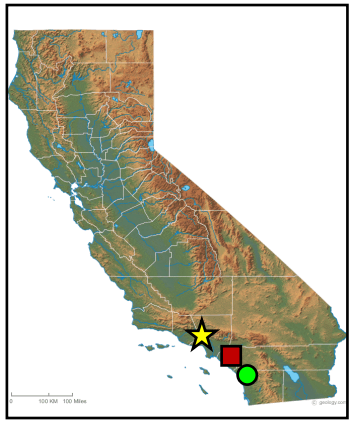
Energy Storage Investments in California

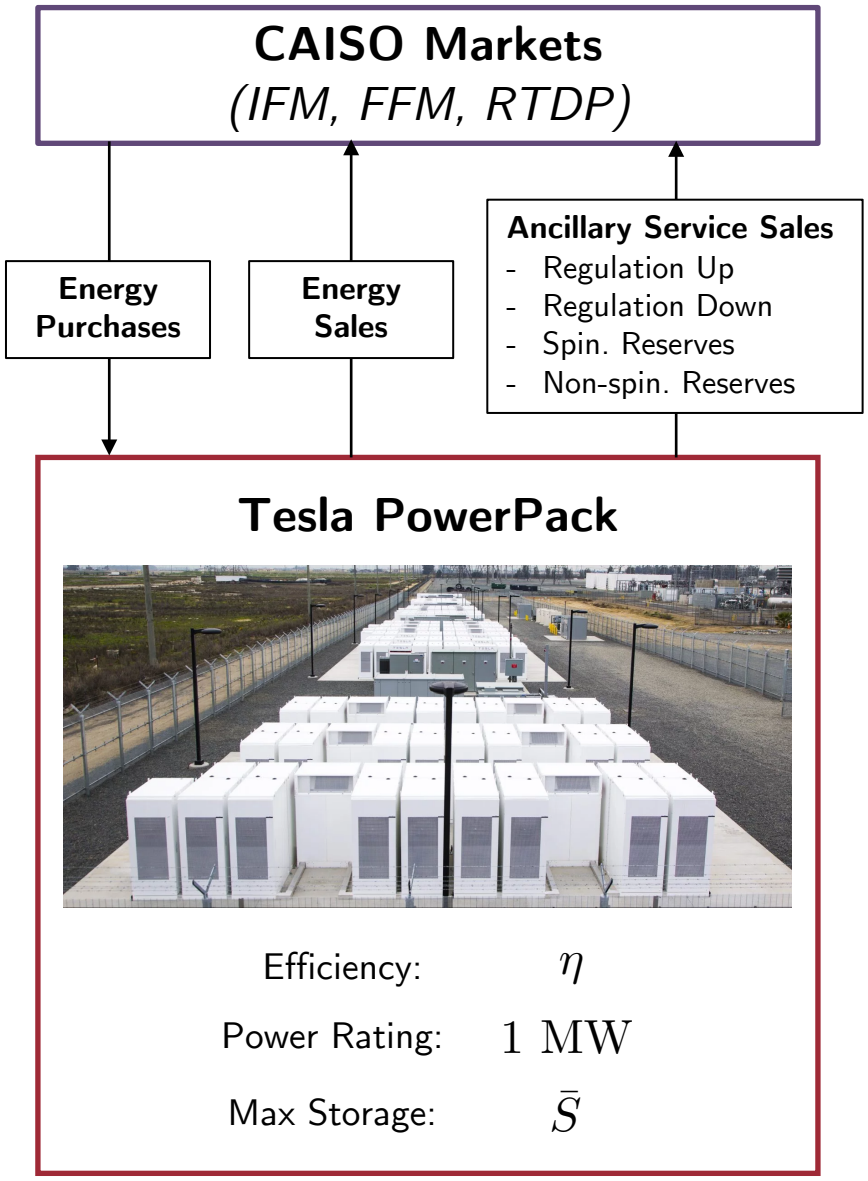
Mandate: procure 1,325 MW of storage by 2020



Escondido, CA ■ **El Cajon, CA** ● **Chino, CA** ★

	Escondido, CA ■	El Cajon, CA ●	Chino, CA ★
Utility	San Diego Gas & Electric	San Diego Gas & Electric	Southern California Edison
Opened	Feb. 2017	Feb. 2017	Dec. 2016
Storage Size	120 MWh	30 MWh	80 MWh
Power Rating	**30 MW**	**7.5 MW**	**20 MW**
Cost	Not Disclosed	Not Disclosed	$45 million (estimate)
Supplier	AES	AES	Tesla
Technology	Li-ion	Li-ion	Li-ion

