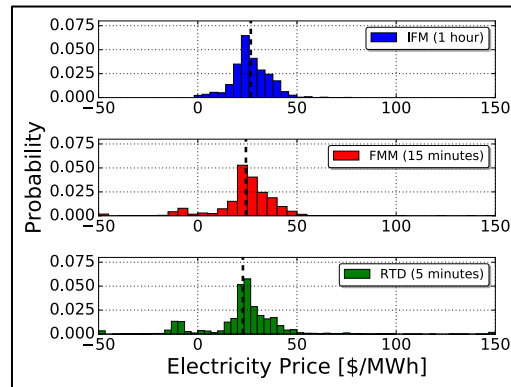
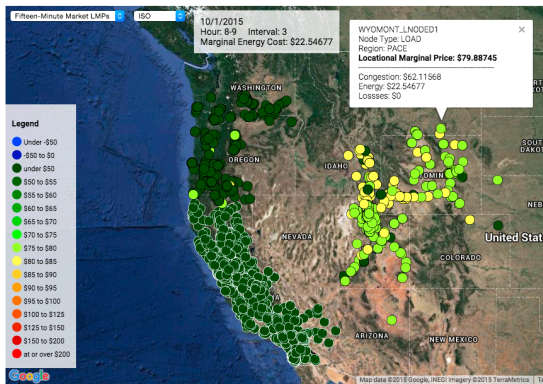


# Economic Opportunities for Energy Storage in Electricity Markets

## *Combining Models, Data, and Large-scale Optimization*



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June 27<sup>th</sup>, 2017, Washington D.C.

FERC Technical Conference:

Increasing Real-Time and Day-Ahead Market Efficiency Through Improved Software

# Paradigm Shift in Energy Technology Landscape



baseload vs. peaking generators



diverse technologies, spectrum of dynamic flexibility

## Technologies



Solar



Natural Gas



Energy Storage



Nuclear



Manufacturing



Buildings

## Electricity Markets

Day-Ahead (slow)

Real-Time (fast)

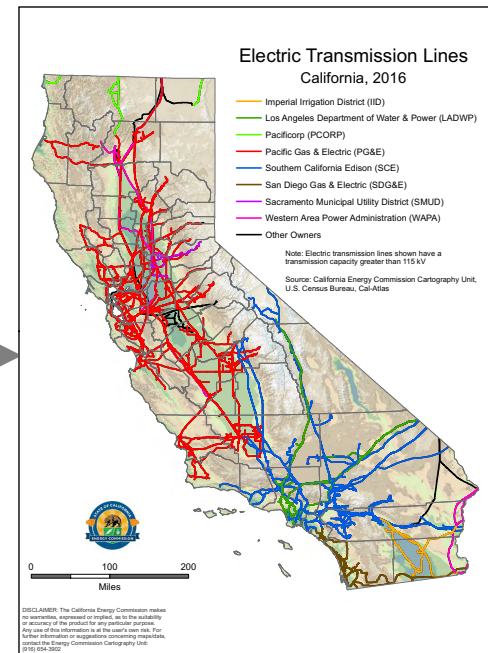
Energy Products

Energy Products

Ancillary Service Products

Ancillary Service Products

## Electric Grid



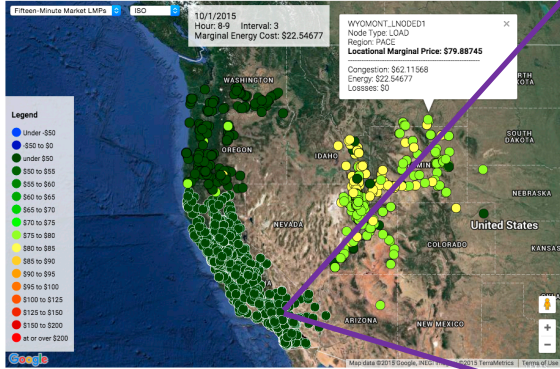
## Key Questions:

