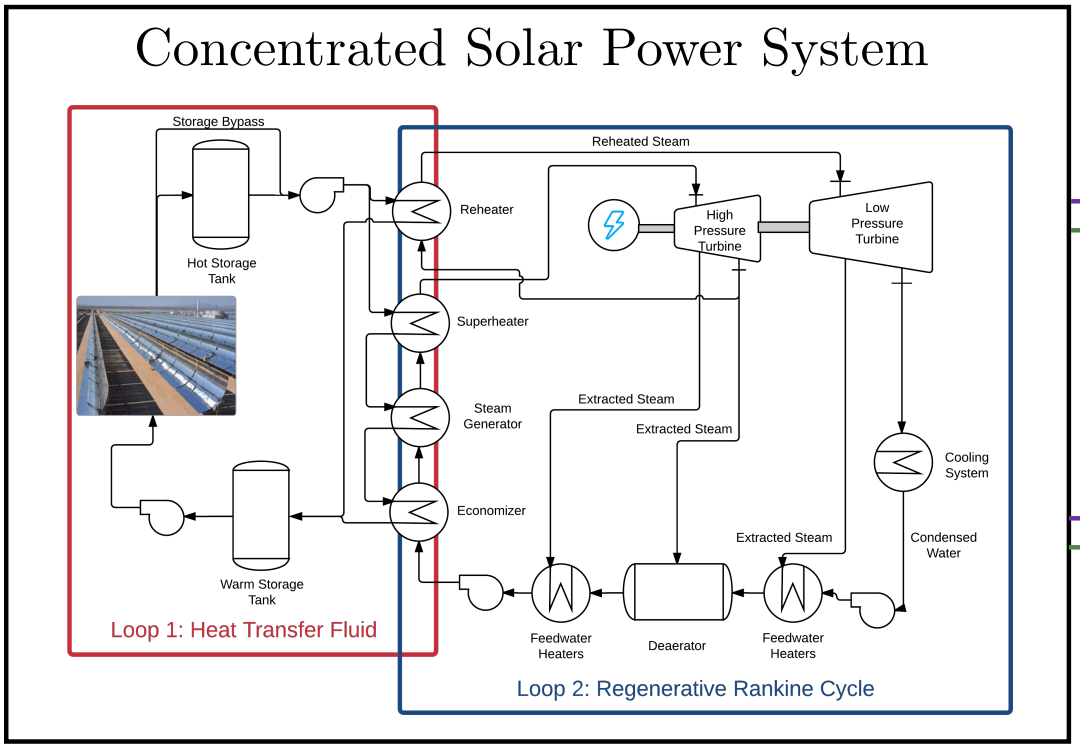
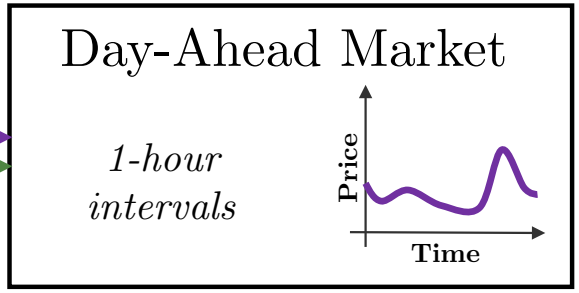
Optimization Framework



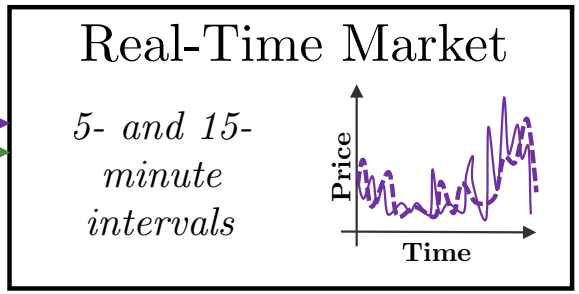
Electrical Energy

Ancillary Services



Electrical Energy

Ancillary Services



Goal: Maximize Revenue

Decision Variables:
- Market participation schedule
- Mass and energy flows

Input Parameters:
- Solar field size (i.e., solar multiple)
- Thermal storage size

