Advanced Grid-Interactive Distributed PV and Storage

CSI RD&D Program
Final Presentation

Project Objectives

- Demonstrate integrated PV and energy storage technology enabling cost effective load shifting, demand reduction and reduced needs for conventional ancillary services
  - Communication and control technology
  - Advanced lithium-ion (Li-ion) battery storage technology
- Show these systems will reduce cost and carbon emissions and improve grid reliability and security
- Identify market mechanisms that will be necessary to bring combined PV and storage to new markets
  - Identify an optimal finance product for storage
  - Evaluate requirements for and benefits of distributed storage at distribution and transmission scales

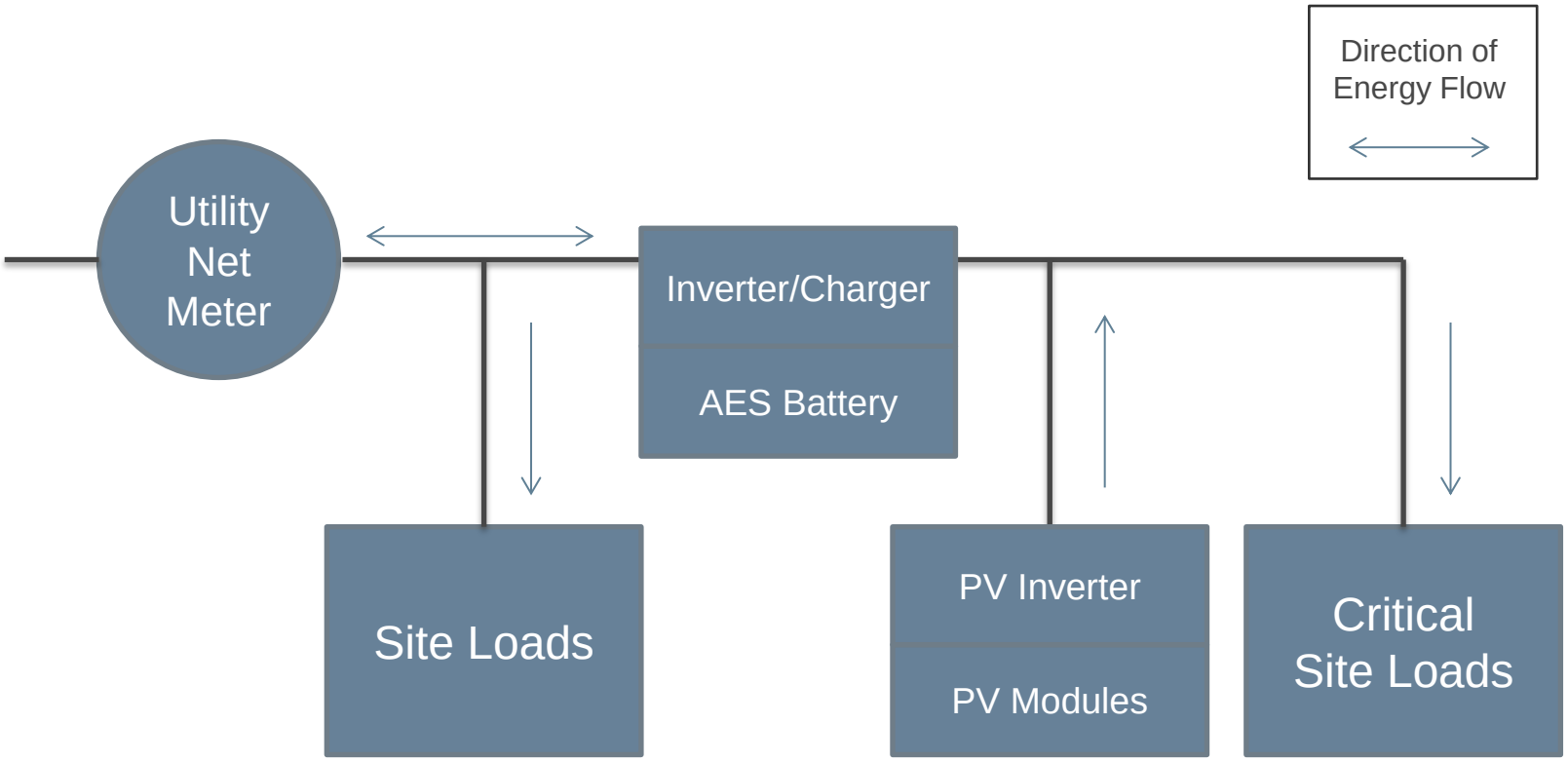
Project Tasks

- **SolarCity Topics:**
  - **Task 2 - Refine communication hardware and deploy prototype low-voltage grid interactive battery systems**
    - Install lead-acid pilot systems
    - Internet-based storage control platform
  - **Task 3 - Deploy integrated FirmPV / high-voltage storage systems**
    - Install Li-ion pilot systems
  - **Task 4 - Monetization of the Value of FirmPV**
    - Marketing analysis of perceived customer benefits
    - Storage financing methods
    - Advances in the product since the grant

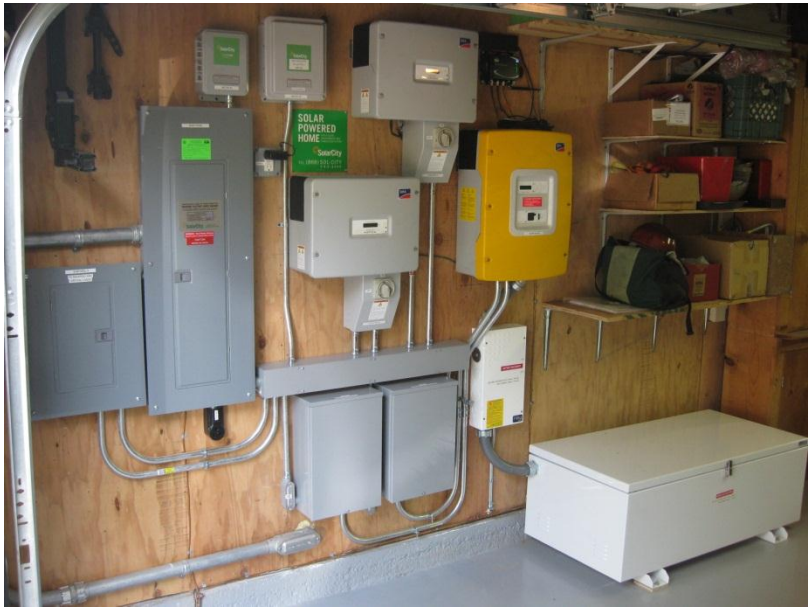
- **Tesla Topics:**
  - **Task 3 - Deploy integrated FirmPV / high-voltage storage systems**
    - Stationary Li-ion battery integration

- **UC Berkeley Topics:**
  - **Task 4 - Monetization of the Value of FirmPV**
    - PV variability analysis
    - Retail and distribution benefits analysis
    - Aggregate control methods
    - Balancing authority benefits

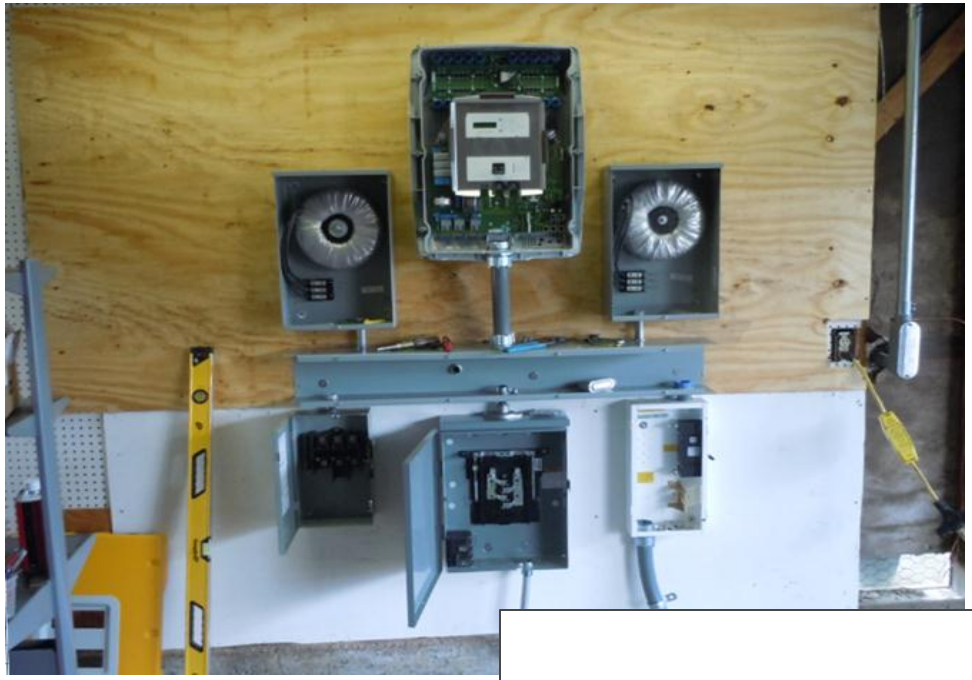
PV and Storage System Components

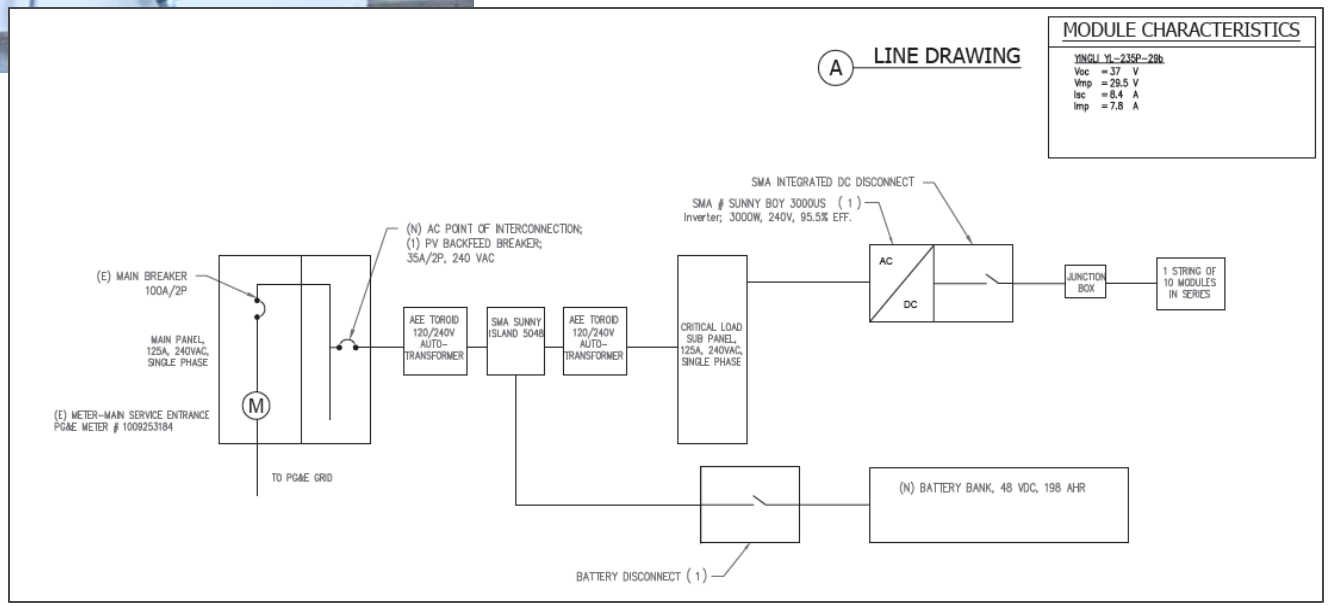


Storage Pilots with Lead Acid Batteries



- Three residential installations
- Bay Area locations
- PG&E territory




A LINE DRAWING
MODULE CHARACTERISTICS
YINGLI YL-235P-29b
Voc = 37 V
Vmp = 29.5 V
Isc = 8.4 A
Imp = 7.8 A
SMA INTEGRATED DC DISCONNECT
SMA # SUNNY BOY 3000US (1)
Inverter; 3000W, 240V, 95.5% EFF.
(N) AC POINT OF INTERCONNECTION;
(1) PV BACKFEED BREAKER;
35A/2P, 240 VAC
(E) MAIN BREAKER
100A/2P
MAIN PANEL,
125A, 240VAC,
SINGLE PHASE
(E) METER-MAIN SERVICE ENTRANCE
PG&E METER # 1009253184
M
TO PG&E GRID
AEE TOROID
120/240V
AUTO-
TRANSFORMER
SMA SUNNY
ISLAND 5048
AEE TOROID
120/240V
AUTO-
TRANSFORMER
CRITICAL LOAD
SUB PANEL,
125A, 240VAC,
SINGLE PHASE
AC
DC
JUNCTION
BOX
1 STRING OF
10 MODULES
IN SERIES
(N) BATTERY BANK, 48 VDC, 198 AHR
BATTERY DISCONNECT (1)