**Where** do market signals incentivize investment?

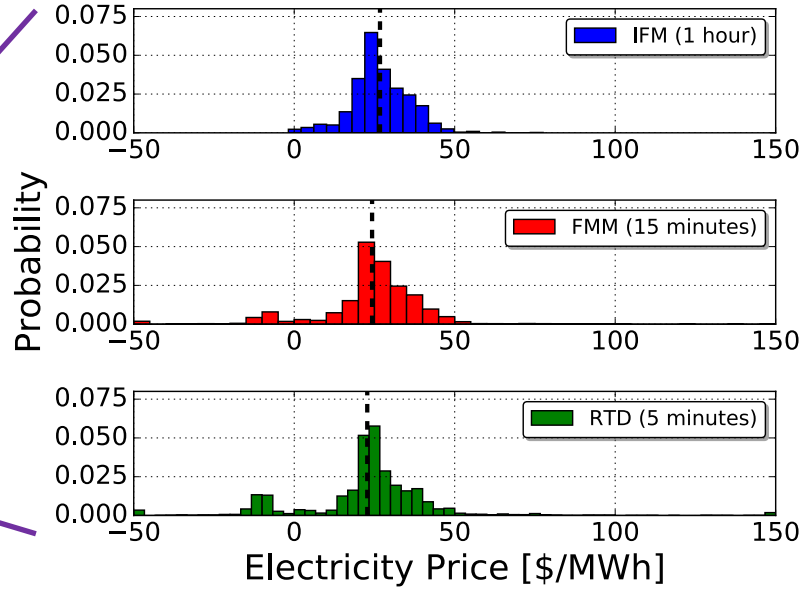
Which market **products/timescale** are most profitable?

How does **market design** impact incentives for specific technologies?

