elec} \, \Delta t_3, \quad t_3^*(t) \in \mathcal{T}_3^*.$$



Markets

$\underline{E}_{t_\ell^*(t)}$

$\bar{E}_{t_\ell^*(t)}$

$s_{t_\ell^*(t)}$
$n_{t_\ell^*(t)}$
$r^+_{t_\ell^*(t)}$
$r^-_{t_\ell^*(t)}$

Storage System(s)

Generator(s)

Nameplate Capacity: Λ^e

$\hat{E}_{t_3^*(t)}$

Onsite Demand(s)

Operating Modes for Thermal Generators (1/2)

$$y^e_{t_1^*(t)},\ y^s_{t_1^*(t)},\ y^n_{t_1^*(t)} \in \{0,1\}^{N_1\times N_0}, \quad y^e_{t_1^*(t)} + y^s_{t_1^*(t)} + y^n_{t_1^*(t)} \leq 1, \quad t_1^*(t) \in \mathcal{T}_1^*$$

Generation Mode: Regulation Capacity

$$\sum_{\ell\in\mathcal{M}} \left(r^+_{t_\ell^*(t)} + r^-_{t_\ell^*(t)} \right) \leq \rho^{max}_{reg} y^e_{t_1^*(t)}, \quad \sum_{\ell\in\mathcal{M}} \left(r^+_{t_\ell^*(t)} + s_{t_\ell^*(t)} + n_{t_\ell^*(t)} \right) \leq \rho^{max}_{reg},$$

$$E_{t_3^*(t)} + \sum_{\ell\in\mathcal{M}} \left(s_{t_\ell^*(t)} + n_{t_\ell^*(t)} + r^+_{t_\ell^*(t)} \right) \leq 1, \quad t_\ell^*(t) \in \mathcal{T}_\ell^*.$$

Generation Mode: Regulation with Onsite Demand

$$x_{t_3^*(t)} \geq 0, \quad x_{t_3^*(t)} \geq \left(\sum_{\ell\in\mathcal{M}} r^-_{t_\ell^*(t)} \right) - \theta_r \hat{E}_{t_3^*(t)}, \quad t_\ell^*(t) \in \mathcal{T}_\ell^*.$$

$$E_{t_3^*(t)} \geq \lambda y^e_{t_1^*(t)} + x_{t_3^*(t)}, \quad t_1^*(t) \in \mathcal{T}_1^*, \quad t_3^*(t) \in \mathcal{T}_3^*.$$

$$\theta_r \hat{E}_{t_3^*(t)} + \sum_{\ell\in\mathcal{M}} \bar{E}_{t_\ell^*(t)} \geq \sum_{\ell\in\mathcal{M}} r^-_{t_\ell^*(t)}, \quad t_\ell^*(t) \in \mathcal{T}_\ell^*.$$

Operating Modes for Thermal Generators (2/2)

$$y^e_{t_1^*(t)},\ y^s_{t_1^*(t)},\ y^n_{t_1^*(t)} \in \{0,1\}^{N_1\times N_0}, \quad y^e_{t_1^*(t)} + y^s_{t_1^*(t)} + y^n_{t_1^*(t)} \le 1, \quad t_1^*(t) \in \mathcal{T}_1^*$$

Ramp Rate Relaxation for Start-up/Shutdown

$$I_1(t_3^*(t)) \in \mathcal{T}_1,$$

$$z_{t_3^*(t)} = \rho_{elec}\Delta t_3 + \max(|I_1(t_3^*(t)) - I_1(t_3^*(t-1))|, 1)(1-\rho_{elec}\Delta t_3)(2 - y_{t_1^*(t)} - y_{t_1^*(t-1)}),$$

$$-z_{t_3^*(t)} \le E_{t_3^*(t)} - E_{t_3^*(t-1)} \le z_{t_3^*(t)}, \quad t_3^*(t) \in \mathcal{T}_3^*.$$

Spinning Reserves

$$\sum_{\ell\in\mathcal{M}} s_{t_\ell^*(t)} \le y^e_{t_1^*(t)} + y^s_{t_1^*(t)}, \quad t_\ell^*(t) \in \mathcal{T}_\ell^*.$$

Non-Spinning Reserves

$$\sum_{\ell\in\mathcal{M}} n_{t_\ell^*(t)} \le y^e_{t_1^*(t)} + y^s_{t_1^*(t)} + y^n_{t_1^*(t)}, \quad t_\ell^*(t) \in \mathcal{T}_\ell^*.$$

Other Energy Systems

$$\sum_{\ell\in\mathcal{M}}\left(r^{+}_{t^*_\ell(t)} + r^{-}_{t^*_\ell(t)}\right) \leq \rho^{max}_{reg}, \quad \sum_{\ell\in\mathcal{M}}\left(r^{+}_{t^*_\ell(t)} + s_{t^*_\ell(t)} + n_{t^*_\ell(t)}\right) \leq \rho^{max}_{reg},$$

$$y^e = 1,$$
$$\lambda = -1$$

→

$$E_{t^*_3(t)} + \sum_{\ell\in\mathcal{M}}\left(r^{+}_{t^*_\ell(t)} + s_{t^*_\ell(t)} + n_{t^*_\ell(t)}\right) \leq 1, \quad t^*_\ell(t) \in \mathcal{T}^*_\ell.$$

$$-1 + x_{t^*_3(t)} \leq E_{t^*_3(t)}, \quad t^*_3(t) \in \mathcal{T}^*_3,$$

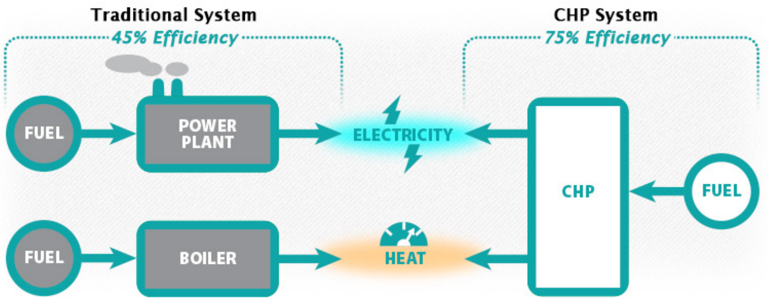
$$x_{t^*_3(t)} \geq 0, \quad x_{t^*_3(t)} \geq \left(\sum_{\ell\in\mathcal{M}} r^{-}_{t^*_\ell(t)}\right) - \theta_r \hat{E}_{t^*_3(t)}, \quad t^*_\ell(t) \in \mathcal{T}^*_\ell.$$

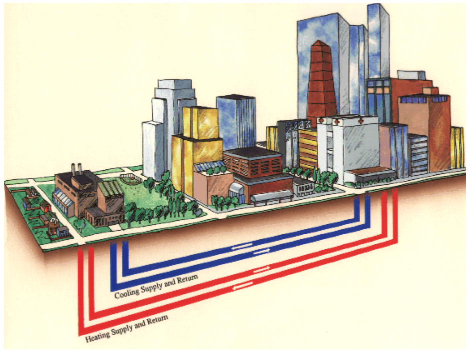
Virtual Bidding

$$\bar{E}_{t^*_1(t)} = \underline{E}_{t^*_2(t)}, \quad \underline{E}_{t^*_1(t)} = \bar{E}_{t^*_2(t)}, \quad \bar{E}_{t^*_3(t)} = \underline{E}_{t^*_3(t)} = 0,$$
$$t^*_1(t) \in \mathcal{T}^*_1, \quad t^*_2(t) \in \mathcal{T}^*_2, \quad t^*_3(t) \in \mathcal{T}^*_3.$$

Combined Heat and Power Utility System

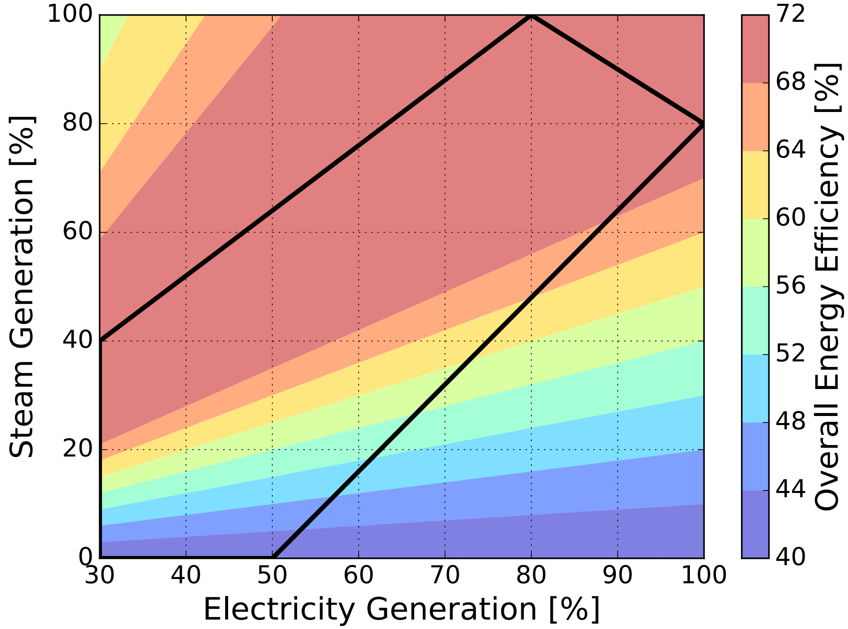
Applications: District Heating, Manufacturing Facilities, etc.