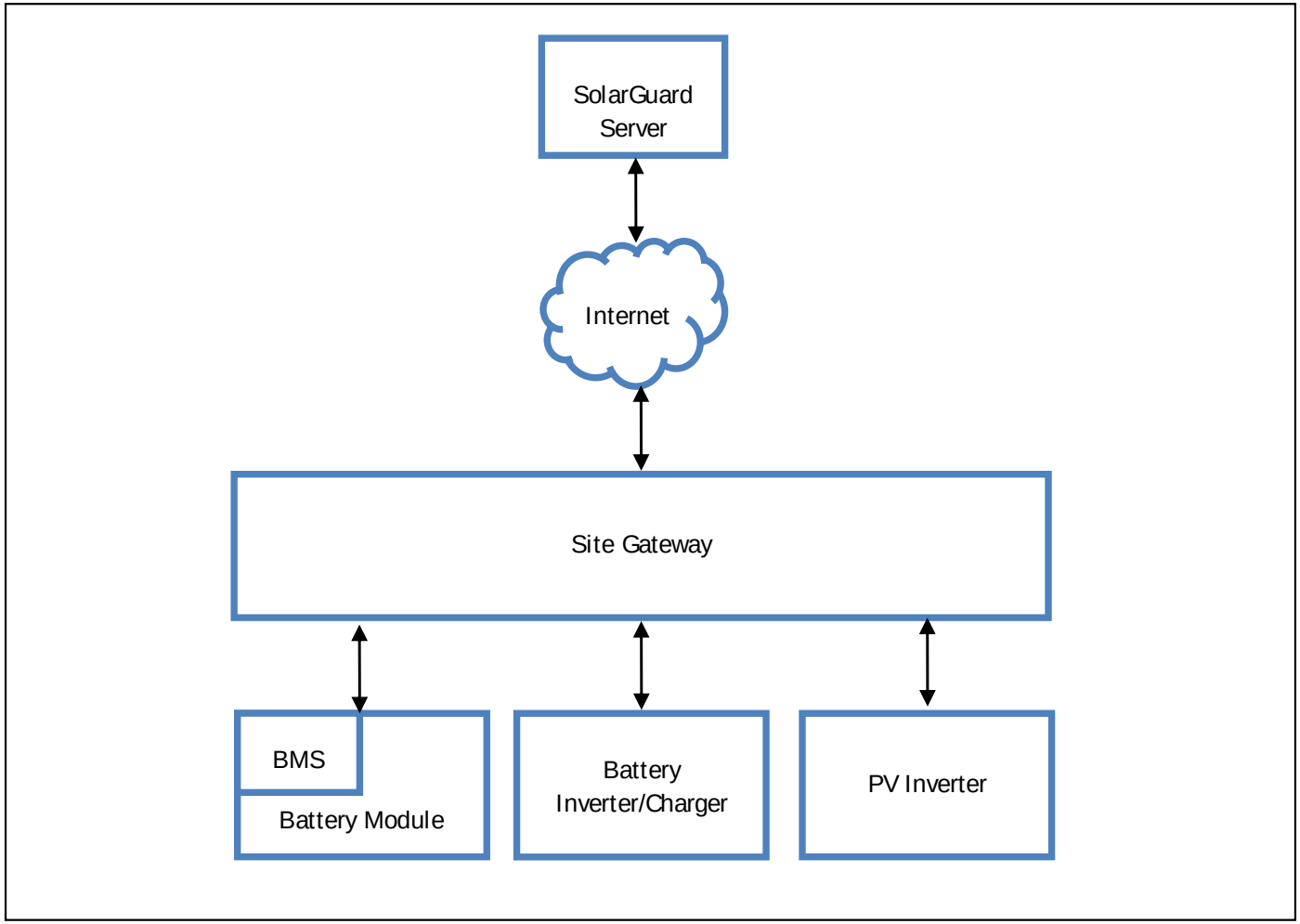
Key Lessons Learned From Lead-acid Pilots

- **Space Constraints**
  - Wall and floor space are a premium
  - Floor mounted batteries in garages are a collision concern
  - Outdoor mounting locations and outdoor rated equipment is mandatory
- **Power Electronics**
  - Native 120/240 VAC split-phase power electronics are required for backup power
  - Power electronics with partial 120 VAC support require significant additional balance-of-system for many sites
- **Electrical Code Compliance**
  - All equipment must be UL Listed and NEC compliant

Lead-acid Pilots At Commercial Installations

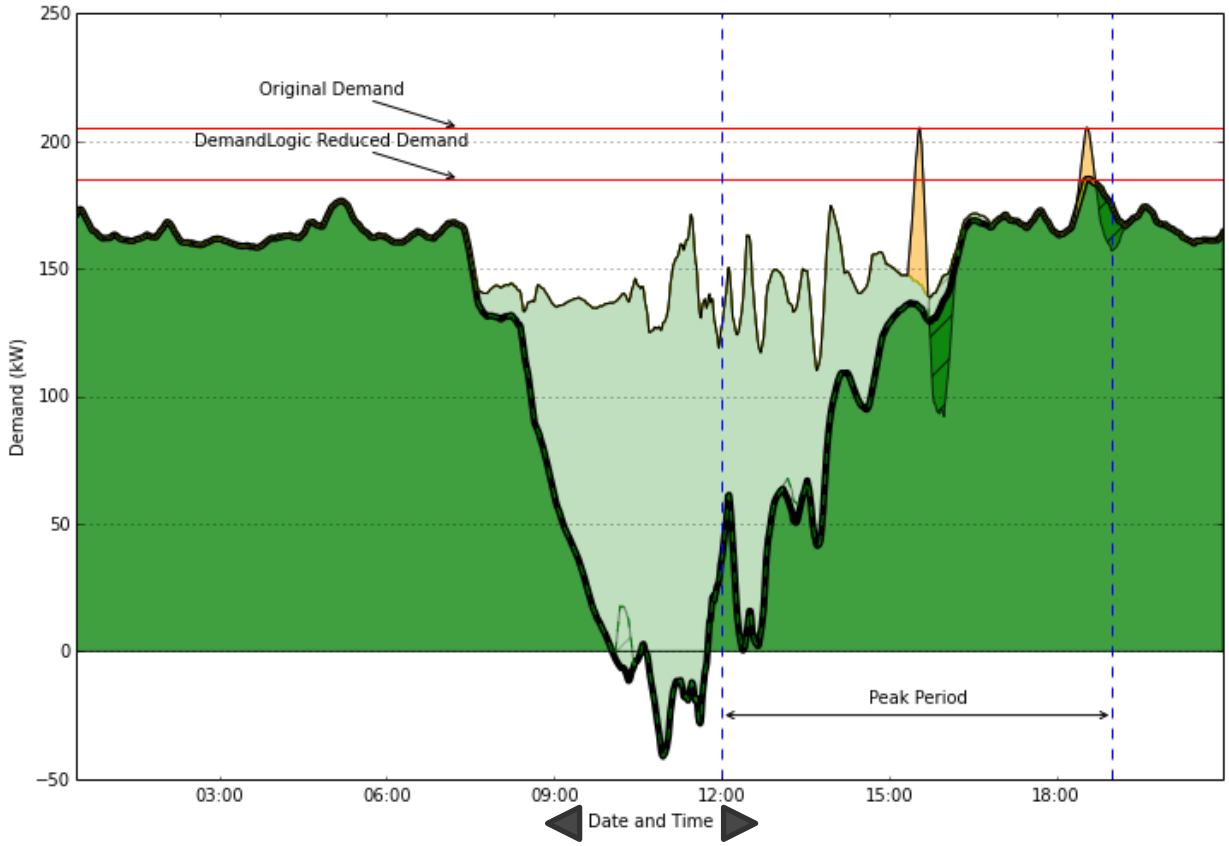
- Commercial pilots of lead-acid chemistry not deemed beneficial due to following characteristics
  - **Limited Cycle Life –** 600 to 800 lifetime cycles at 80% depth-of-discharge
  - **Frequent Maintenance** – Every 6 months to 1 year, depending on type (flooded versus sealed)
  - **Low Throughput Efficiency** – 25%+ efficiency loss at 2 hour or faster discharges
  - **Voltage limitations** – Individual cell maintenance requires low voltage (48 V) systems. Low voltage, high amperage systems are less efficient and higher cost
  - **Limited Warranty** – 1 to 5 years
  - **Size** – 60 – 75 Wh/L versus 250-730 Wh/L for Li-ion. Significant bulk requires dedicated “battery rooms” at commercial scale.
  - **Limited Packaging Options** - Lead-acid cells require external, third-party enclosures. Outdoor rated options limited and extremely expensive.

Building a Storage Control System



SolarCity

DAY WEEK MONTH YEAR



Site Demand

Solar Demand Reduction

Battery Demand Reduction

Battery Recharge

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Storage Control System – Key Lessons

- **Communication Standards -** Significant need for communications standards development at all layers of communication
  - Battery <-> Inverter/Charger
  - Inverter <-> Site Gateway
  - Site Gateway <-> Central Server
- **Security -** End-to-end, standards based security such as TLS/SSL is mandatory
- **Cellular backhauls -** Cellular communications are reliable and approaching cost effectiveness for residential applications
- **Local, multi-layered intelligence** – Central, server driven control best optimizes a fleet of systems, but most data processing and decision making is best done locally. Autonomous, predictable and stable operation is mandatory

Tesla Li-ion System Development

Key topics:

- Development process
- Summary of battery technology
- The evolution of the battery packs
- Power electronics

CSI RD&D Project Summary

December 2013

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Director, Powertrain Business Development
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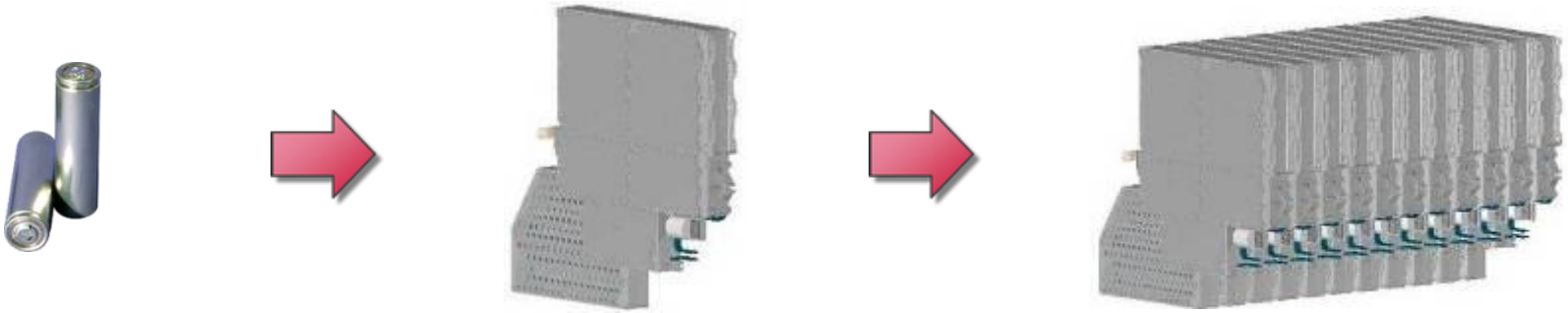
Summary of Battery Technology

- Tesla uses automotive grade lithium-ion batteries, and stationary packs are designed/tested/validated to automotive standards
  - Produced in same factory and using same cells, modules as Tesla vehicle
- 18650 cylindrical form factor
- Cells – Module – Pack concept
- Integrated Battery Management System (BMS)
- Passive and active safety features



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Development Process

- Tesla adapted OEM automotive battery pack for residential use. This involved:
  - Electrical reconfiguration
  - Mechanical packaging development
  - Communication implementation
  - Thermal validation

Proof of Concept

Prototype

Released Product

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Proof of Concept

- 18.5 kWh capacity proof of concept prototype built in the first 2 weeks of work on the grant program

- Battery modules leveraged from low volume OEM product
- Design work included:
  - Electrical design
    - DC voltage interconnection, from series to parallel
  - Safety architecture changes in hardware and firmware
  - Communication updates for integration with Solar City controller
  - Validation testing

Initial Prototype in clear box (background), SMA inverter (foreground)

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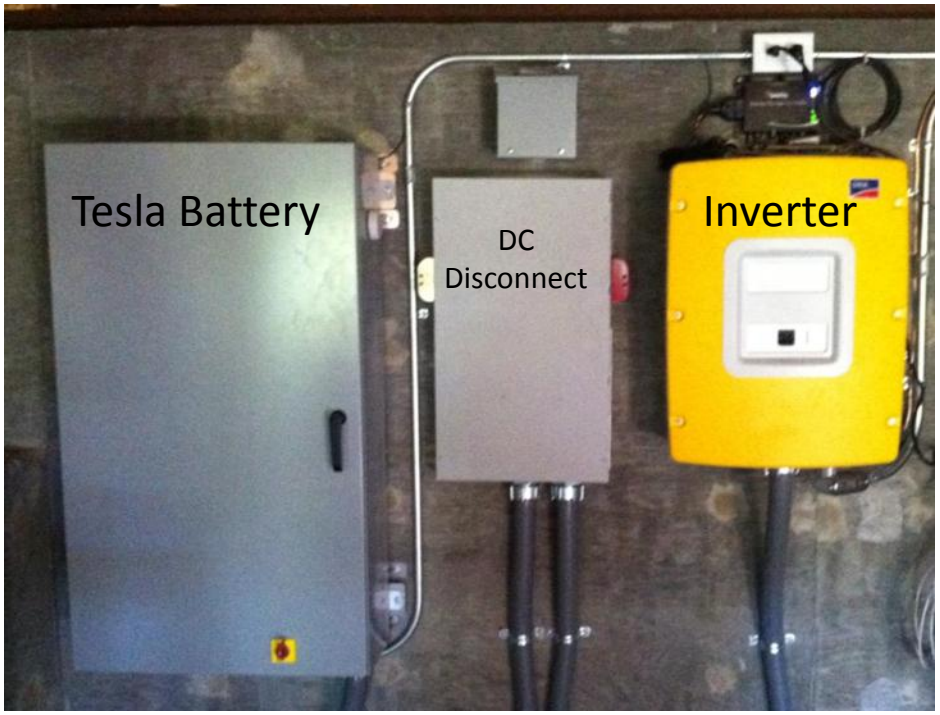
Field Prototypes