# California Energy Price Signals

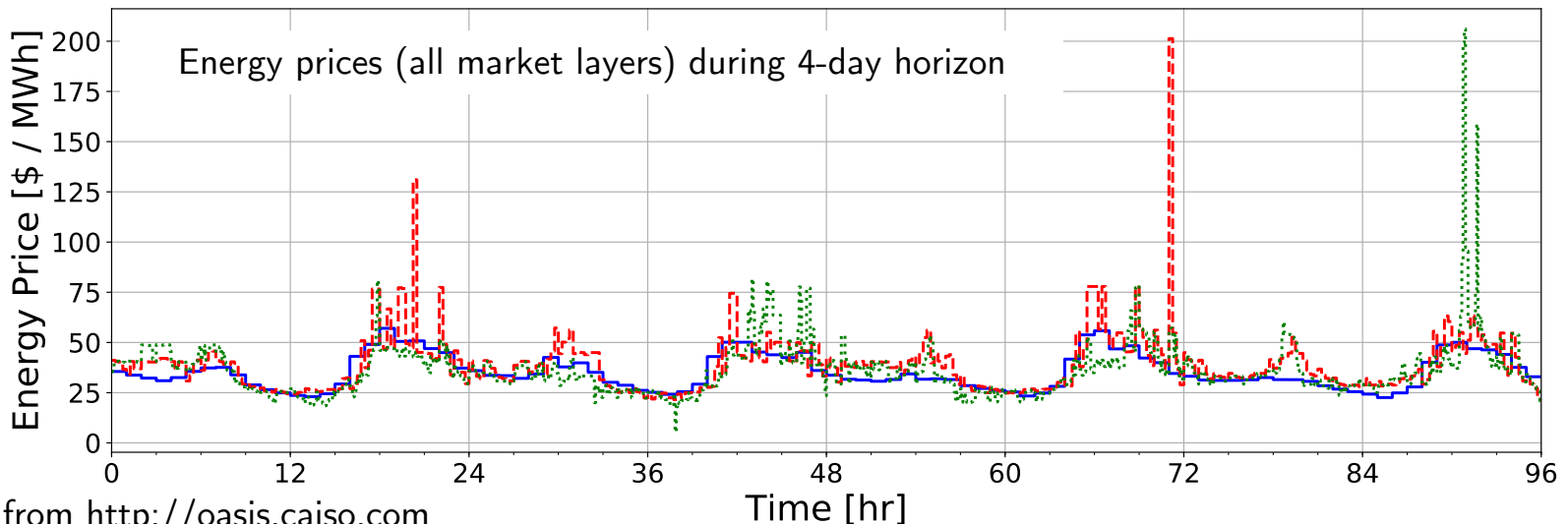


Annual price distribution for 1-3pm



Day-Ahead Market

Real-Time Market

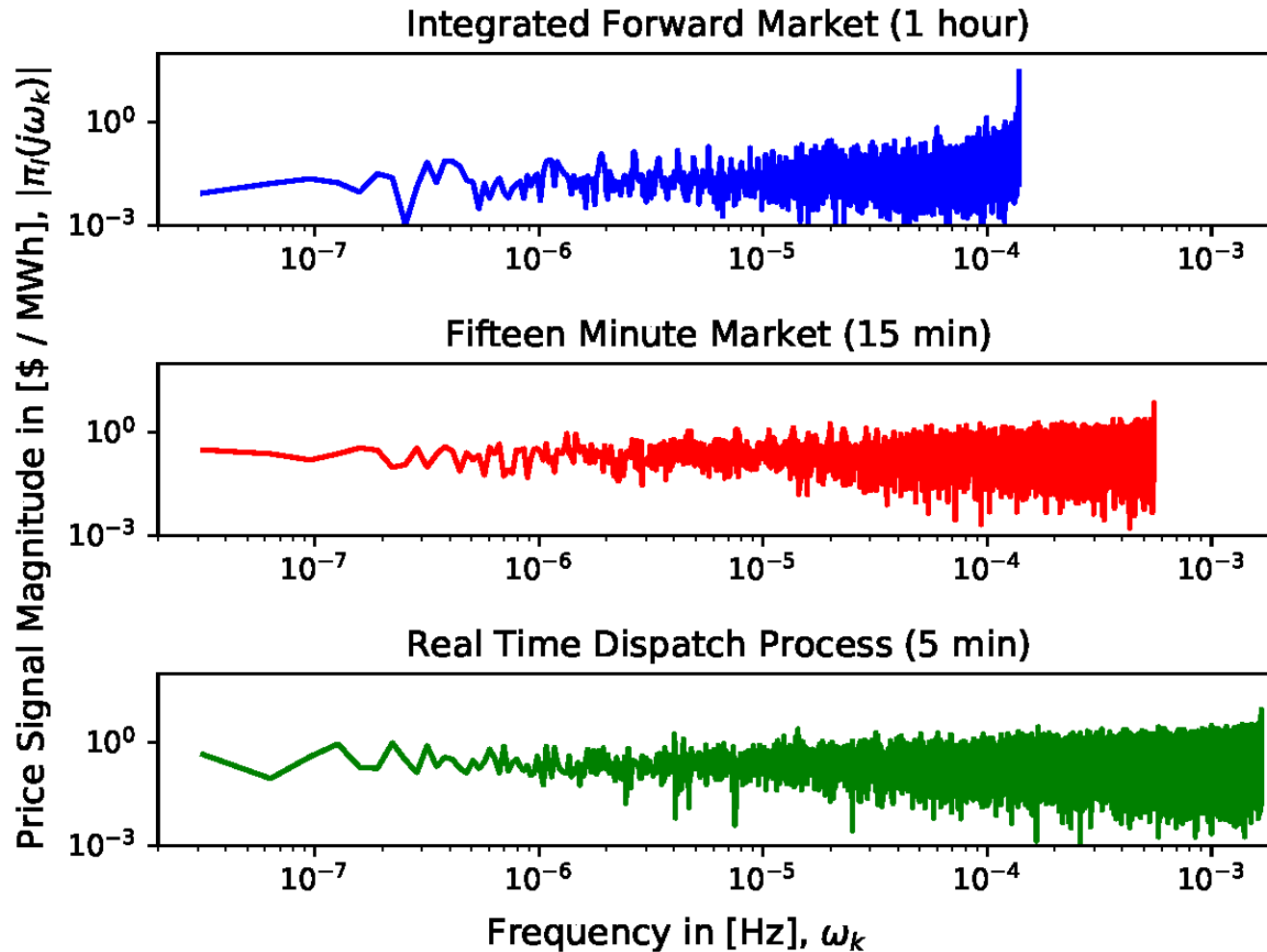


300% increase during < 1 hour



# Fourier Analysis of CAISO Energy Prices

$$\pi(t) = \sum_{k=0}^N A_k \sin(\omega_k t) + B_k \cos(\omega_k t) \quad |\pi(j\omega_k)| = \sqrt{A_k^2 + B_k^2}$$