Constraints:
- Market rules
- Start-up/shut-down times
- Physical limits

Time horizon: 1 year

Dowling et al (to appear), *Proceedings of SolarPACES 2016*, preprint at `zavalab.engr.wisc.edu`

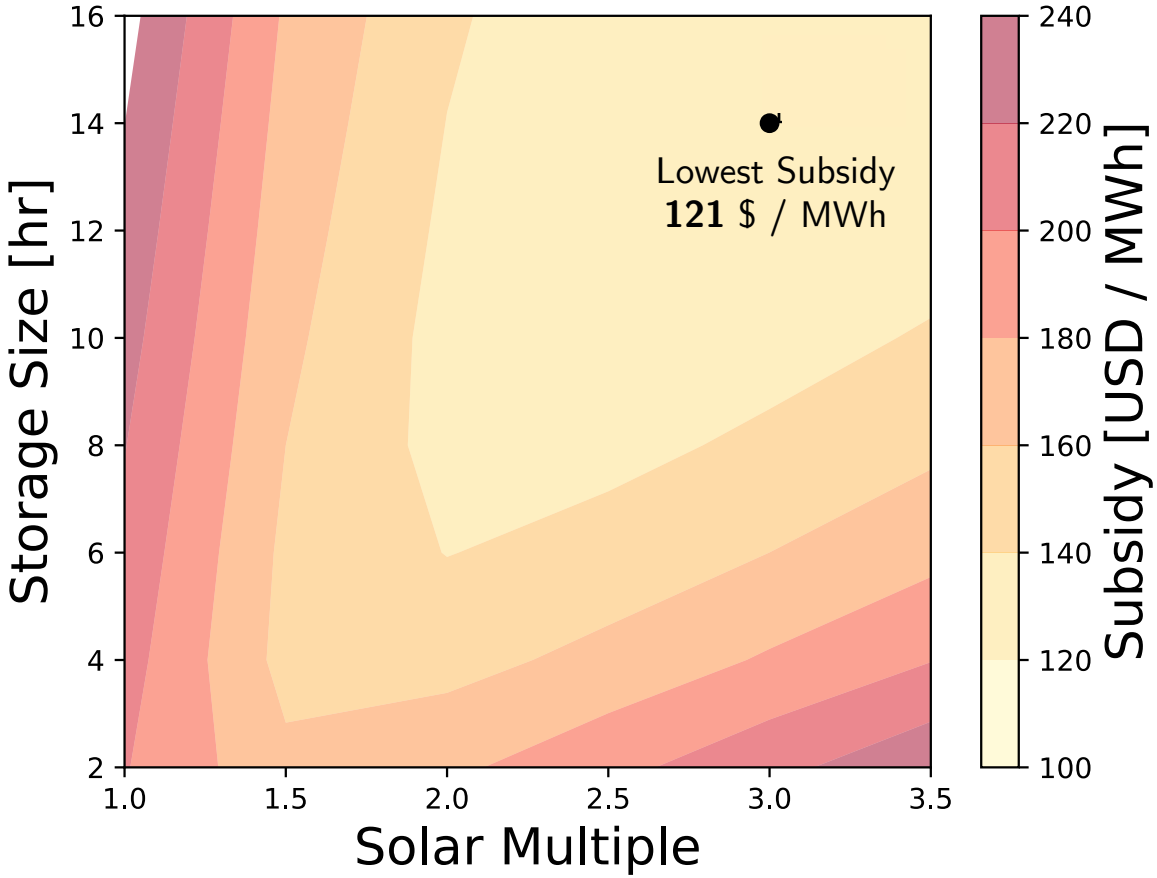
Levelized Cost of Electricity (LCOE)-Centric Designs

$$\text{LCOE} = \frac{\text{total costs over lifetime}}{\text{total electricity generated over lifetime}}$$

$$\text{Subsidy} = \underbrace{(\text{LCOE}) \times \sum_{t \in \mathcal{T}} E_t}_{\text{CSP Revenue}} - \underbrace{\sum_{t \in \mathcal{T}} \pi_t E_t}_{\text{Market Value of Energy}}$$

E_t Generation during hour t (in MWh)