- 4 systems built, 3 installed
- Same basic architecture as initial prototype, packaged robustly for field deployment



Field installation at a residence

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Field Prototypes

- Specifications
  - 18.5 kWh capacity
  - 56.25 nominal voltage (45 – 63 V range)
  - 250 A peak DC current
  - 2'x4'x8", 150kg
  - Compatible with SMA Sunny Island 5048 and Schneider/Xantrex XW6048 inverters for single or three phase connection
- Field listed by TUV SUD America to UL508a and NFPA79

Field installation at commercial site in Stockton, CA

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Field Prototypes

- Design work included:
  - Wall mounting bracket with clevis
  - Outdoor rated (NEMA 4) enclosure selection and interface with mount and batteries
  - Wiring compartment design
  - Additional safety features including, UL508 compliant interlock switch in door and shielding of all live parts

Wiring compartment (black polycarbonate shield, yellow and white interlock switch)

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Lessons learned

- A smaller capacity battery is a better target for residential applications
  - Size, weight, capacity
- Leveraging a higher volume module architecture will improve costs
- NEC compliant field wiring is expensive and takes up a lot of wall space
  - Integrate as much as possible into the unit
- Desirable to plan wiring terminals/compartment with compatible inverters in mind
- Battery and inverter controls need to be more closely coupled
- Battery should expose a higher level interface to the user
- UL listing needs to be considered from the initial planning stages
- Installation details

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Tesla GTB-X – 10kWhr Grid Tied Battery

- Residential scale storage solution (10 kWh)
- New battery architecture leverages many high volume production benefits from Model-S
- Custom designed enclosure (outdoor rated) and mounting system with integrated DC branch protection
- Compliant with emerging standard UL 1973 – Batteries for Stationary Applications
- 2 units delivered as part of Grant in October
- Initial production in Q2 2013

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Power Electronics

- Off the shelf, SMA Sunny Island and Xantrex XW
- Communication not on par with state-of-art
- Operational modes not designed for advanced li-ion

Clear market need for better solutions

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Evolution of Battery Packs

- CSI program allowed for development of prototypes, which was platform for subsequent commercial and industrial units

10kWh

60kWh

400kWh

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Grant Funded Commercial Pilots

- Three commercial sites
- Two California sites on retail locations, one in PJM territory
- 8 kW systems
- Focused on peak-shaving

Li-ion Pilots – Commercial

Residential Li-ion Pilots in the Field

Key Lessons from Li-ion Pilots

- **Power Electronics** – Native 3-phase, 480 VAC, UL 1741 listed inverter/chargers are needed to minimize design and balance-of-system construction costs.
- **Permitting** – Extensive plan checker and inspector education is needed. Clear fire and chemical safety documentation is required.
- **Physical Space** – Even with high density Li-ion storage, indoor space in retail environments is extremely limited. Weatherized power electronics are needed.

Continuing Challenges of Power Electronics

- Limitations of power electronics are key barrier to widespread deployment of storage
  - Battery inverter costs are 3x to 4x PV inverter costs
  - System integration between inverter, battery and PV is complicated and costly

<u>Opportunity for CSI RD&D funding to drive innovation</u>

UCB Market Need and Tariff Design

Key Topics:

- PV Variability Analysis
- The opportunity for storage to fill the gap
- Rate design for PV and storage
- Maximizing value of storage and PV

Advanced Grid-Interactive Distributed PV and Storage

CSI RD&D Webinar

December 12, 2013

UC Berkeley:
PI: Duncan Callaway

Students and Postdocs: Michael Cohen, Autumn Petros-Good, Michaelangelo Tabone, Josh Taylor

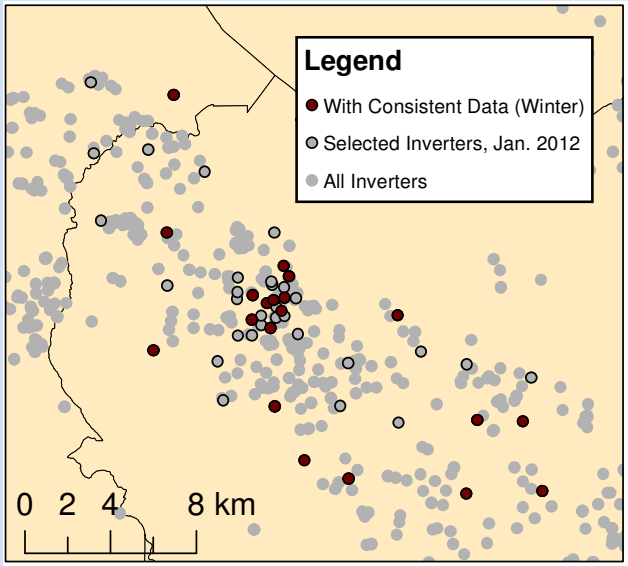
Overview

- Task 4.2: Variability analysis
- Task 4.3: Distribution feeder impacts
- Task 4.4: Systemic benefits of storage
- Task 4.5: Evaluation of system-level market products

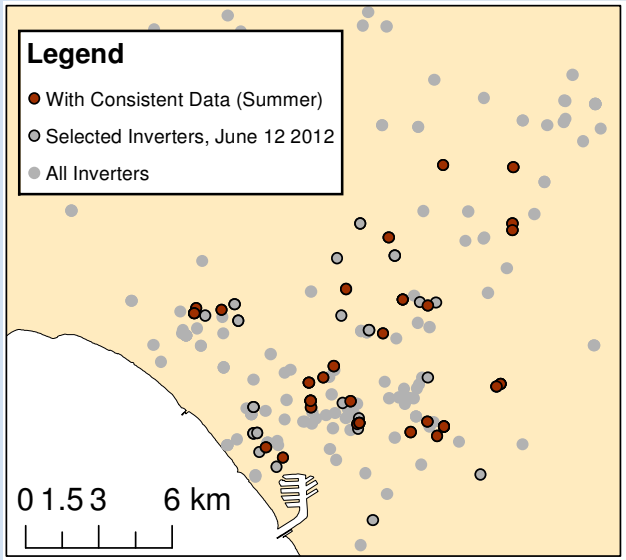
Variability analysis: research question

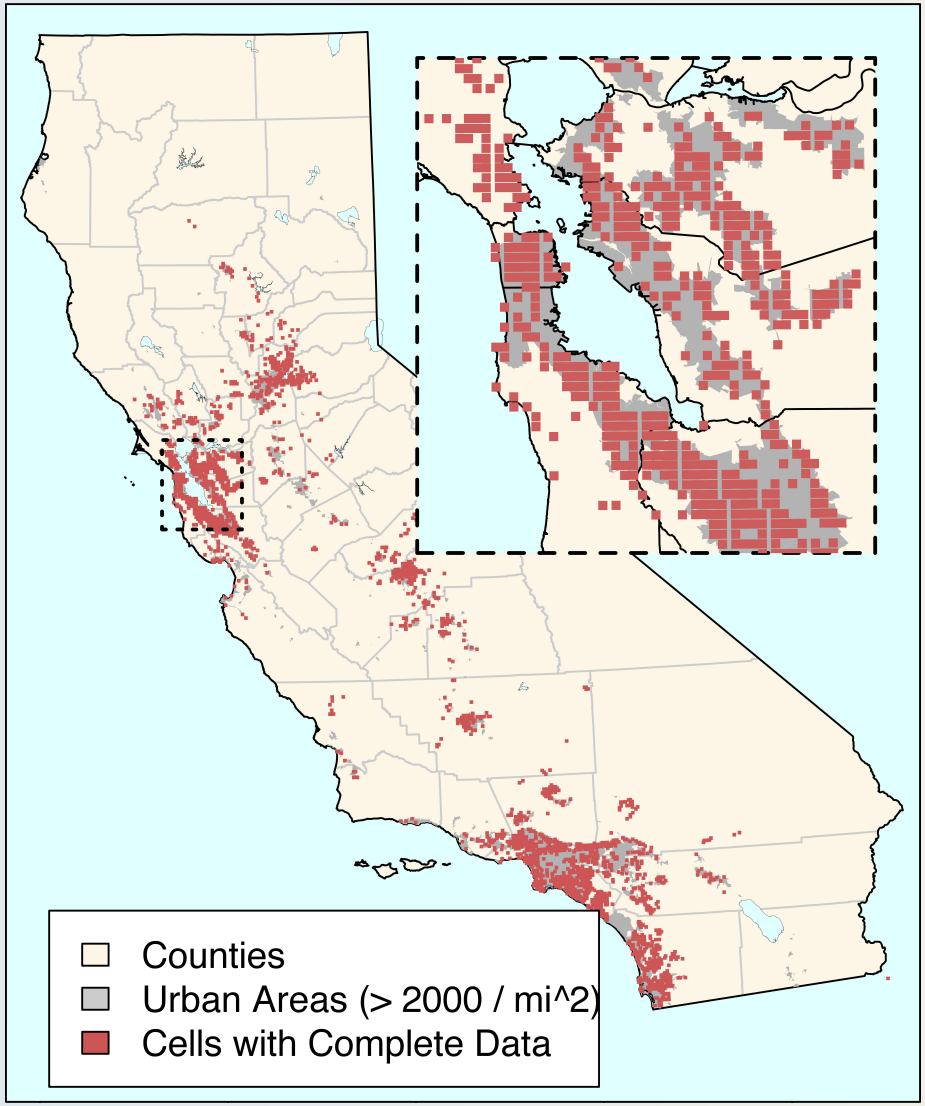
- How large are distributed PV impacts on California power system operations? Factors to consider:
  - Spatial distribution
  - Total penetration (up to 12 GW)
  - Time of year
  - Specifics of power system dispatch process
  - Location of the mitigation option (local balancing versus "pooled")

Variability analysis: Sites

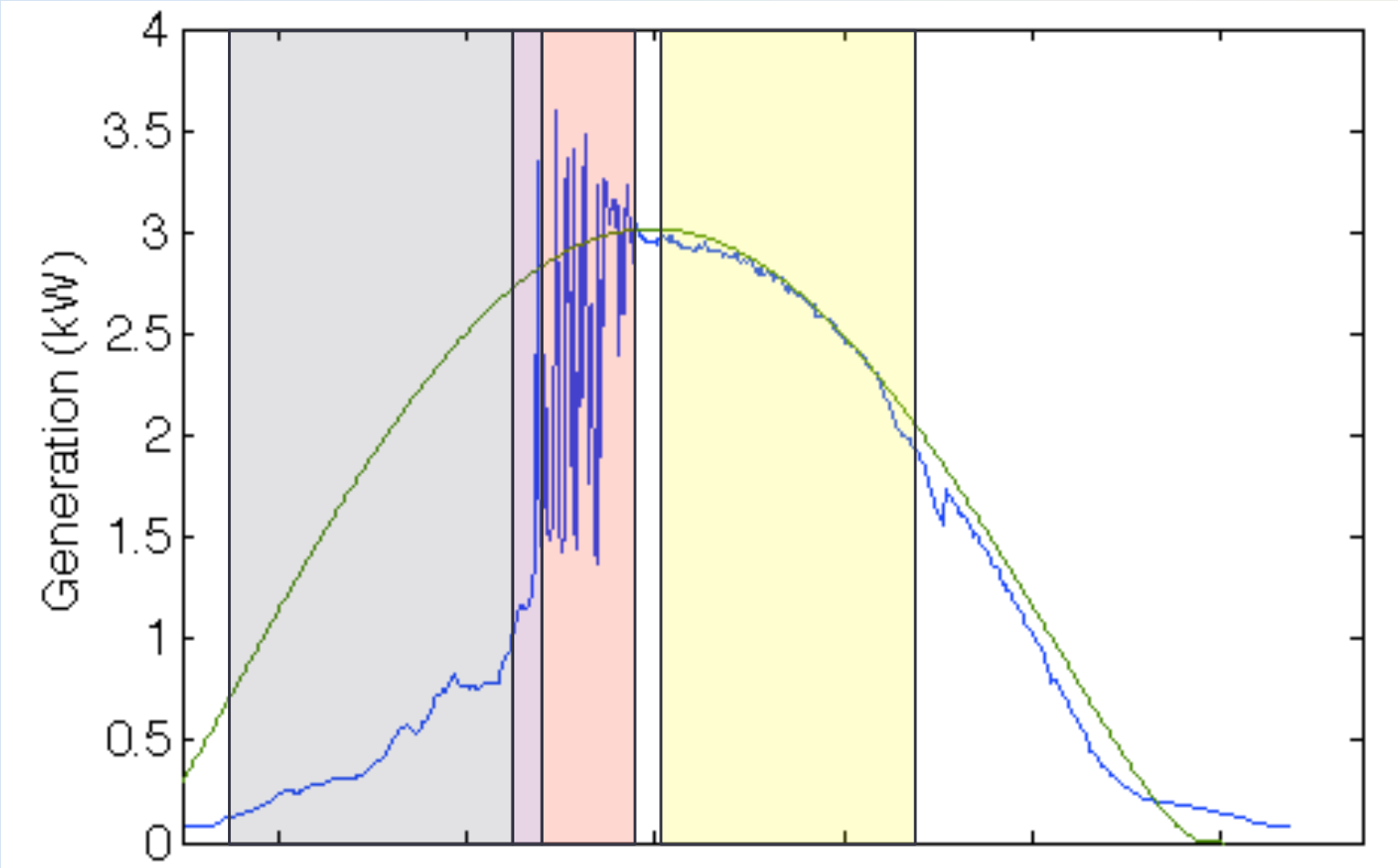


Fresno (above), LA (below)