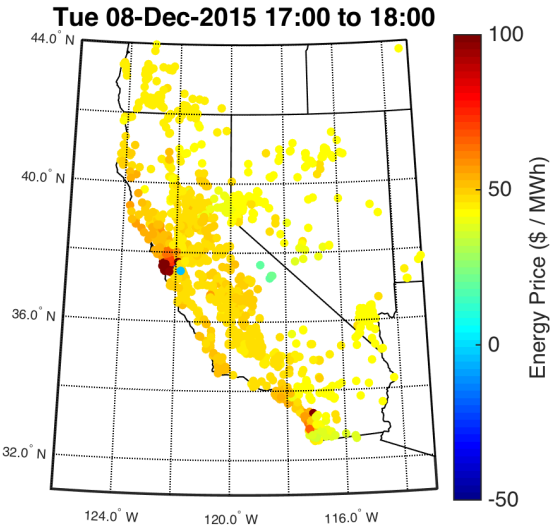


97% of signal magnitude is from  $10^{-5}$  Hz (day-to-day) and faster frequencies

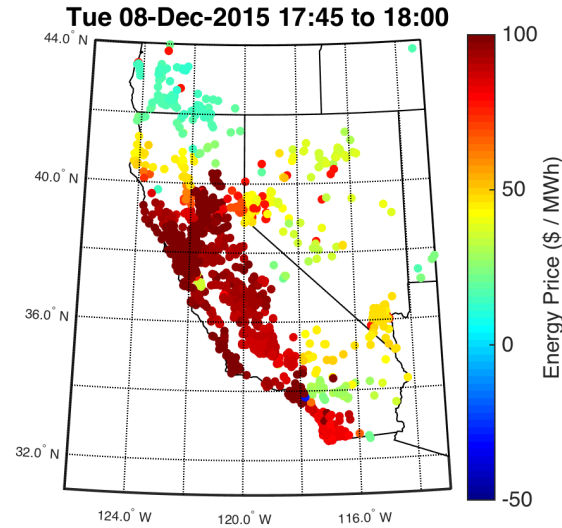
# Spatial Price Variations in CAISO



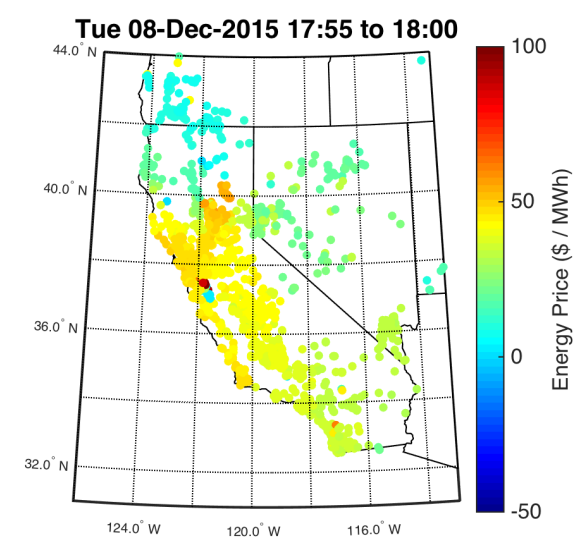
## Integrated Forward Market (1-hour intervals)



## Fifteen Minute Market (15-min. intervals)



## Real-Time Dispatch Process (5-min. intervals)



## Observations:

- Over **1 trillion** prices for CA system in 2015 (500 GB uncompressed text)
- Faster timescales are most volatile
- Localized volatility at slower timescales
- System-wide volatility at faster timescales