π_t DAM price during hour t (in \$/MWh)



Design with Lowest Implicit Subsidy

Total Revenue	103.8 M$ / yr
Energy Delivered	681 GWh / yr
LCOE	152.2 $ / MWh
Subsidy	**121.1 $ / MWh**
Market Value of Energy	21.2 M$ / yr 31.2 $ / MWh
Storage Size	14 hours
Solar Multiple	3.0
Capital Cost	948.9 M$

Market-Based Designs

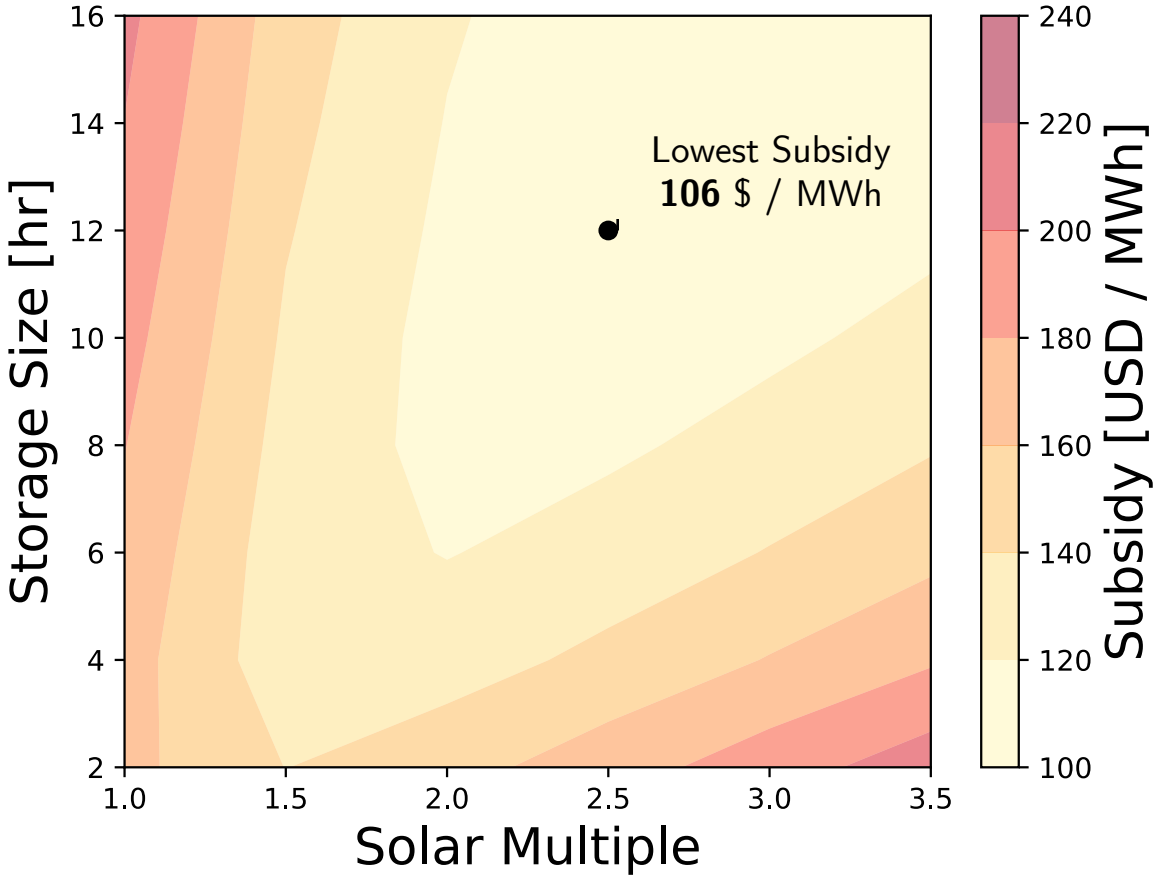
$$\text{Revenue} = \text{Market Revenue} + \lambda \sum_{t \in \mathcal{T}} E_t$$

E_t Generation during time interval t (in MWh)

λ Solar subsidy (in \$/MWh)

Key Findings:

- 12% lower subsidy
- Smaller solar field and storage
- Generation and AS schedule aligned with grid needs