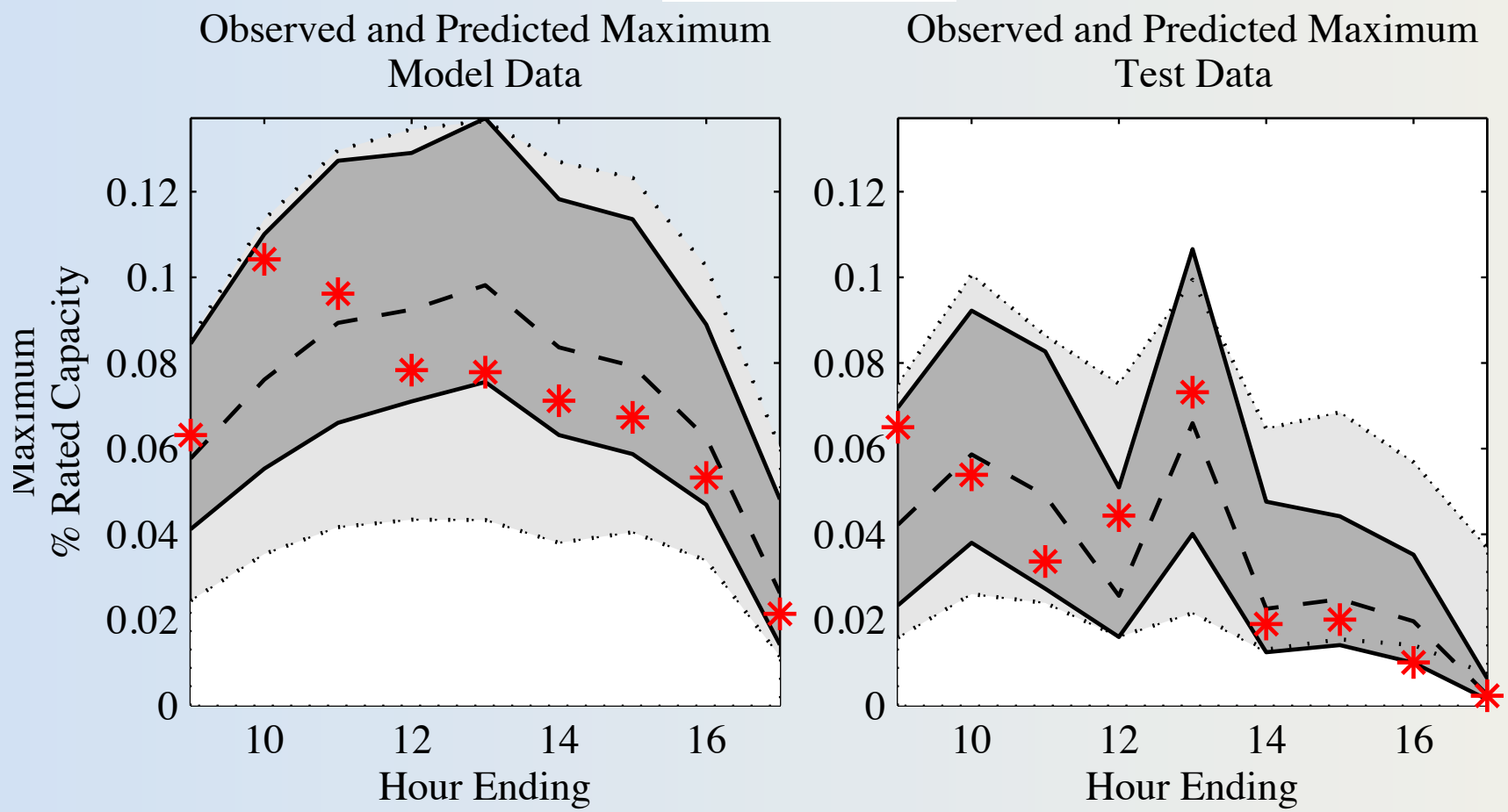
Variability analysis: single site example



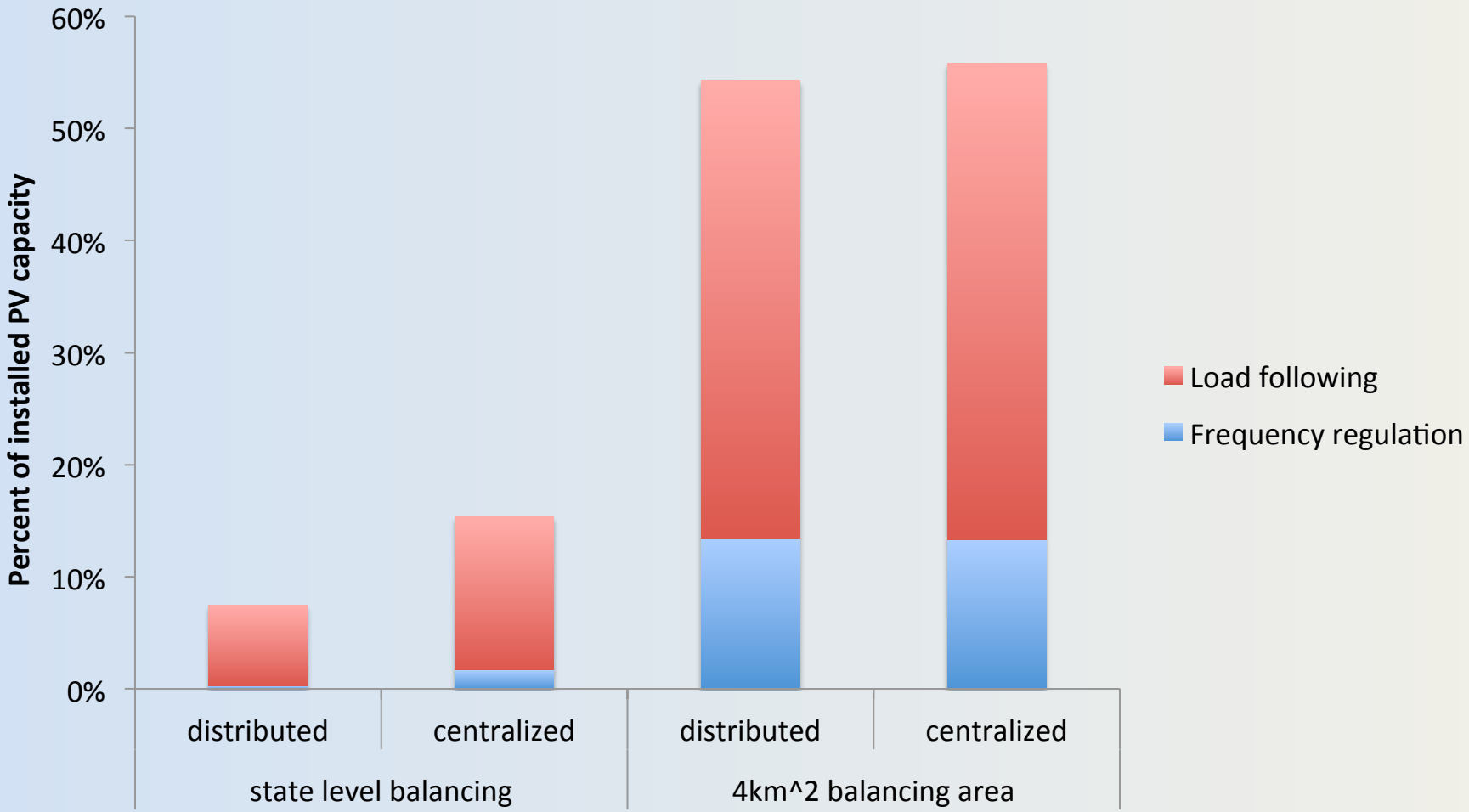
Variability analysis: model

- Model describes probability distribution of dispatched frequency regulation or load following for each 1-minute site in data set
  - Model includes different dispatch requirements for different weather conditions
  - Captures spatial autocorrelation between sites
  - Models requirements for PV in isolation
  - Very conservative (accurate) forecast error model
- Uses 15-minute data as inputs to simulate statewide requirements

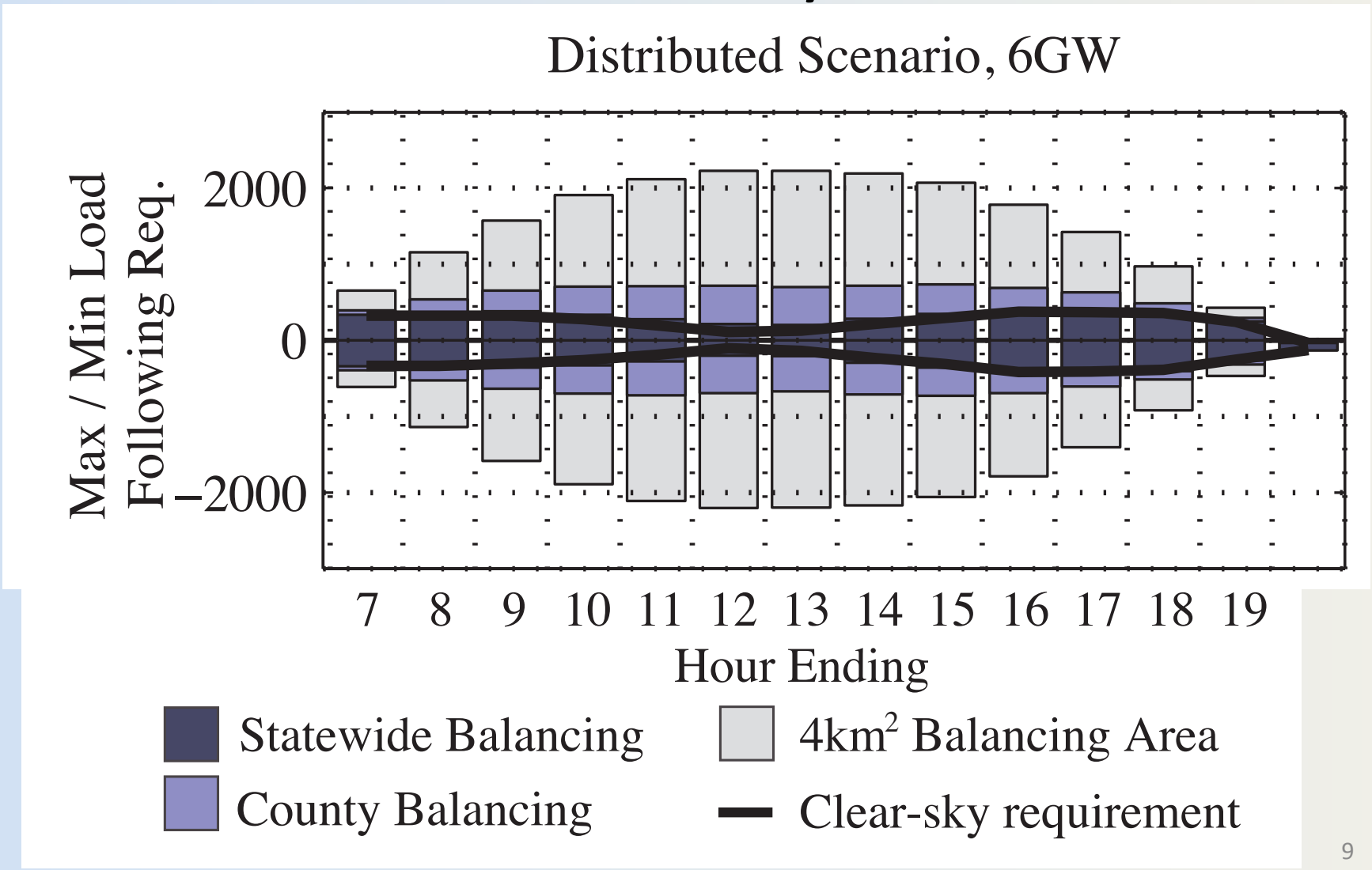
Variability analysis: model validation (load following)