How can a market participant **take advantage of price variations?**

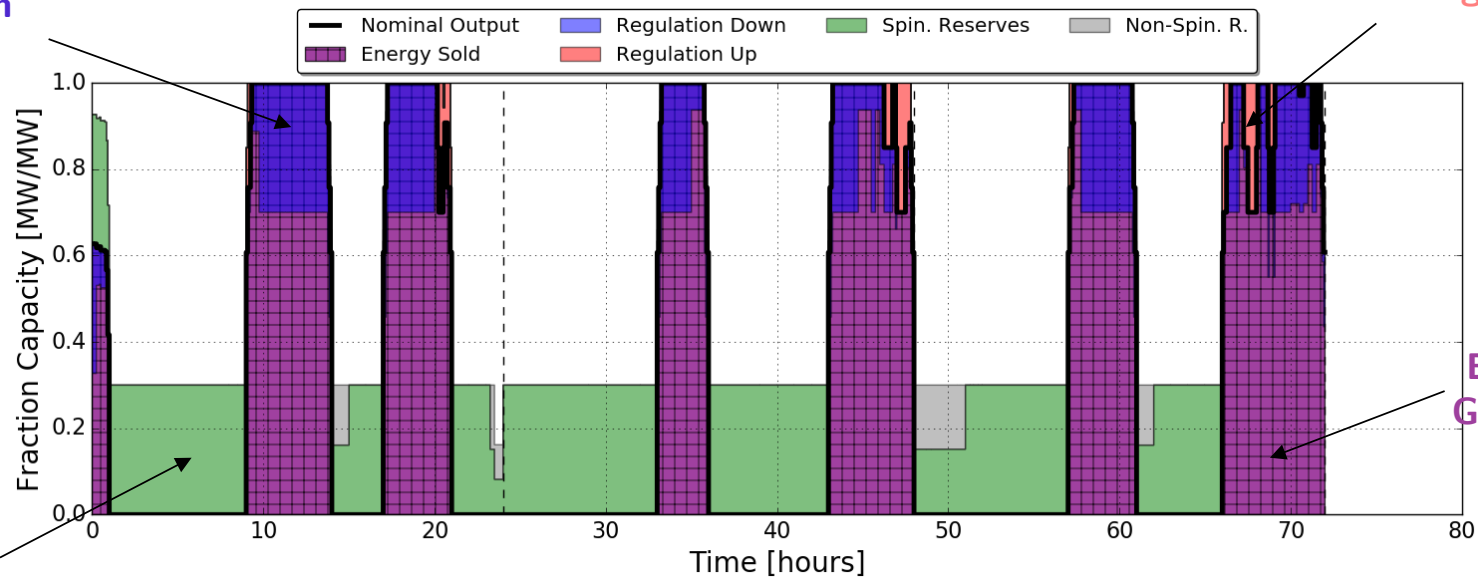
# Market Participation Problem



	Day-Ahead Market	Real-Time Market	
	Integrated Forward Market (IFM) 1 hour	Fifteen Minute Market (FMM) 15 minutes	Real-Time Dispatch (RTD) 5 minutes
<i>Energy</i>	✓	✓	✓
<i>Ancillary Services</i>			
Regulation Down	✓	✓	—
Regulation Up	✓	✓	—
Spinning Reserves	✓	✓	—
Non-Spin. Reserves	✓	✓	—