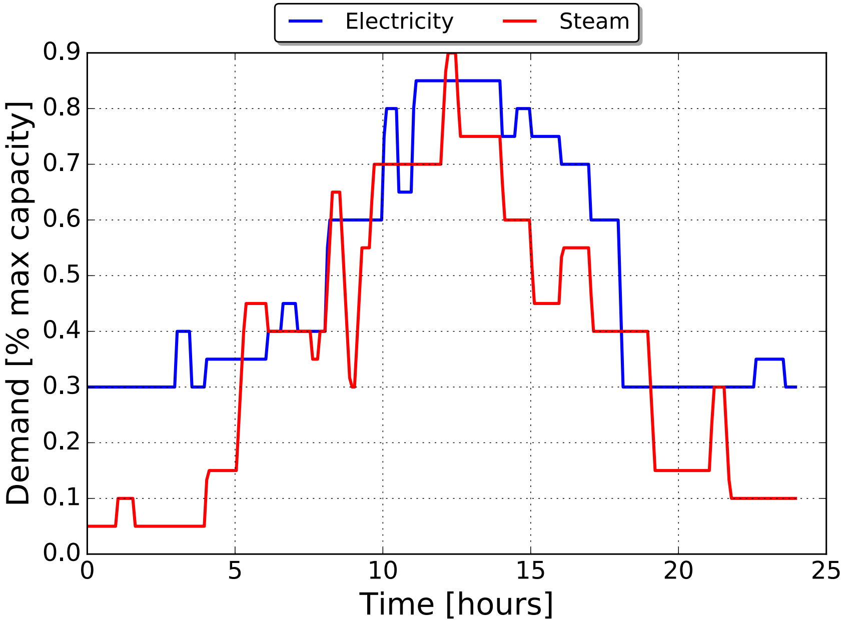




What are the ***economic incentives*** *for CHP systems to participate in electricity markets?*

Are there sufficient incentives to increase the ***flexibility of the coupled process(es)****?*





Mathematical Model (1/2)

$$\mathcal{A} := \{s, n, r^+, r^-\}, \quad \ell \in \mathcal{M}$$

$$0 \leq f_{t_3^*(t)}, \quad 0 \leq \hat{s}_{t_3^*(t)} \leq 1, \quad 0 \leq \hat{E}_{t_3^*(t)} \leq 1, \quad t_3^*(t) \in \mathcal{T}_3^*.$$

Fuel Consumption (Efficiency)

$$f_{t_3^*(t)} \geq \frac{\Lambda^s \hat{s}_{t_3^*(t)} + \Lambda^e E_{t_3^*(t)}}{\eta^{total}}, \quad t_3^*(t) \in \mathcal{T}_3^*.$$

$$f_{t_3^*(t)} \geq \frac{\Lambda^s \hat{s}_{t_3^*(t)}}{\eta^{steam}}, \quad t_3^*(t) \in \mathcal{T}_3^*.$$

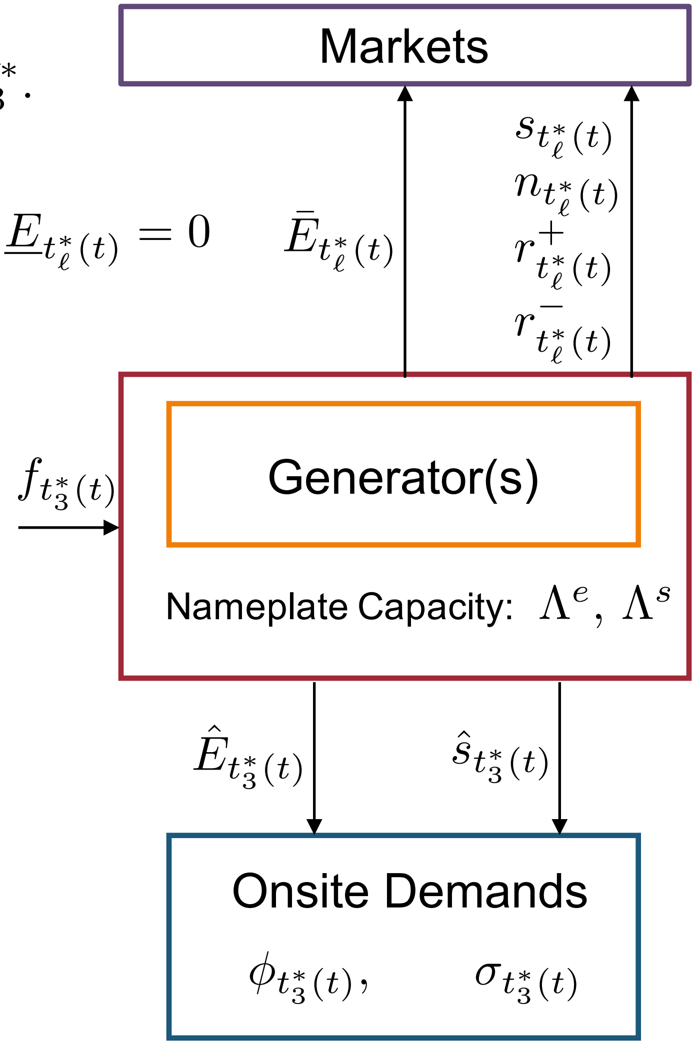
$$f_{t_3^*(t)} \geq \frac{\Lambda^e E_{t_3^*(t)}}{\eta^{elec}}, \quad t_3^*(t) \in \mathcal{T}_3^*.$$

Operating Region

$$\vec{a}\ \hat{s}_{t_3^*(t)} + \vec{b}\ E_{t_3^*(t)} \geq \vec{c}, \quad t_3^*(t) \in \mathcal{T}_3^*.$$

Fuel Cost

$$C_{fuel} = \pi^{fuel}\ \Delta t_3 \sum_{t \in \mathcal{T}^*} f_{t_3^*(t)}.$$



Mathematical Model (2/2)

$\mathcal{A} := \{s, n, r^+, r^-\}, \quad \ell \in \mathcal{M}$

$$0 \le f_{t_3^*(t)}, \quad 0 \le \hat{s}_{t_3^*(t)} \le 1, \quad 0 \le \hat{E}_{t_3^*(t)} \le 1, \quad t_3^*(t) \in \mathcal{T}_3^*.$$

Steam Ramp Rate

$$-\Delta t_3 \ \rho_{steam} \le \hat{s}_{t_3^*(t)} - \hat{s}_{t_3^*(t-1)} \le \Delta t_3 \ \rho_{steam}, \quad t_3^*(t) \in \mathcal{T}_3^*.$$