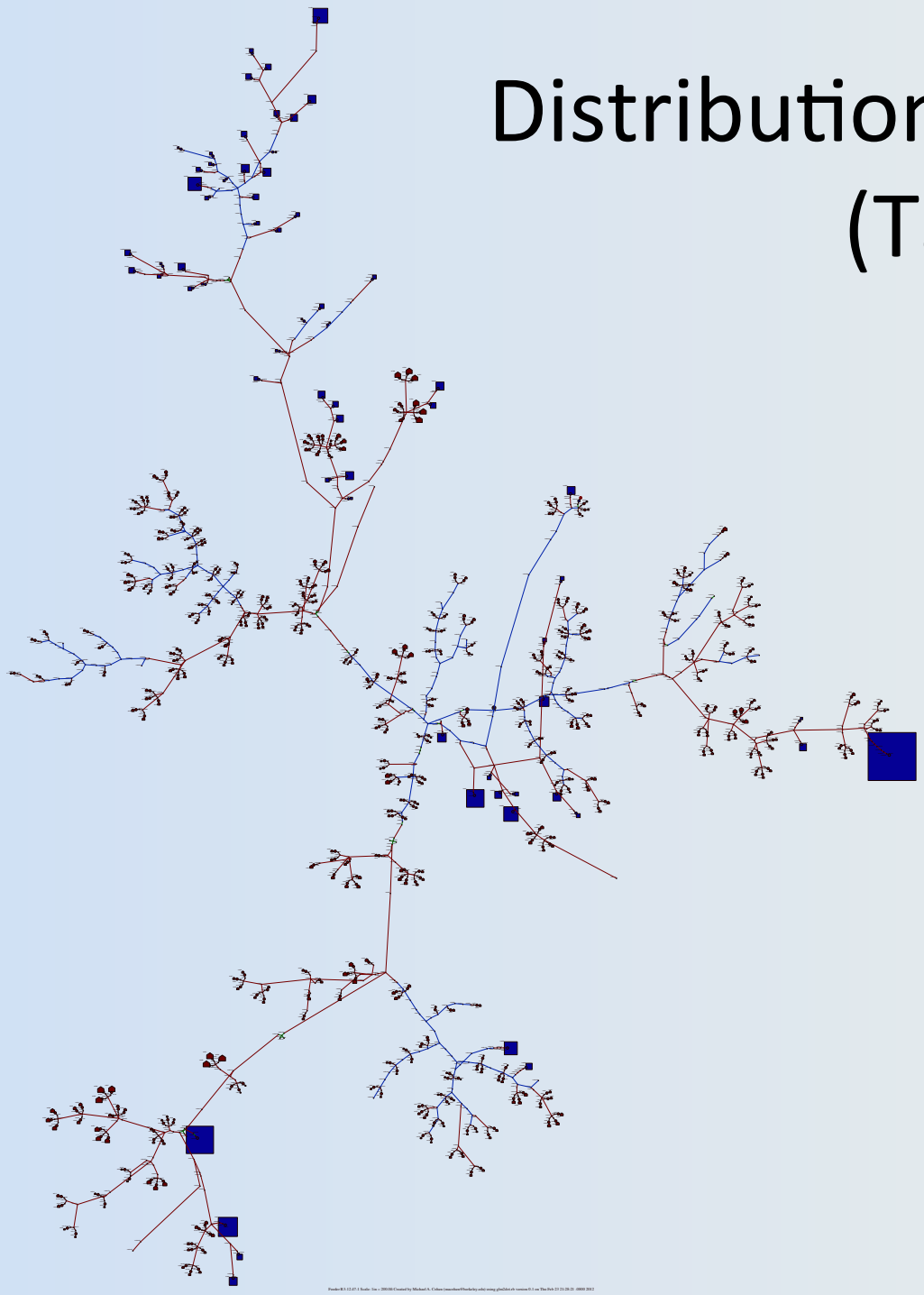


Variability analysis: operational impacts



Variability analysis: requirements vs. clear sky



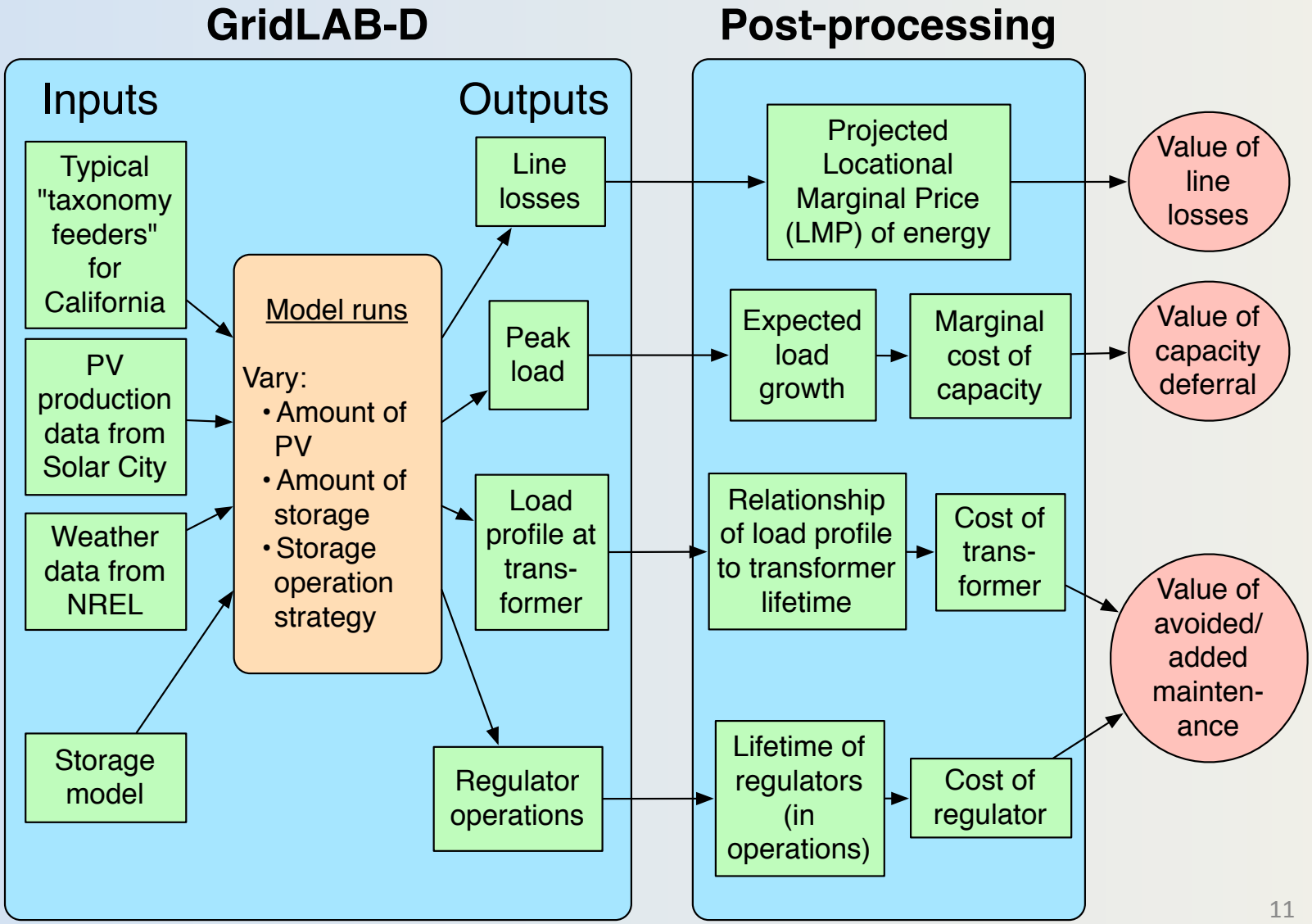


Distribution system impacts (Task 4.3)

Research questions

- How do physical impacts of distributed PV and storage vary with PV penetration?
  - Substation capacity
  - Resistive losses
  - Transformers
  - Voltage regulation
- What are the economic implications, in the context of load serving entity costs?

Distribution impacts: Basic framework



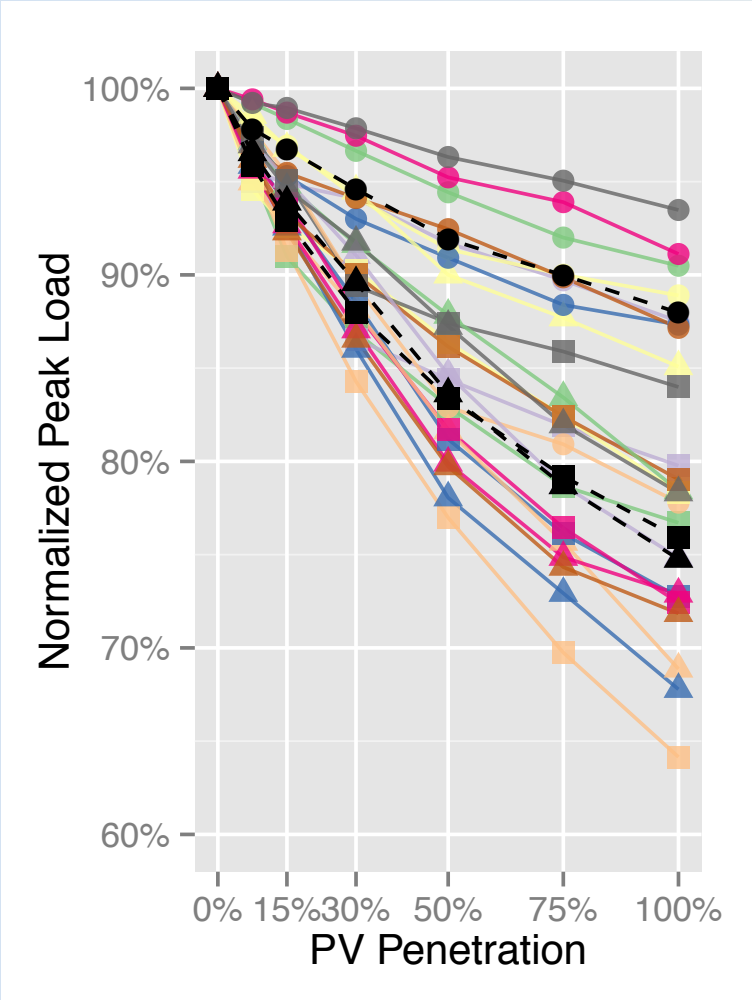
Distribution impacts: Feeders used

	Name*	Serves [6]	Nominal Peak Load (MW) [6]	Dist. Trans-formers	Avg House (kW) [7]	Approx Length (km)	Baseline Peak Load (MW) Berk.	L.A.	Sac.
	R1-12.47-1	mod. suburban & rural	7.15	618	4.0	5.5	5.56	5.38	7.59
	R1-12.47-2	mod. suburban & lt. rural	2.83	264	4.5	10.3	2.00	2.04	2.82
	R1-12.47-3	moderate urban	1.35	22	8.0	1.9	1.27	1.25	1.60
	R1-12.47-4	heavy suburban	5.30	50	4.0	2.3	4.31	4.09	5.65
	R1-25.00-1	light rural	2.10	115	6.0	52.5	2.35	2.23	3.00
	R3-12.47-1	heavy urban	8.40	472	12.0	4.0	6.64	6.30	8.70
	R3-12.47-2	moderate urban	4.30	62	14.0	5.7	3.45	3.27	4.40
	R3-12.47-3	heavy suburban	7.80	1,733	4.0†	10.4	7.54	7.00	9.67

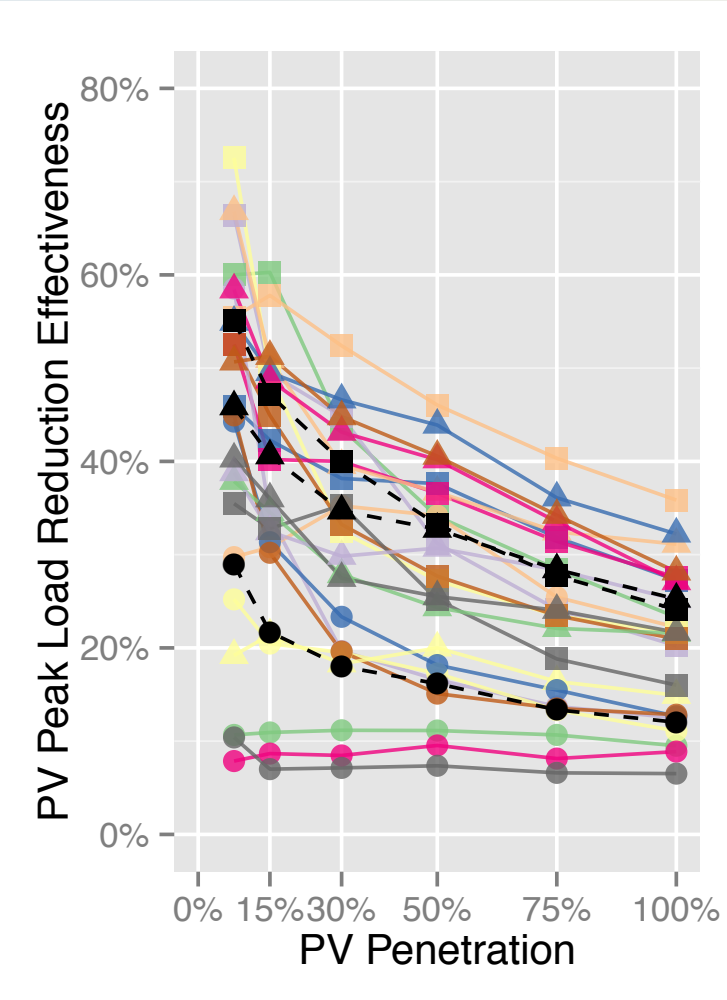
In subsequent figures, shape indicates Berkeley (square), Los Angeles (circle) and Sacramento (triangle) results