Battery Energy Storage System



Data from **www.tesla.com/powerpack**, accessed March 2017

Goal: Maximize Revenue

Decision Variables:
- Market participation schedule

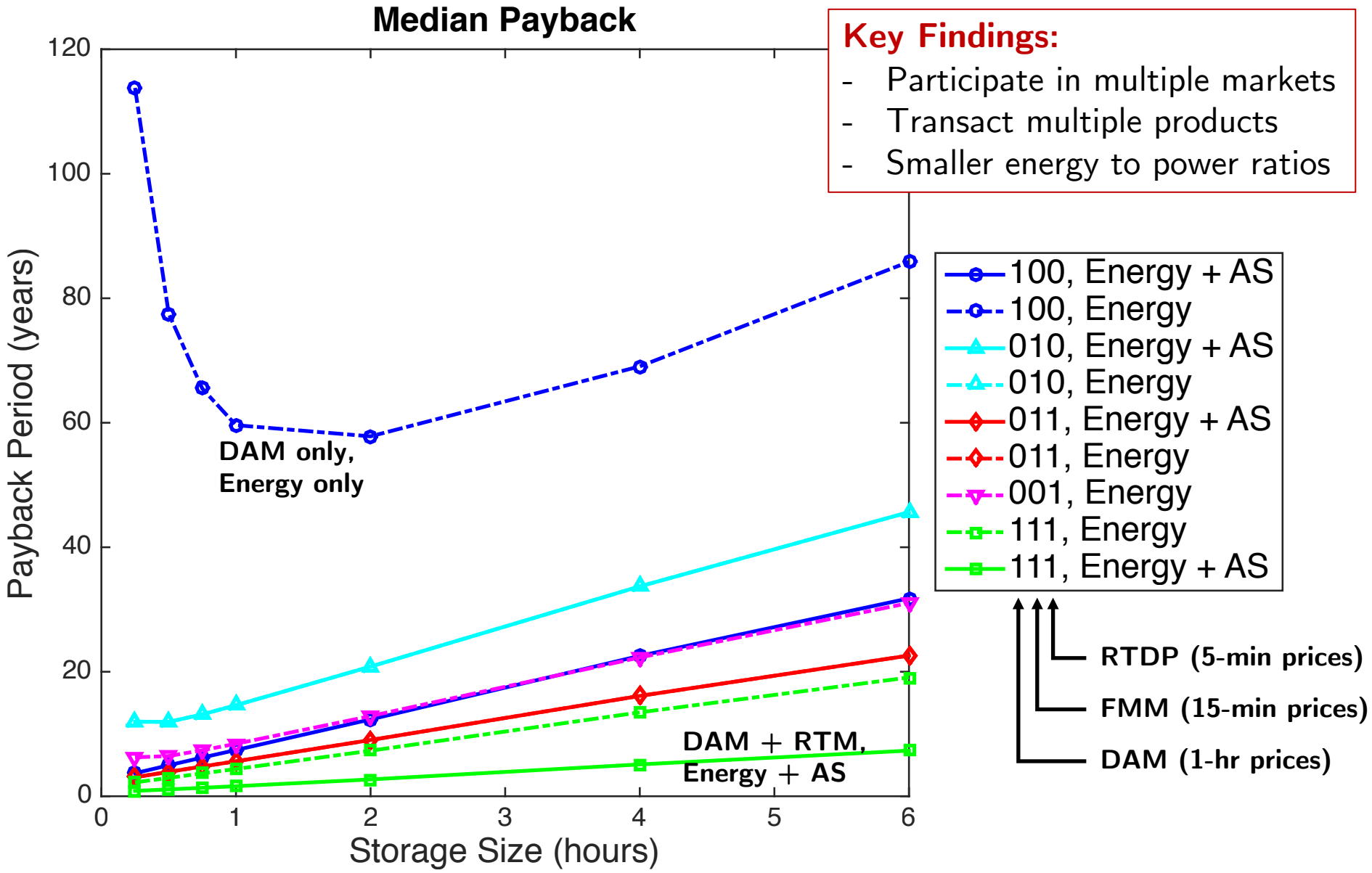
Constraints:
- California market rules
- Battery physics

Input Parameters:
- Which markets/products to transact?
- Location in CAISO
- Storage size (in hours)

Time horizon: 1 year

Tesla PowerPack System
- 88% to 89% round trip efficiency
- 50 kW to 2.5 MW
- 2 hr to 6 hr of storage
- 900 $/kW to 2,700 $/kW

What Size and How to Interact with Markets?



Key Findings:

- Participate in multiple markets
- Transact multiple products
- Smaller energy to power ratios

Where to Locate?