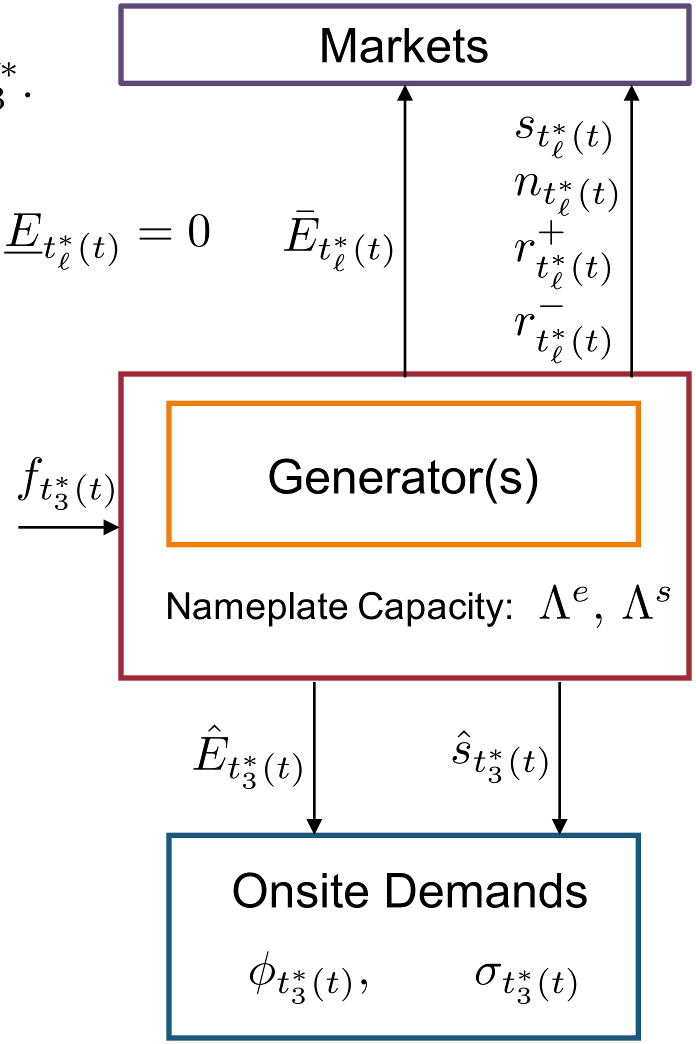
Onsite Demand Flexibility

$$\phi_{t_3^*(t)}(1-\theta_e) \le \hat{E}_{t_3^*(t)} \le \phi_{t_3^*(t)}(1+\theta_e), \quad t_3^*(t) \in \mathcal{T}_3^*,$$

$$\sigma_{t_3^*(t)}(1-\theta_s) \le \hat{s}_{t_3^*(t)} \le \sigma_{t_3^*(t)}(1+\theta_s), \quad t_3^*(t) \in \mathcal{T}_3^*.$$

$$\sum_{t \in \mathcal{T}:\ t_0^*(t) = i_0} \left(\hat{E}_{t_3^*(t)} - \phi_{t_3^*(t)}\right) = 0, \quad i_0 \in \mathcal{T}_0^*,$$

$$\sum_{t \in \mathcal{T}:\ t_0^*(t) = i_0} \left(\hat{s}_{t_3^*(t)} - \sigma_{t_3^*(t)}\right) = 0, \quad i_0 \in \mathcal{T}_0^*.$$



Markets

$s_{t_\ell^*(t)}$

$n_{t_\ell^*(t)}$

$r^+_{t_\ell^*(t)}$

$r^-_{t_\ell^*(t)}$

$\underline{E}_{t_\ell^*(t)} = 0$

$\bar{E}_{t_\ell^*(t)}$

$f_{t_3^*(t)}$

Generator(s)

Nameplate Capacity: $\Lambda^e, \ \Lambda^s$

$\hat{E}_{t_3^*(t)}$

$\hat{s}_{t_3^*(t)}$

Onsite Demands

$\phi_{t_3^*(t)}, \quad \sigma_{t_3^*(t)}$

Problem Formulation

Minimize (Fuel Cost – Market Revenue)

s.t. Electricity Market Model
Utility System Model

Input Parameters

$$\Lambda^e = 1 \text{ MW}_\text{e},$$
$$\Lambda^s = 1 \text{ MW}_\text{t},$$
$$\rho_{elec} = 180 \text{ \%/hour},$$
$$\rho_{steam} = 100 \text{ \%/hour},$$
$$\eta^{total} = 70\%,$$
$$\eta^{steam} = 45\%,$$
$$\eta^{elec} = 40\%,$$
$$\theta_s = \theta_e = \theta_r = 0,$$
$$\phi_{t_3^*(t)},\ \sigma_{t_3^*(t)},$$
$$\pi^{fuel} = 4.0 \text{ \$/MBtu},$$

$$\pi^{energy}_{t_\ell^*(t)},\ \pi^{AS}_{a,t_\ell^*(t)}.$$

Real price data for 2015

Assumptions

Price-taker, perfect information

Always on, $y^e_{t_1^*(t)} = 1 \quad \forall t \in \mathcal{T}$

Manipulated Variables

$$\underline{E}_{t_\ell^*(t)},\ \bar{E}_{t_\ell^*(t)},\ E_{t_3^*(t)},\ s_{t_\ell^*(t)},\ n_{t_\ell^*(t)},\ r^+_{t_\ell^*(t)},\ r^-_{t_\ell^*(t)}$$
$$f_{t_3^*(t)},\ \hat{s}_{t_3^*(t)},\ \hat{E}_{t_3^*(t)}$$

Problem Size

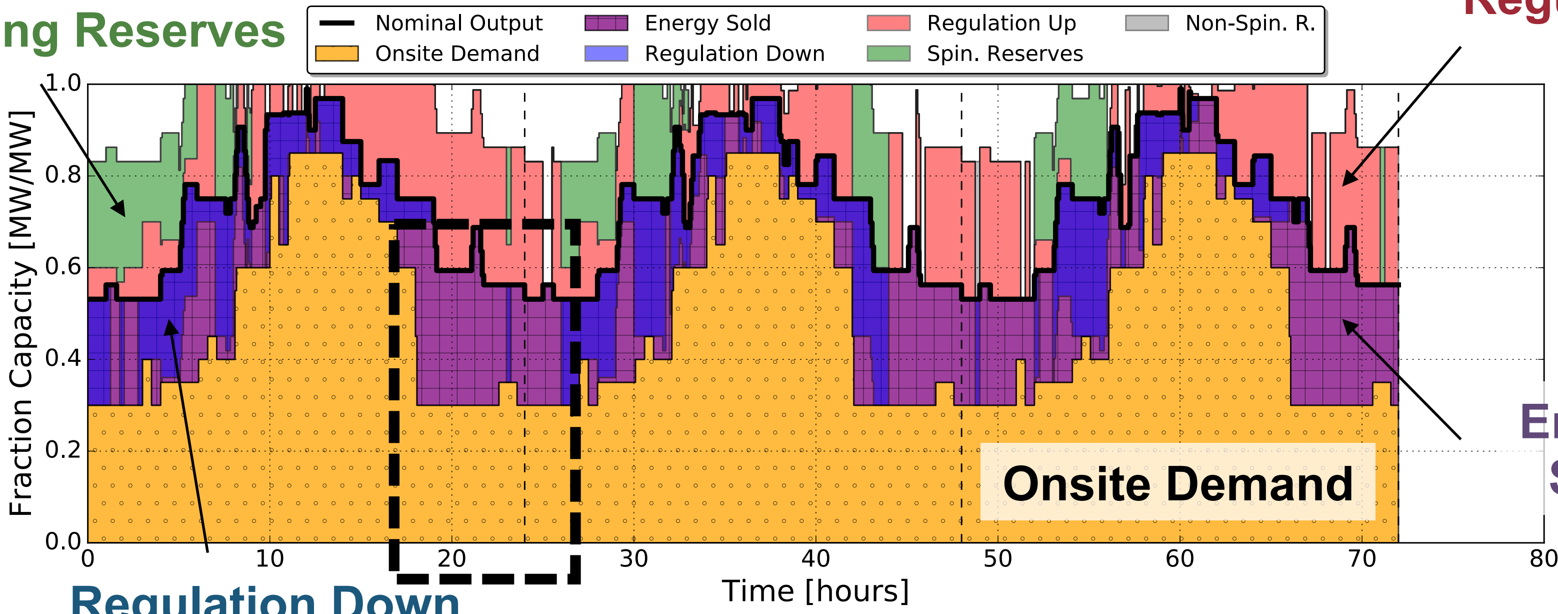
$N_0 = 365$ days, $\Delta t_3 = 5$ minutes