Distribution impacts: Site selection example

Distribution impacts: Peak load reduction

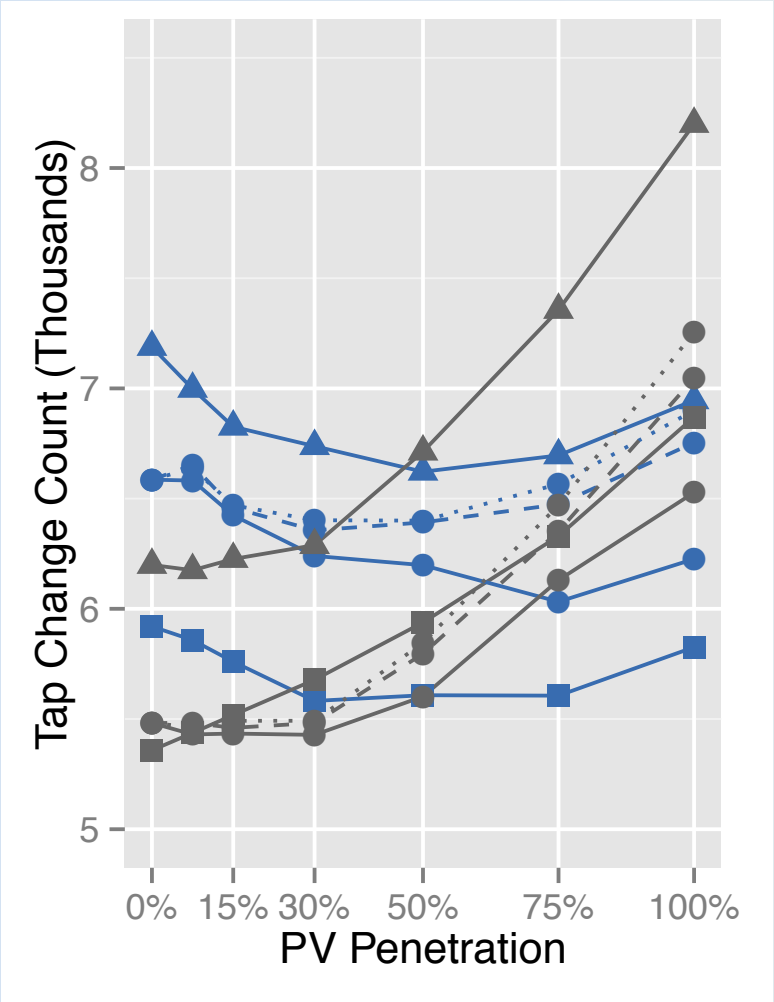


(a) Normalized peak loads.

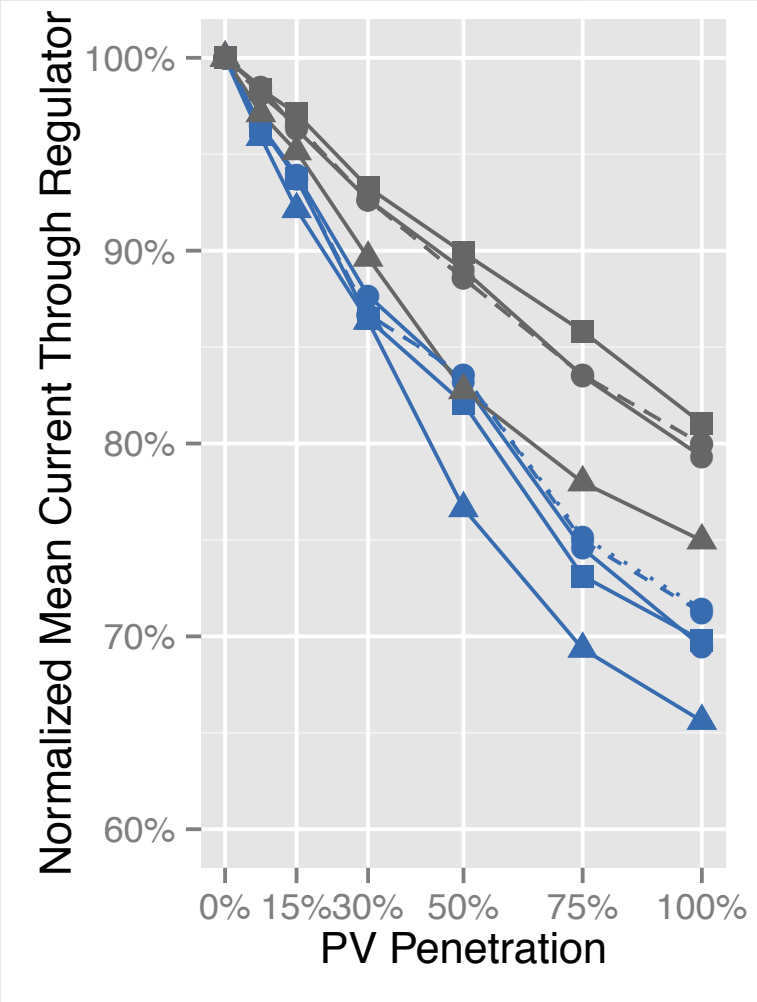


(b) Ratio of peak load reduction to penetration

Distribution impacts: voltage

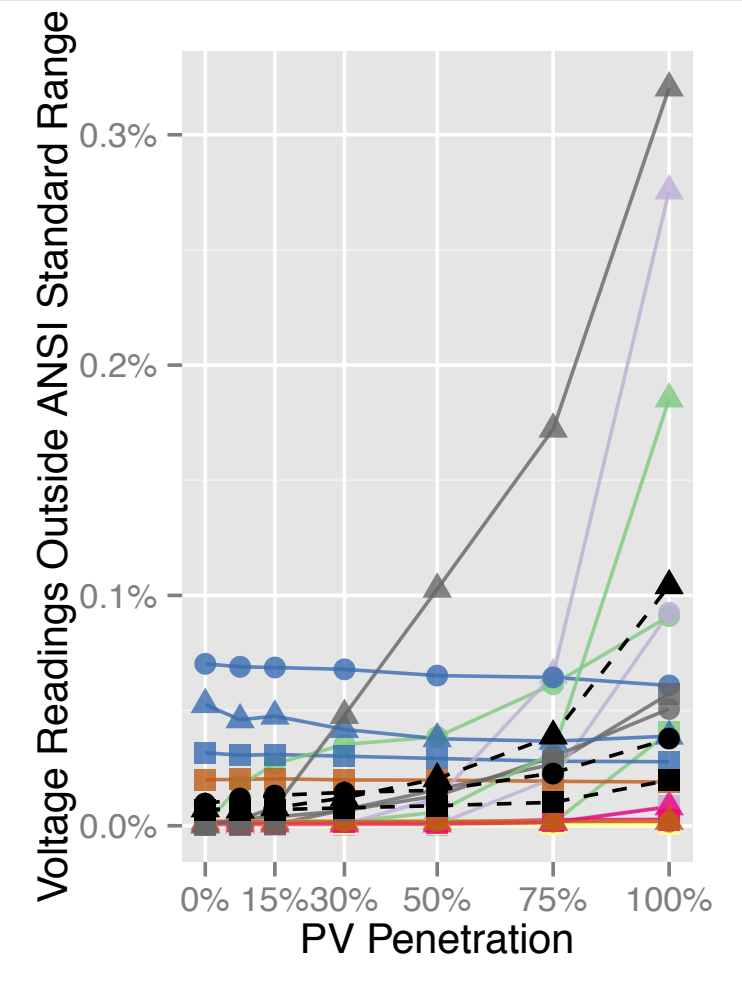


(a) Tap changes.

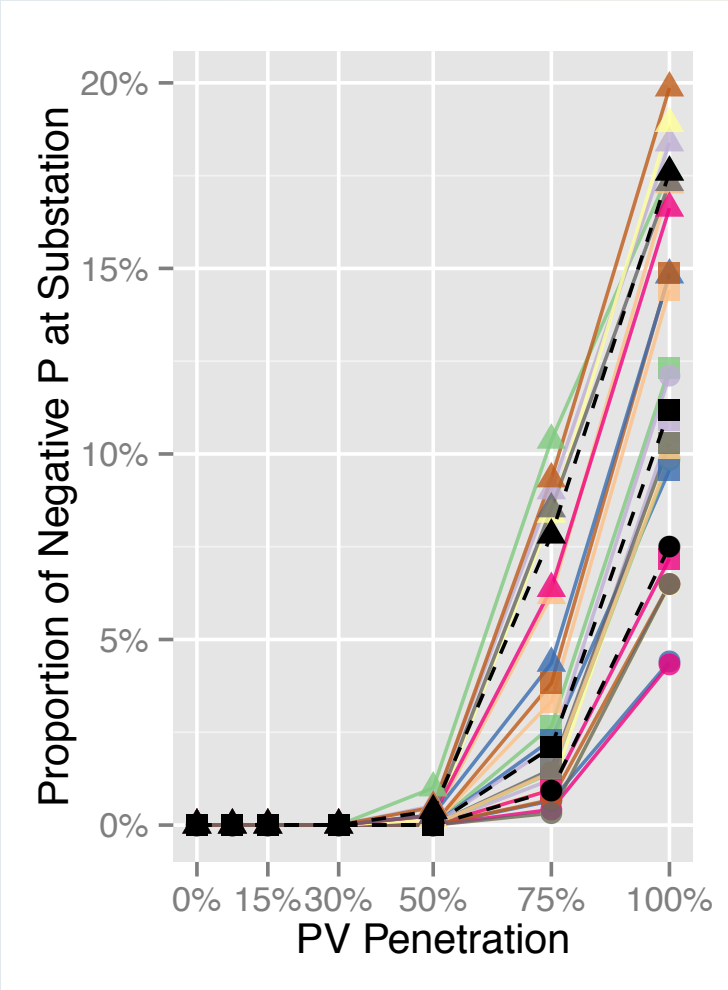


(b) Mean current duty.

Distribution impacts: voltage (2)



(a) Proportion of voltages outside ANSI standards.



(b) Incidence of negative real power flow through substation.

Distribution impacts: economic model

- Major cost considerations:
  - Avoided wholesale purchases; includes reduction in resistive losses
  - Deferred capacity expansion; cost data taken from PG&E workpapers submitted for last rate case
  - All other costs deemed negligible based on simulated engineering impacts
- Major findings:
  - Avoided energy purchases save **3.5¢/kWh** of PV generated
  - Substation capacity upgrade deferral benefit of **0.2-0.7¢/kWh** of PV generated

Systemic benefits of control (Task 4.4)

Objectives

- Develop storage control algorithms that can be decentralized with low computing requirements
- Understand how the value of storage changes at the transmission level
  - As a function of the amount of energy capacity available
  - Including energy shifting and ancillary services
- Today will focus on value at transmission level

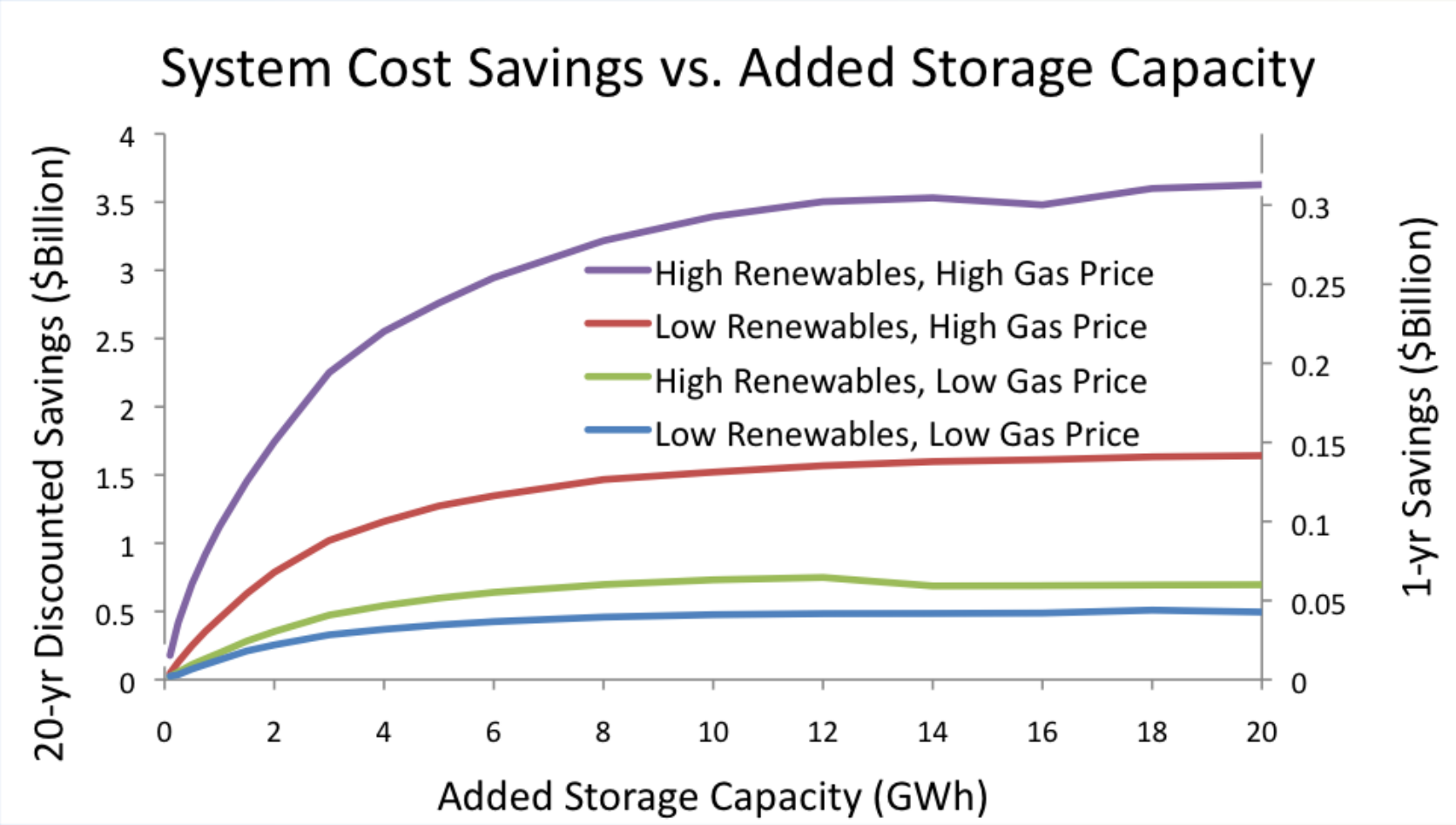
Systemic benefits: model description

- 240 bus reduced form model of WECC developed by Jim Price at CAISO
  - DC power flow
- Mixed integer programming approach to
  - First locate storage optimally
  - Then run unit commitment of generators and economic dispatch of generators and energy storage for one year of data
- Storage can
  - shift energy (arbitrage)
  - provide 2 hour reserve ("load following")
  - provide 15 minute reserve ("AGC").