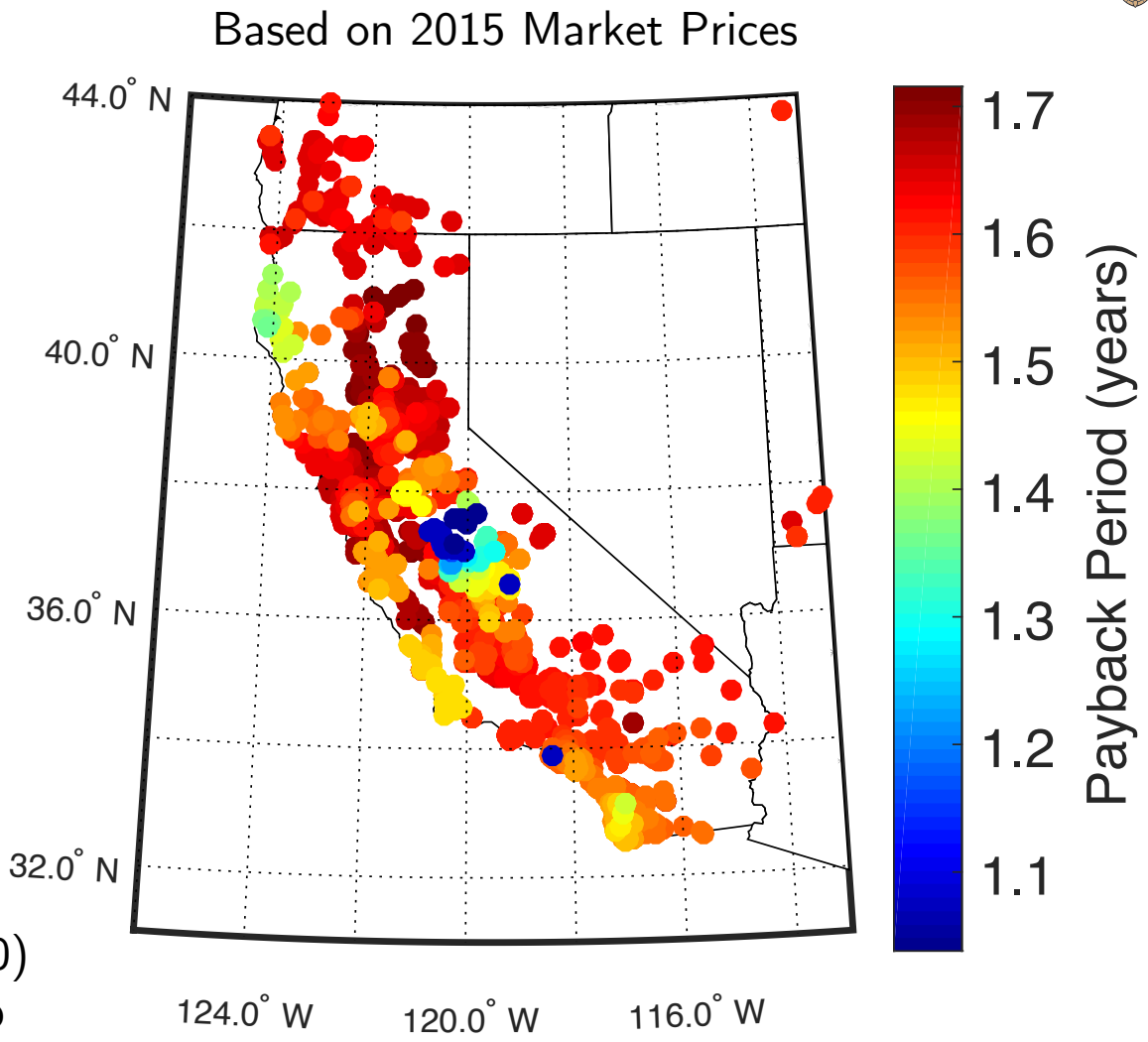
Full Market Participation
DAM and RTM
Energy and Ancillary Services

Storage Size:
1 hour

Investment:
$570,000 / MW

Revenue:
$330,000 to $550,000 / MW / yr

Computational Stats:
- 6,600 nodes analyzed
- 10s to 24s per node (Gurobi 7.0)
- 200 CPU-hours (serial) for map



Is **central CA** optimal location for storage from **grid operator's perspective**?
(e.g., maximize overall reliability, minimize overall system cost)

How important are degradation effects?

Sodium Sulfur Battery
69% round trip efficiency
4,000 cycles to *failure* (80% loss in capacity)
$370,000 investment for 1 MWh system

Degradation Model

$$\text{Cycle Counter}: \quad C_t = |S_t - S_{t-1}| + C_{t-1},$$
$$\text{Max. Storage}: \quad S_t \leq \bar{S} - \varepsilon_d C_t, \quad t \in \mathcal{T}.$$

Goal: Maximize Net Present Value

Decision Variables:
- Market participation schedule
- **Storage size** (design)

Constraints:
- California market rules
- Battery physics

Input Parameters:
- Which markets/products to transact?
- Replacement horizon (N)
- Degradation rate (ϵ_d)

Problem Stats. ($N = 5$ yrs):
- Linear program
- 3 to 5 million variables
- 4 to 7 million constraints
- 2 CPU-hours (mean) per instance

Degradation Data: Rodrigues et al (2015), *Energy* Cost Data: Dicorato et al (2012), *IEEE Trans. STE*