Regulation Down

Regulation Up

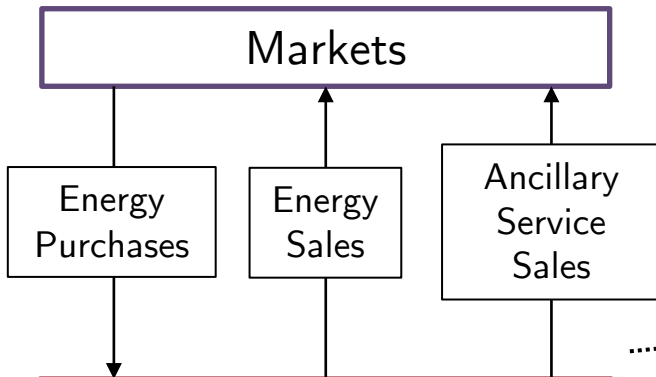


Spinning Reserves

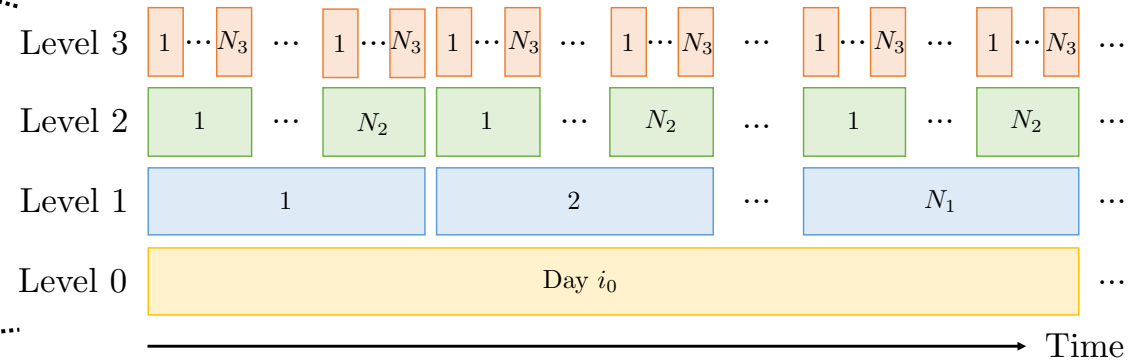
Electrical Generation

Observation: No previous framework considers **multi-market multi-product** participation

# Optimization Framework for Market Participation



## Multiscale Time Discretization



## Mathematical abstraction supports:

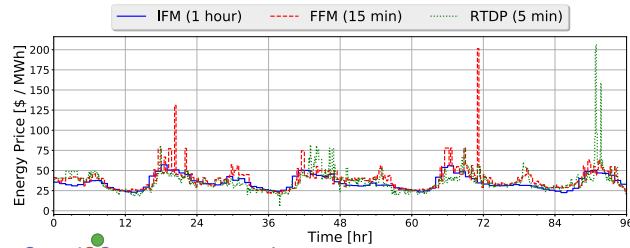
- Arbitrary technologies
- Arbitrary hierarchical levels & timescales
- Many market designs (e.g., PJM, MISO, CAISO)

Multi-scale market participation involves **huge number of decisions**

- What products to sell/buy and at what times?
- Constrained by resource's physics
- **Example:** 1-year horizon  $\rightarrow$  300,000 variables

# Market Analysis Software Framework

## Automated Data Acquisition



## Resource Physics Model

### Model Template

- Express as algebraic equations
- Link to market model via energy variables

### Examples



batteries

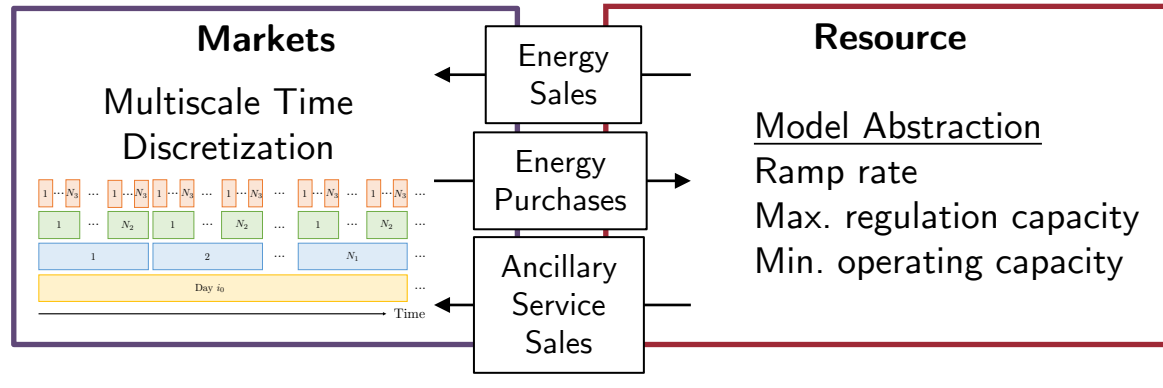


industrial utilities



solar thermal

## Electricity Market Models



## Numerical Optimization



Easy to Parallelize