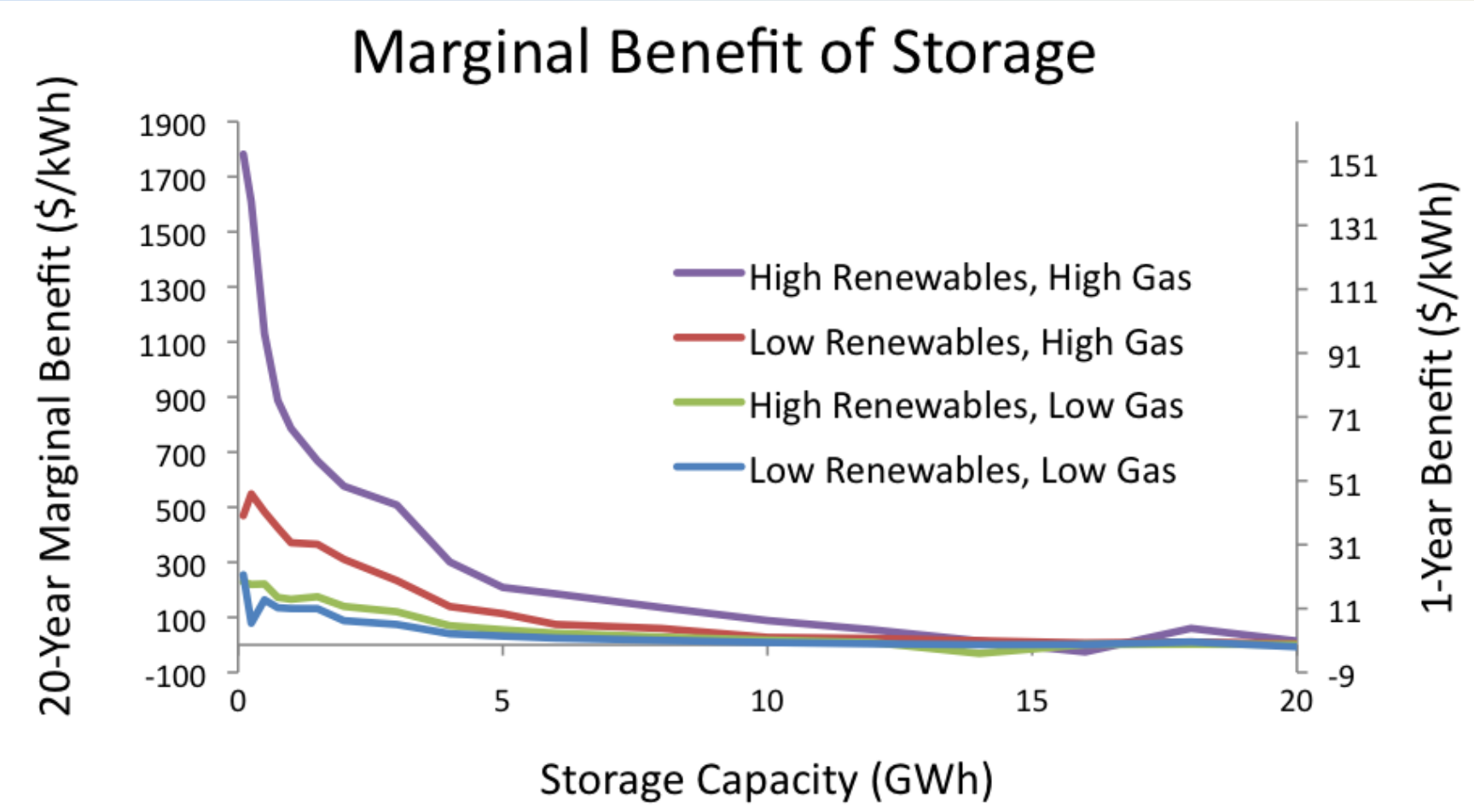
Study scenarios focus on fuel price and renewables penetration

- 20 RPS vs. 33% RPS in California (taken from Price model)
  - 20% scenario: 6.5 GW wind, 0.5 GW solar
  - 33% scenario: 24.7 GW wind, 7 GW solar
- 2007 fuel prices vs. 2012 fuel prices
  - 2007: Gas: $7.09/MMBtu, Coal: $1.77/MMbtu
  - 2012: Gas: $3.14/MMBtu, Coal: $2.22/MMBtu

Systemic benefits: total operating cost impact



Systemic benefits: marginal operating cost impact



NOTE: This does not include any potential capacity value

Conclusions

- Distributed PV impact on AGC, LF impacts potentially very small
  - Local storage can balance, but capacity requirements much greater than centralized
  - Centralized PV locations could have larger AGC, LF impacts than previous estimates
- PV impact on distribution systems small; net benefit on the order of 4 cents per kWh PV
- Storage marginal value rapidly declines in near-term systems

Energy Storage Commercialization Beyond RD&D

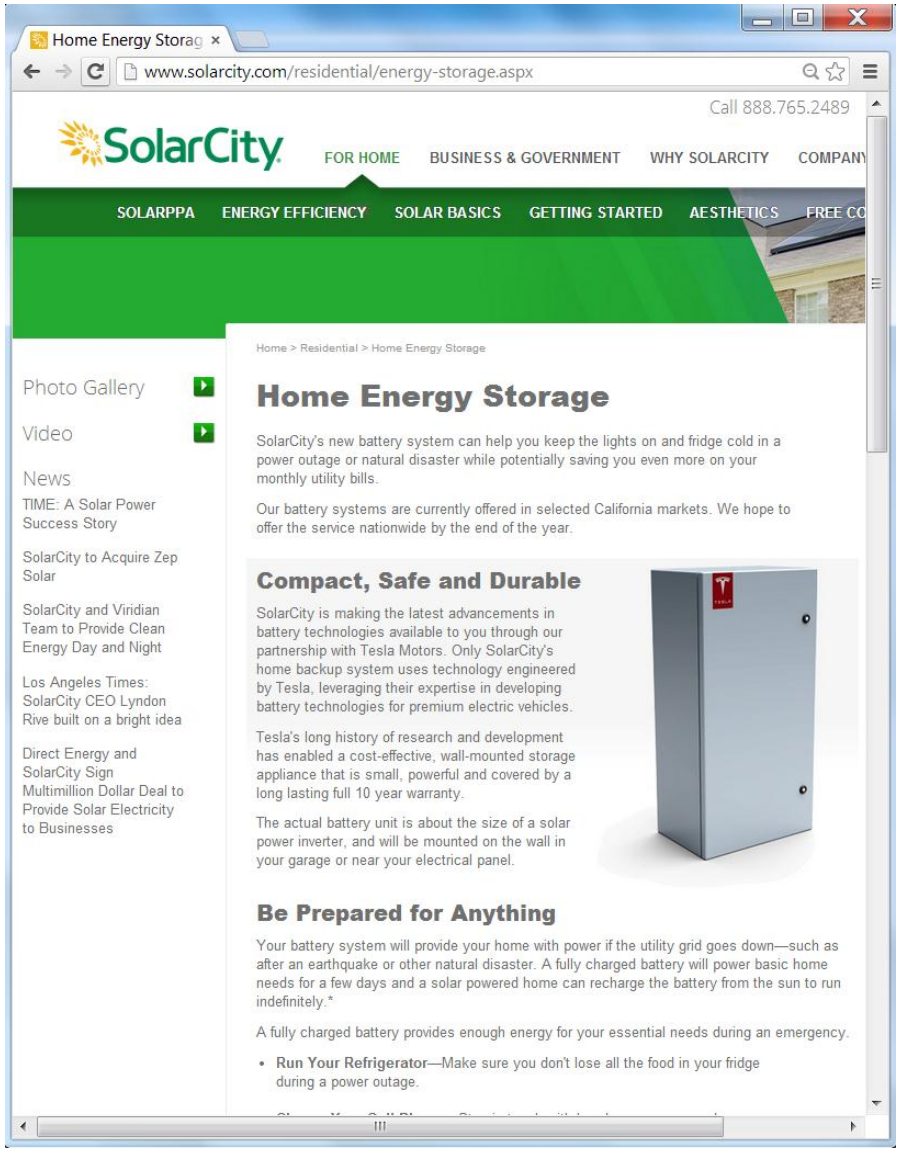
Interconnection Challenges

As of July 1, 2013, there were 667 active incentive applications in the SGIP queue for storage systems, totaling 33 MW of capacity. Of these, 319 applications, totaling 10 MW of capacity, are for storage paired with RPS-eligible generating facilities, primarily rooftop solar PV [emphasis added]. While the incentives provided by SGIP have supported increased storage deployment, ***the majority of these paired storage and generation applications have stalled during the interconnection process due to the lack of clear policy guidance*** *on their eligibility for the NEM tariff schedule, which describes the NEM billing credits, exemptions from various charges, and metering arrangements.*

Source: Assigned Commissioner's Ruling Regarding the Interconnection of Energy Storage Systems Paired with Renewable Generators Eligible for Net Energy Metering (ACR) in Rulemaking (R.) 12-11-005

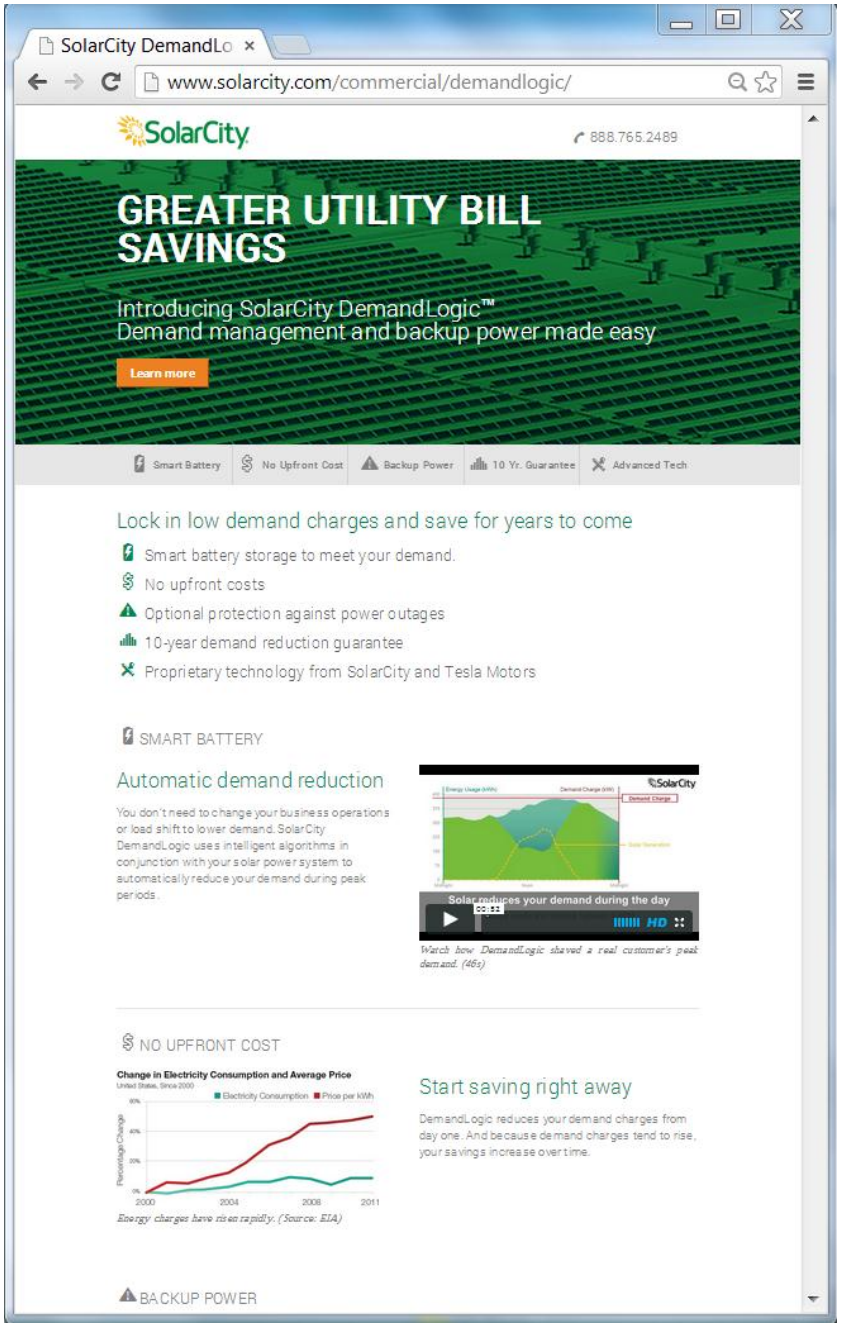
Residential Deployments

- Expanded Pilot in California
  - 20-30 installations per week
  - 5 kW / 10 kWh Tesla Li-ion system
  - SGIP program funding