1.7 to 2.0 million linear constraints

0.6 to 1.0 million continuous variables

Gurobi CPU time: 5 to 31 seconds

Results: Operating Profiles

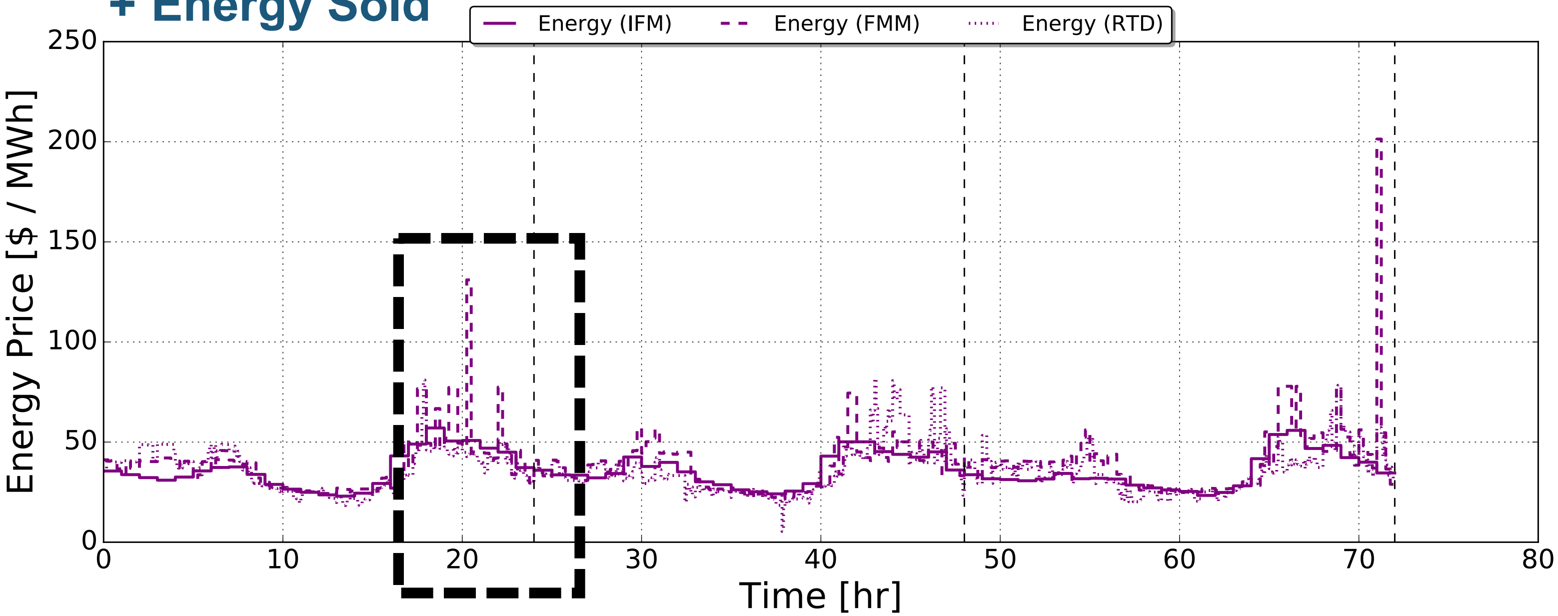


Spinning Reserves

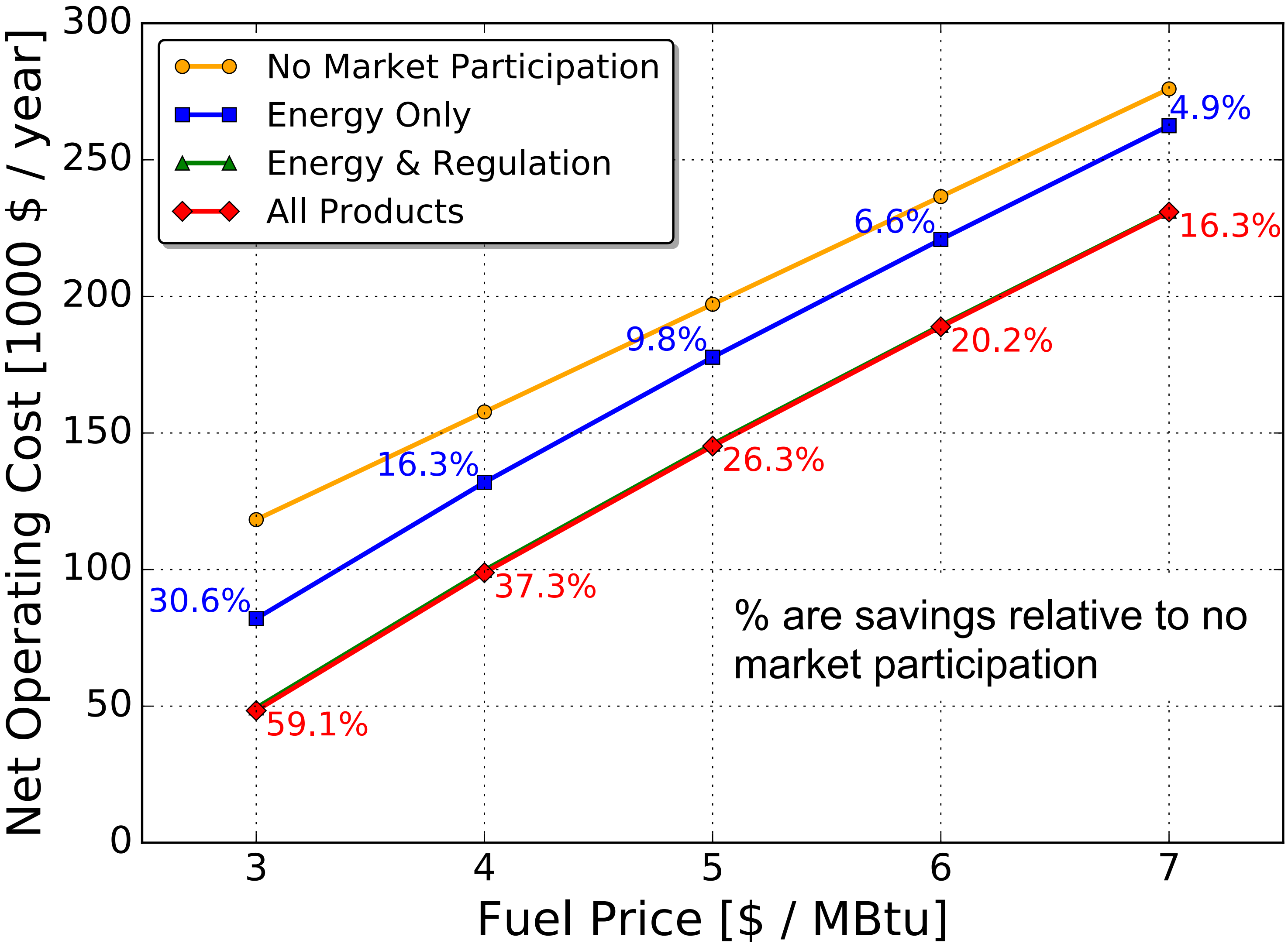
Regulation Up

Energy Sold

Regulation Down + Energy Sold

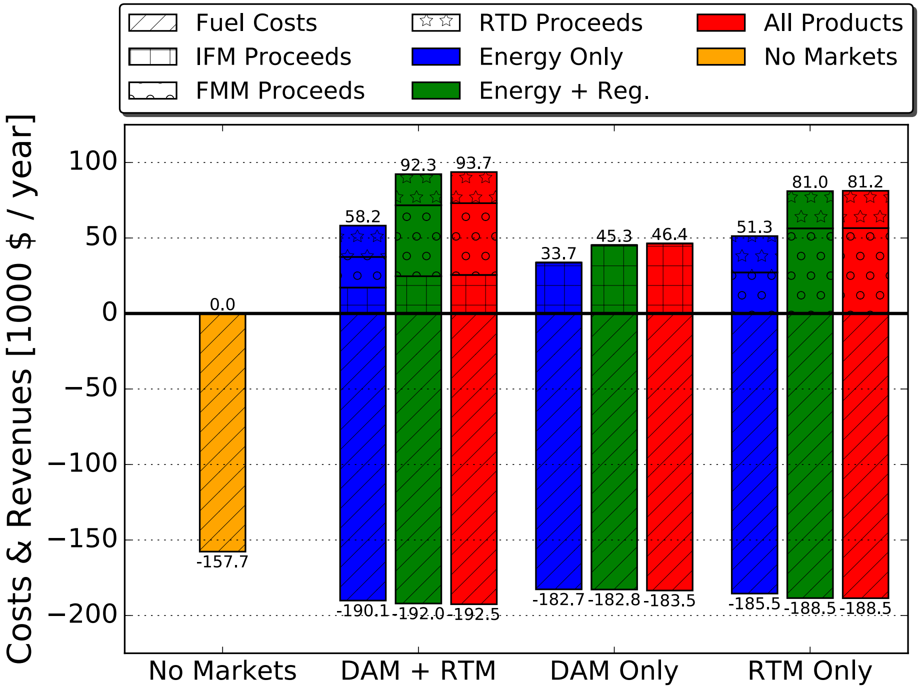


Fuel Price Sensitivity