Design with Lowest Solar Subsidy

Total Revenue	90.2 M$ / yr
Energy Delivered	605 GWh / yr
LCOE	149.0 $ / MWh
Subsidy	**106.1 $ / MWh**
Market Value of Energy + AS	26.0 M$ / yr 43.0 $ / MWh
Storage Size	12 hours
Solar Multiple	2.5
Capital Cost	852.7 M$

Conclusions

Propose framework to **elucidate market incentives**

- Combines models, data, and large-scale optimization

Batteries

- **Payback in 1 to 2 years** with full market participation
- Smaller storage sizes are optimal
- Incentives concentrated in **central CA** (near Fresno)
- Economics improve only 10% with 10x slower degradation

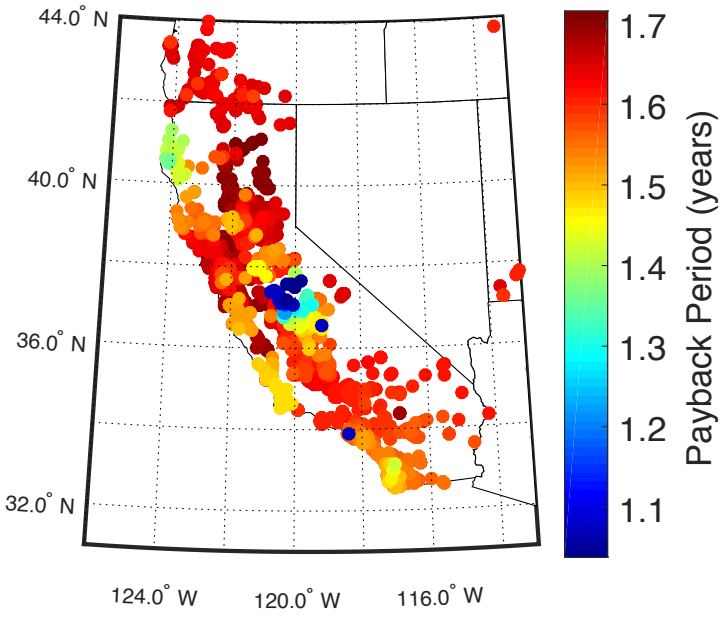
Solar Thermal

- **12% lower subsidy** with market-based incentives

Incorporate **stochastic effects**

Systematic, data-driven **market design**

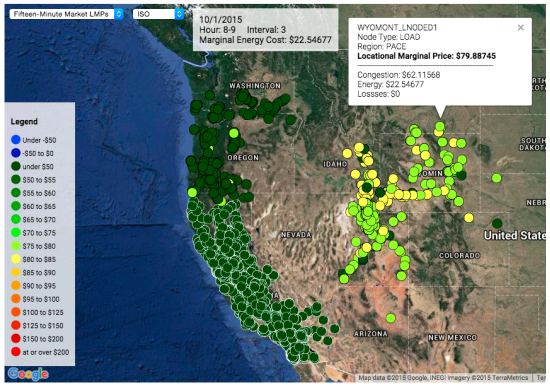
- Do market designs induce the expected or desired incentives?
- How to **shape market incentives** to promote ISO flexibility and other common goals?

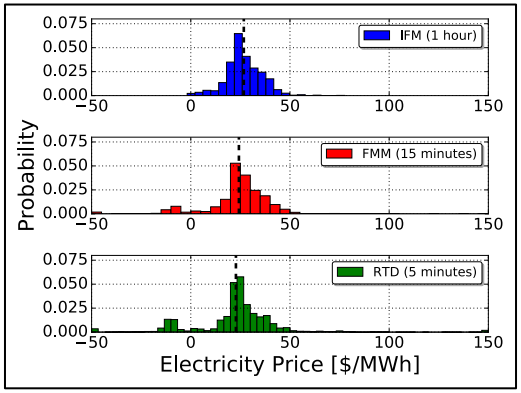


*Does optimization from **ISO perspective** locate storage in central CA?*

Economic Opportunities for Energy Storage in Electricity Markets

Combining Models, Data, and Large-scale Optimization





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