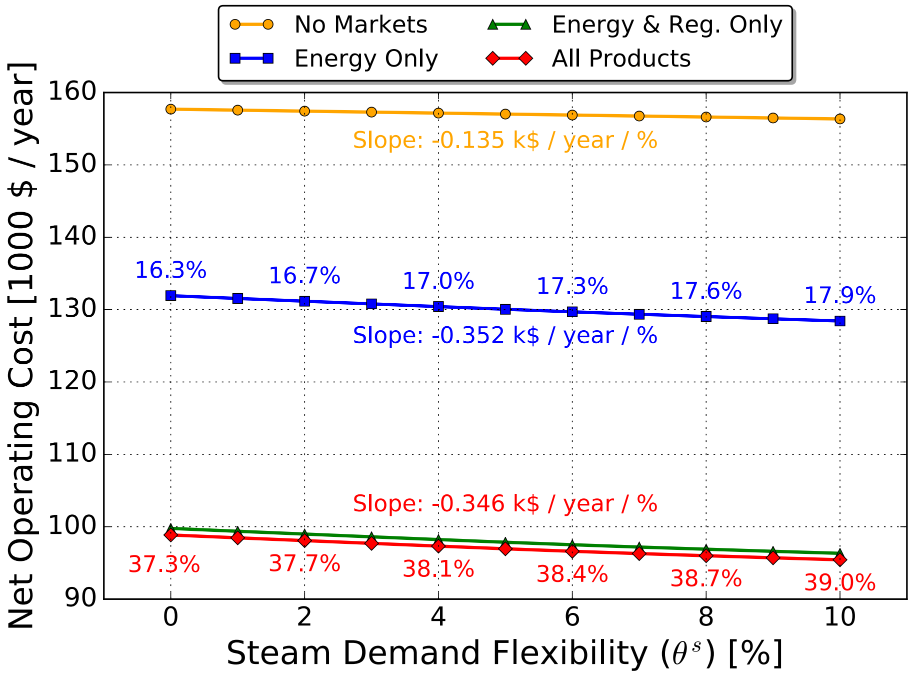
% are savings relative to no market participation

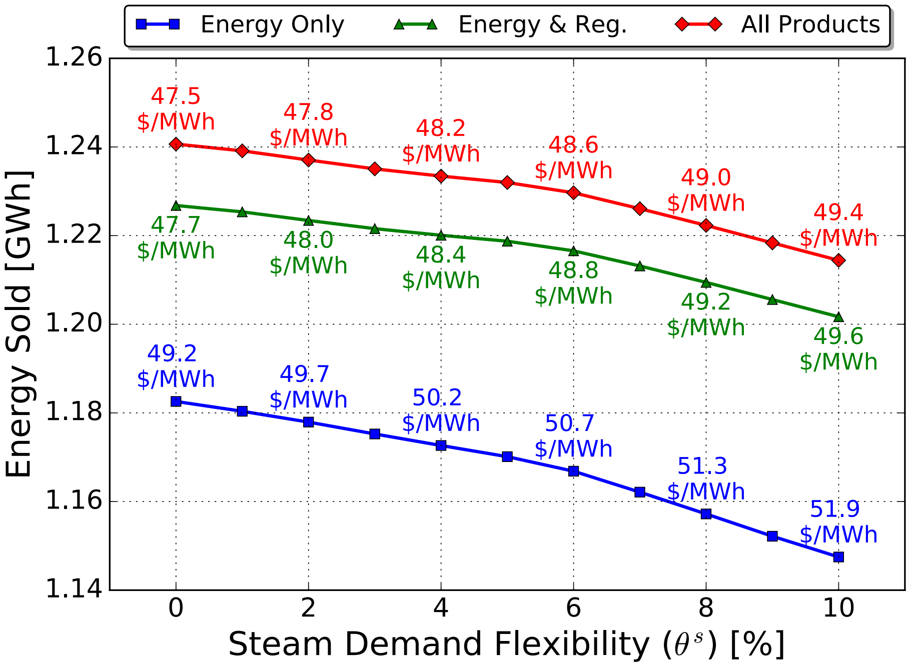
Net Savings from Different Markets



	DAM + RTM	DAM only	RTM only
Energy only	25.8 k$/year 100%	8.7 k$/year 34 %	23.5 k$/year 91%
Energy & Regulation	57.9 k$/year 100%	20.2 k$/year 35 %	50.6 k$/year 87%
All Products	58.8 k$/year 100%	20.7 k$/year 35%	50.4 k$/year 86%

Onsite Steam Demand Flexibility

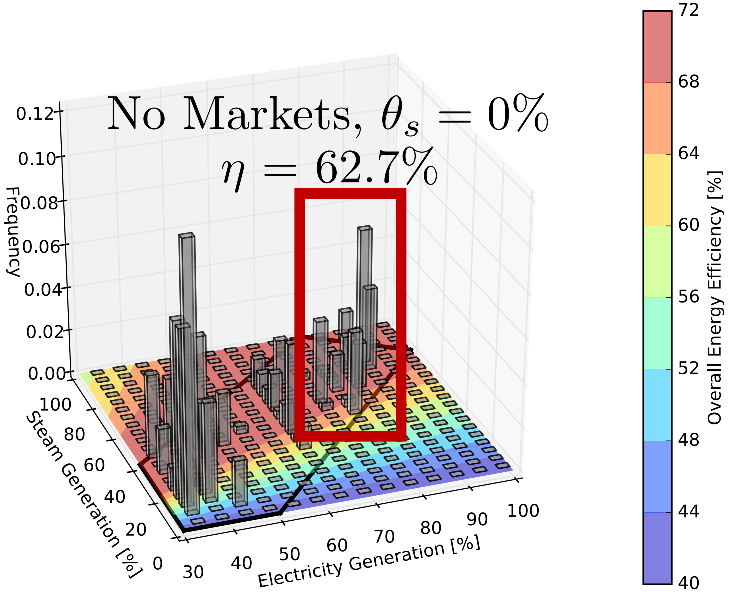


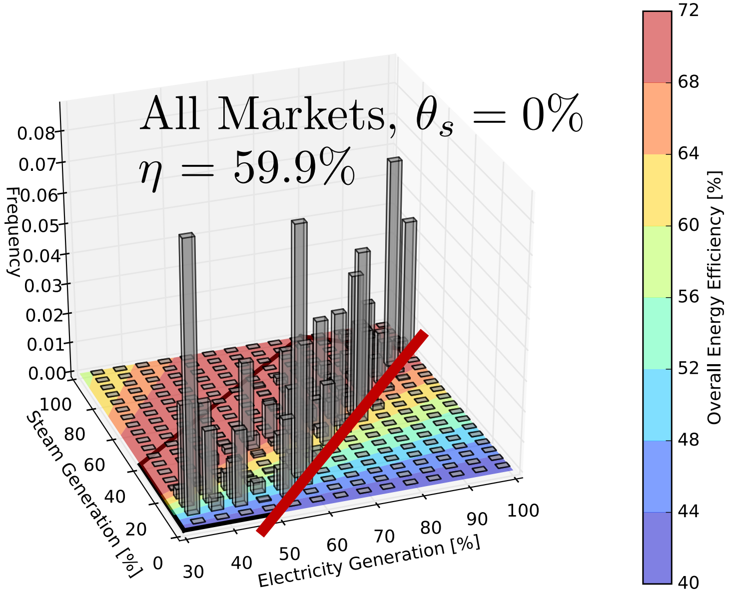


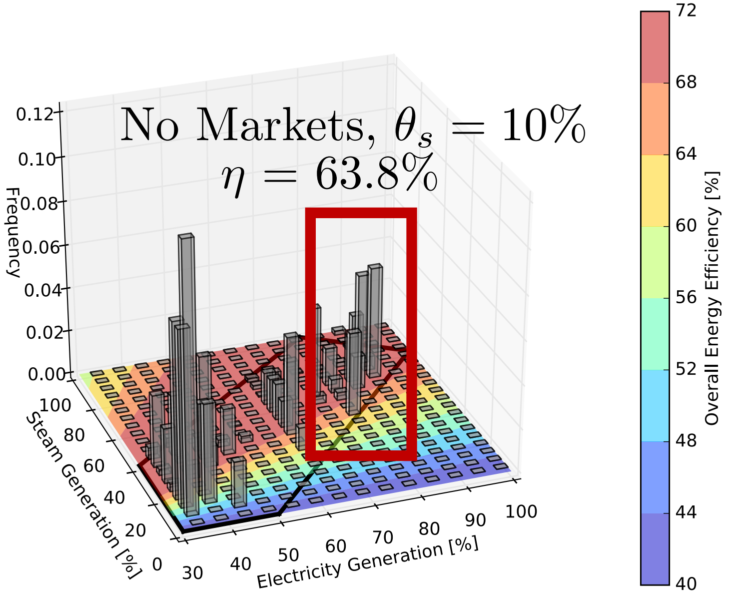
Average Overall Energy Efficiency

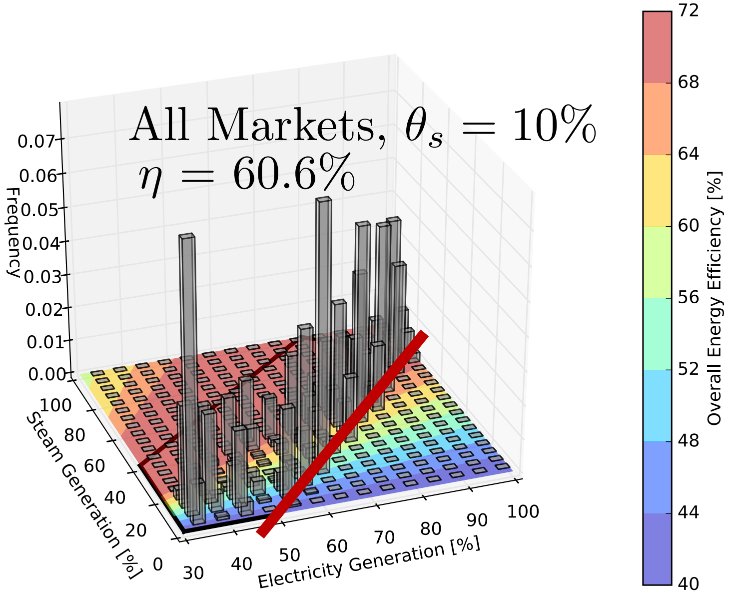
Market Participation	$\theta_s = 0\%$	$\theta_s = 10\%$
None	62.7%	63.4%
Energy only	60.1%	60.8%
Energy & Regulation	59.9%	60.6%
All Products	59.9%	60.6%

Operation and Efficiency Trends

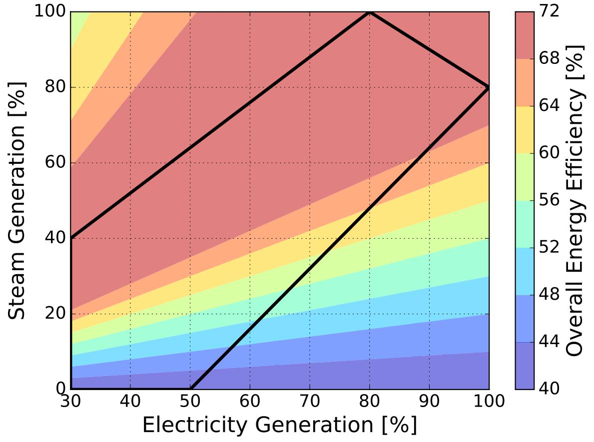






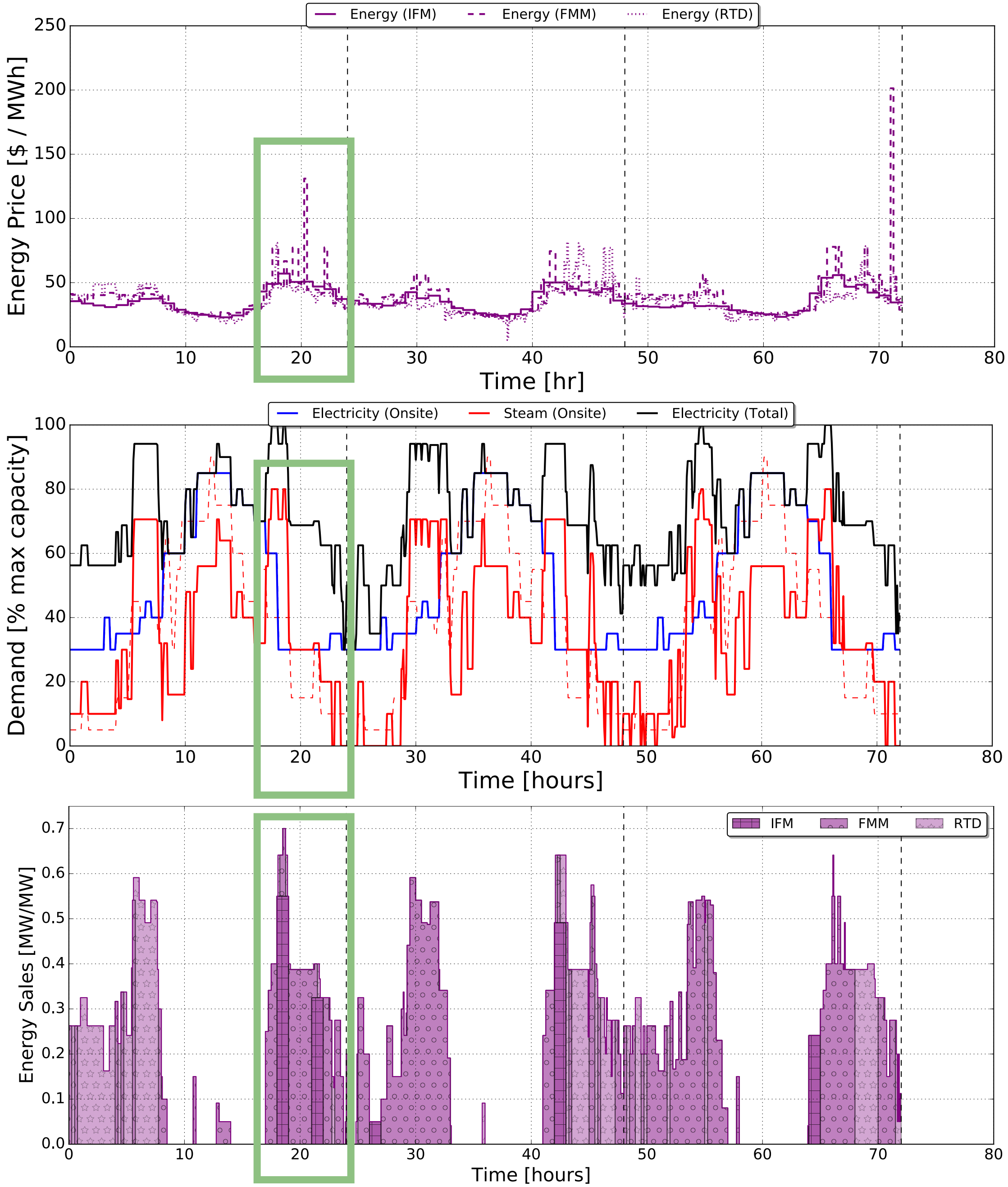


Full Steam Demand Flexibility $(\theta_s = 100\%)$

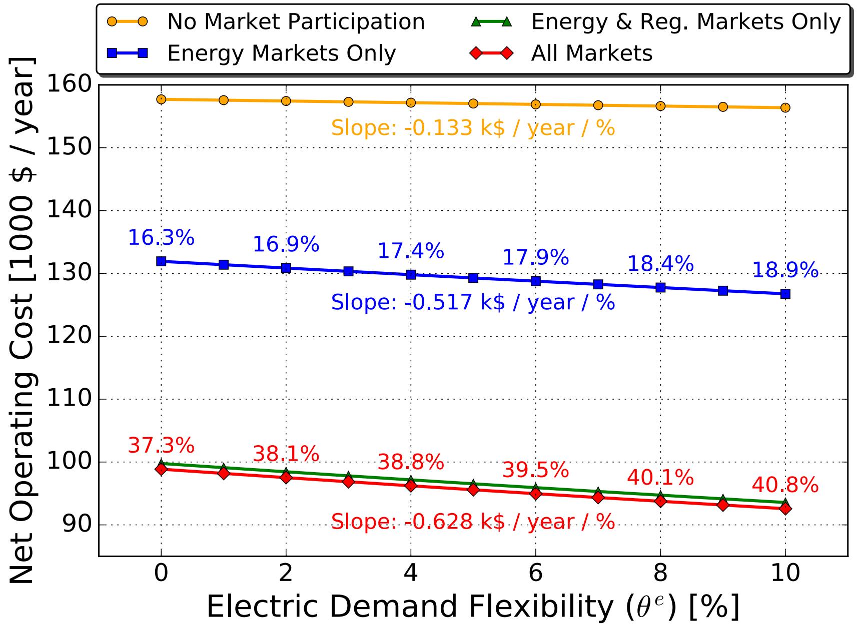


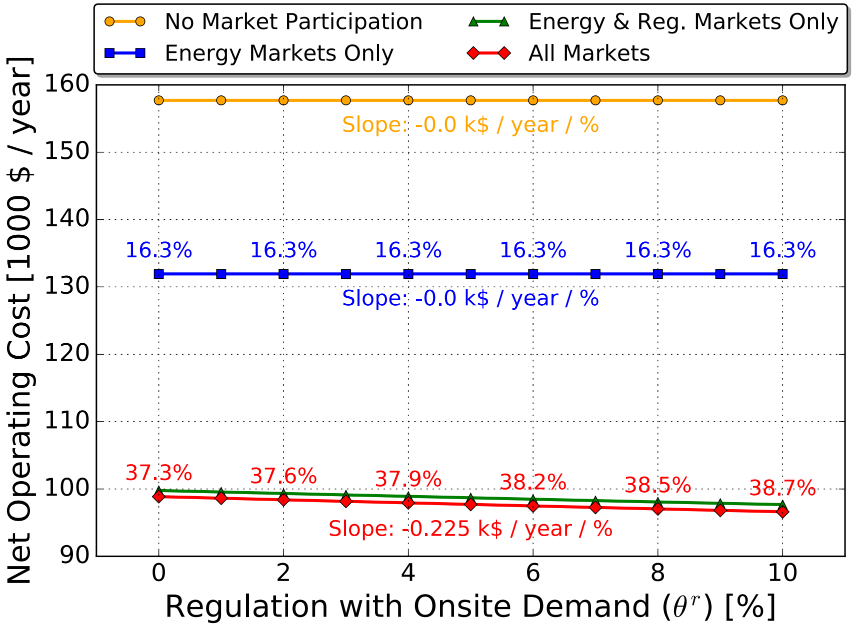
High Energy Prices:
- Elevated Steam Delivery
- High Energy Sales

Low Energy Prices:
- Depressed Steam Delivery
- Low/No Energy Sales



Onsite Electrical Demand Flexibility





Value of Flexibility
[k$ / year / %]

	No Markets	All Markets
θ_s	-0.135	-0.346
θ_e	-0.133	-0.628
θ_r	0	-0.225

Market participation increases value of flexibility by factor of 2.6 to 4.7

Case Study Conclusions

Market participation reduces net operating costs by

- 31 to 59% (3 $/MBtu fuel)
- 5 to 16% (7 $/MBtu fuel)

Participation in both DAM and RTM yields highest net operating cost savings

- Only 35% of potential savings with DAM-only operation
- 86% - 91% of potential savings with RTM-only operation

Onsite demand flexibility is 2.6 to 4.7 times more valuable with market participation

2015 market price signals offered substantial incentives for flexible CHP systems with excess capacity

Battery Energy Storage System

Storage Energy Balance and Limits

$$S_{t_3^*(t)} = S_{t_3^*(t-1)} + \eta^+ \Delta t_3 \left(\sum_{\ell\in\mathcal{M}} \underline{E}_{t_\ell^*(t)} \right) - \frac{\Delta t_3}{\eta^-}\left(\hat{E}_{t_3^*(t)} + \sum_{\ell\in\mathcal{M}} \bar{E}_{t_\ell^*(t)} \right), \quad t_\ell^*(t) \in \mathcal{T}_\ell^*$$

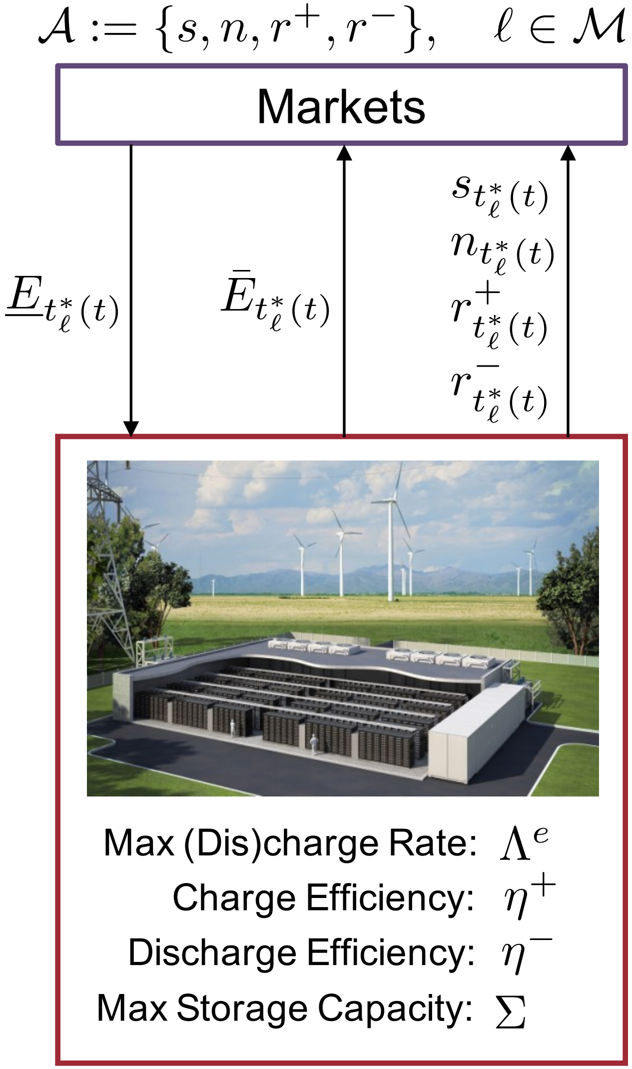
$$0 \leq S_{t_3^*(t)} \leq \Sigma, \quad t_3^*(t) \in \mathcal{T}_3^*,$$

$$S_0 = S_{N_3,N_2,N_1,i_0}, \quad i_0 \in \mathcal{T}_1.$$

Worst Case Regulation Dispatch

$$S_{t_3^*(t)} + \eta^+ \Delta t_3 \sum_{\ell\in\mathcal{M}} r^-_{t_\ell^*(t)} \leq \Sigma, \quad t_3^*(t) \in \mathcal{T}_3^*,$$

$$S_{t_3^*(t)} - \frac{\Delta t_3}{\eta^-} \sum_{\ell\in\mathcal{M}} r^+_{t_\ell^*(t)} \geq 0, \quad t_3^*(t) \in \mathcal{T}_3^*.$$



$\mathcal{A} := \{s, n, r^+, r^-\}, \quad \ell \in \mathcal{M}$

Markets

$\underline{E}_{t_\ell^*(t)}$

$\bar{E}_{t_\ell^*(t)}$

$s_{t_\ell^*(t)}$

$n_{t_\ell^*(t)}$

$r^+_{t_\ell^*(t)}$

$r^-_{t_\ell^*(t)}$

Max (Dis)charge Rate: Λ^e

Charge Efficiency: η^+

Discharge Efficiency: η^-

Max Storage Capacity: Σ

Problem Formulation

Maximize Net Market Revenue

s.t. Electricity Market Model

Battery Model

Input Parameters

$$\epsilon = 10^{-6},$$

$$\Lambda^e = 1 \text{ MW}_\text{e},$$

$$\Sigma = 1 \text{ MW}_\text{e}\text{h},$$

$$\rho_{elec} = 50 \text{ \%/minute},$$

$$\theta_r = 0,$$

$$\eta^+ = 95\%,$$

$$\eta^- = 95\%,$$

$$\pi^{energy}_{t_\ell^*(t)}, \; \pi^{AS}_{a,t_\ell^*(t)}.$$

Real price data for 2015

Assumptions

Price-taker, perfect information

Always on, $y^e_{t_1^*(t)} = 1 \quad \forall t \in \mathcal{T}$

Manipulated Variables

$$\underline{E}_{t_\ell^*(t)}, \; \bar{E}_{t_\ell^*(t)}, \; E_{t_3^*(t)}, \; s_{t_\ell^*(t)}, \; n_{t_\ell^*(t)}, \; r^+_{t_\ell^*(t)}, \; r^-_{t_\ell^*(t)}$$

$$S_{t_3^*(t)}, \; S_0$$

Problem Size

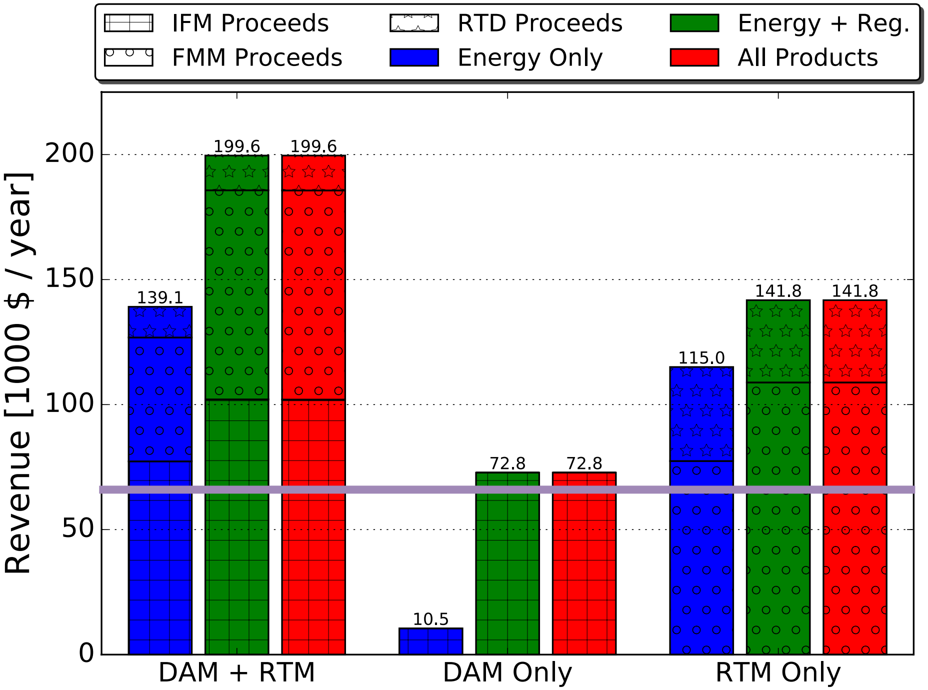
$N_0 = 365$ days, $\Delta t_3 = 5$ minutes

0.6 to 1.1 million linear constraints

0.2 to 0.7 million continuous variables

Gurobi CPU time: 7 to 53 seconds

Revenues by Market Participation



Virtual Bidding

	DAM + RTM	DAM only	RTM only
Energy only	139.1 k$/year 100%	10.5 k$/year 8 %	115.0 k$/year 83%
Energy & Regulation	199.6 k$/year 100%	72.8 k$/year 36 %	141.8 k$/year 71%
All Products	199.6 k$/year 100%	72.8 k$/year 36%	141.8 k$/year 71%
Virtual Bidding		67.1 k$/year	

Net Energy Transactions and Average Prices

Observations:

- Energy is purchased at faster timescales, sold at slower timescales
- Largest average price difference (sale vs. purchase) at fastest timescales

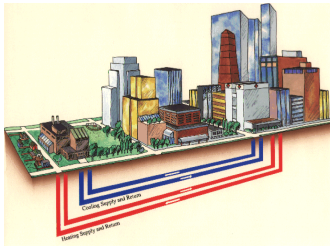
	Integrated Forward Market		Fifteen Minute Market		Real Time Dispatch	
	Sold	Purchased	Sold	Purchased	Sold	Purchased
Energy only						
DAM + RTM	3.16 GWh 34.3 $/MWh	1.17 GWh 26.6 $/MWh	1.94 GWh 44.3 $/MWh	1.80 GWh 20.3 $/MWh	1.22 GWh 71.9 $/MWh	4.03 GWh 18.7 $/MWh
DAM only	0.62 GWh 41.5 $/MWh	0.69 GWh 22.3 $/MWh	– –	– –	– –	– –
RTM only	– –	– –	2.74 GWh 38.2 $/MWh	1.43 GWh 19.0 $/MWh	1.45 GWh 63.2 $/MWh	3.22 GWh 16.9 $/MWh
All Products						
DAM + RTM	2.86 GWh 33.5 $/MWh	1.18 GWh 27.2 $/MWh	1.81 GWh 38.9 $/MWh	1.66 GWh 21.1 $/MWh	1.27 GWh 67.1 $/MWh	3.75 GWh 19.1 $/MWh
DAM only	0.55 GWh 39.0 $/MWh	0.61 GWh 24.5 $/MWh	– –	– –	– –	– –
RTM only	– –	– –	2.64 GWh 34.3 $/MWh	1.47 GWh 21.8 $/MWh	1.60 GWh 58.1 $/MWh	3.23 GWh 18.6 $/MWh
Virtual Bidding	5.2 GWh 32.4 $/MWh	3.5 GWh 29.6 $/MWh	3.5 GWh 37.2 $/MWh	5.2 GWh 24.6 $/MWh	– –	– –

Summary and Conclusions

- Present a multi-scale optimal control framework for energy systems participating in CAISO electricity markets

- Discover majority of economic opportunities are at **fastest timescales** (Real-Time Market)

- Study incentives for **industrial systems** from price signals



Future Work

- Extend framework to consider market **uncertainty** and **bidding strategies**

A Multi-Scale Optimal Control Framework for Electricity Market Participation

Alexander Dowling, PhD

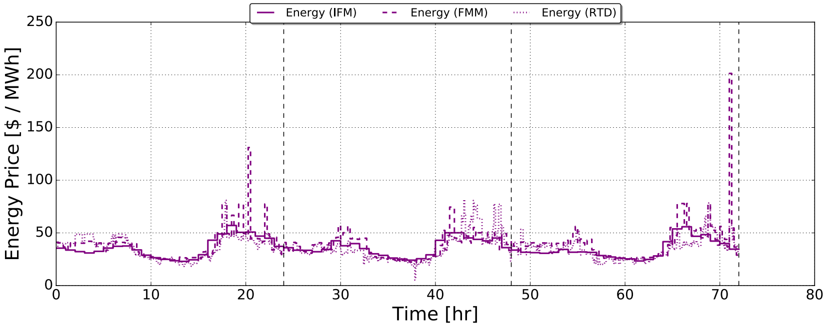
with **Prof. Victor Zavala**

Scalable Systems Laboratory

`zavalab.engr.wisc.edu`

Department of Chemical and Biological Engineering

University of Wisconsin-Madison



FERC Meeting: Increasing Market and Planning Efficiency through Improved Software

June 29th, 2016