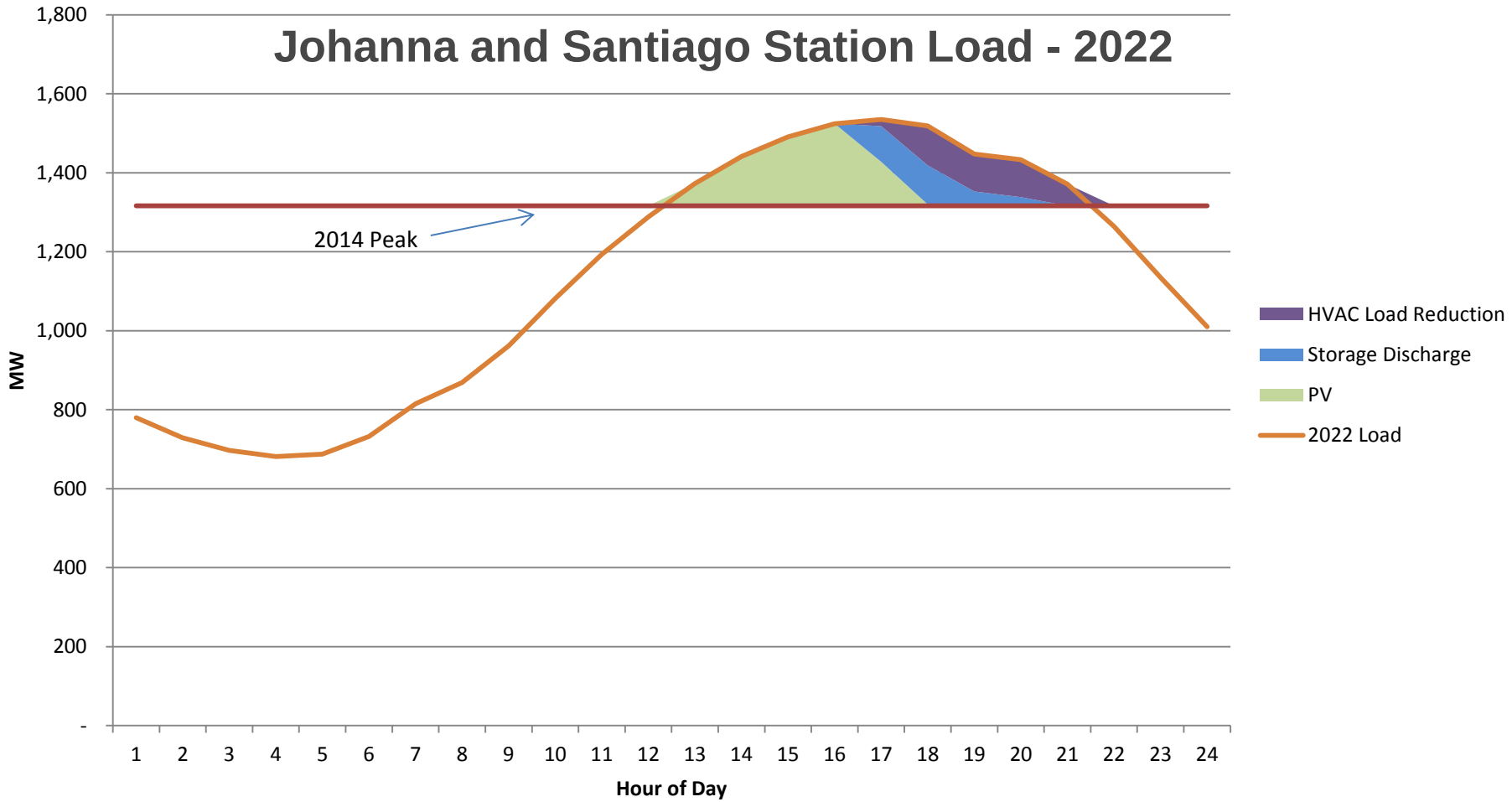
DemandLogic C&I Demand Management

- 10-year guaranteed Demand Reduction service
- Zero upfront cost
- Available in California, Connecticut and Massachusetts
- Tesla advanced Li-ion battery
- Sales launched December 5th, 2013



CPUC Preferred Resources Pilot Proposal

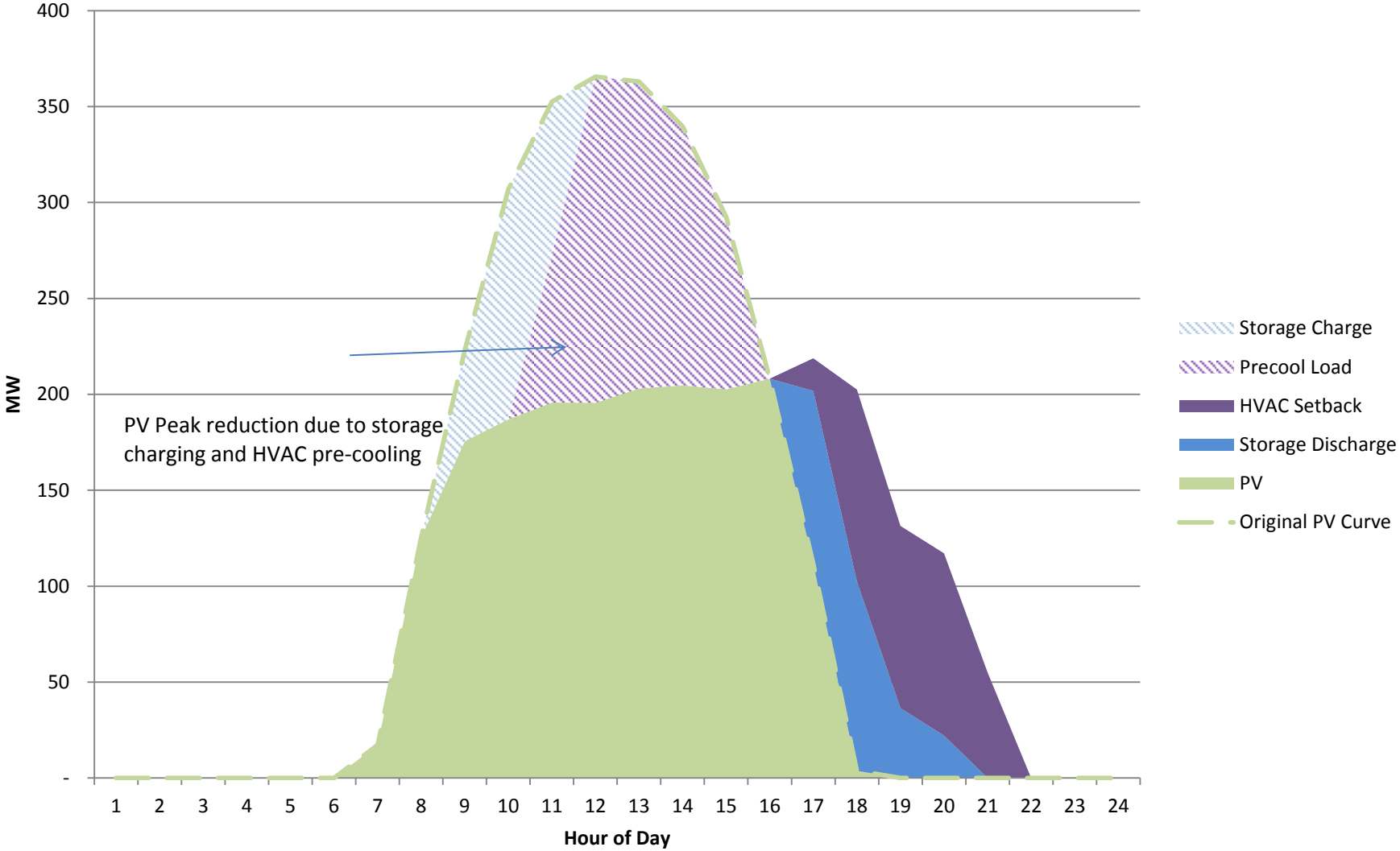
Replacing SONGS Capacity



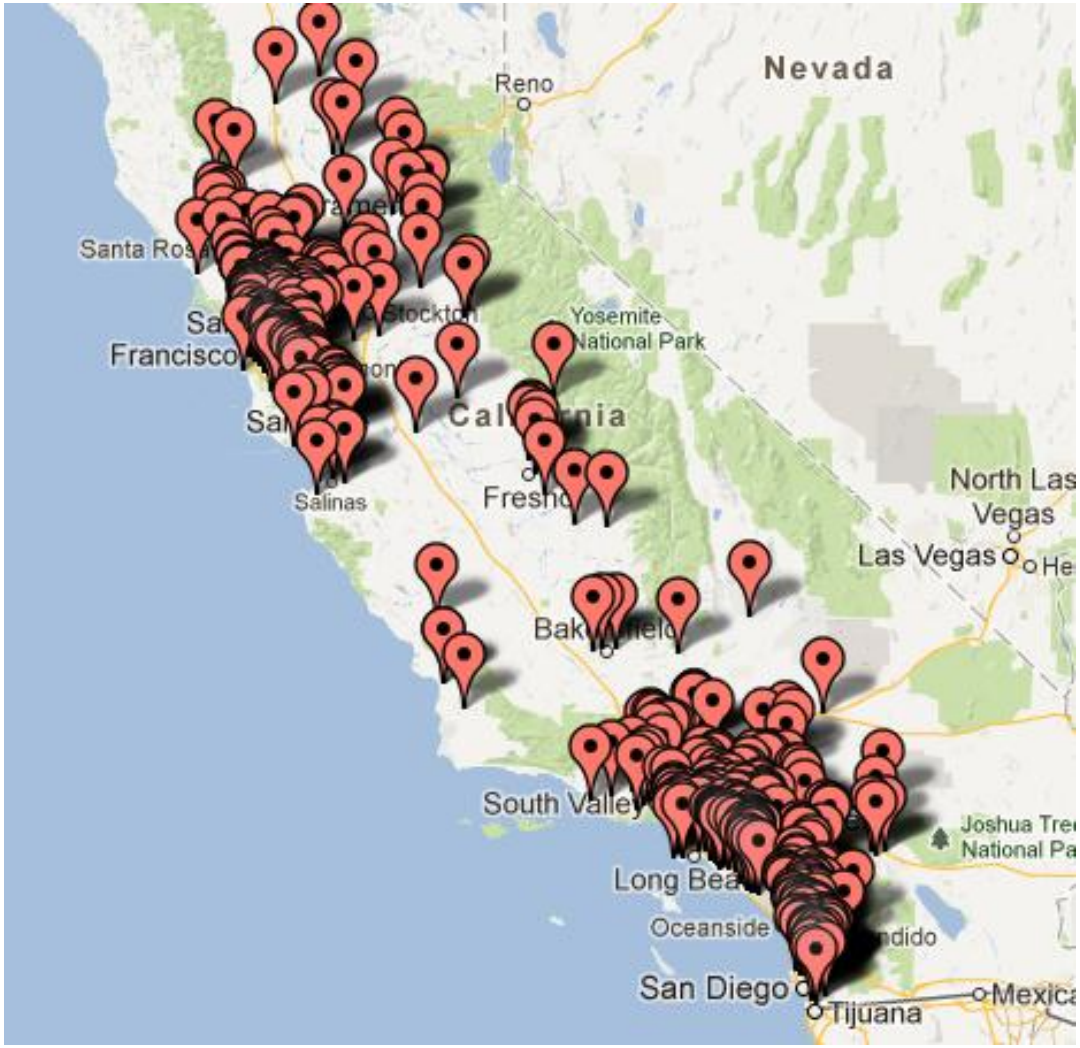
Source: SolarCity Proposal for SCE Living Pilot Symposium

Replacing SONGS Capacity

Impact of Storage and Pre-cooling on Solar Profile



What Next for SolarCity and PV+Storage?



Forward-Looking Statements

This presentation contains forward-looking statements that involve risks and uncertainties, including, but not limited to, statements regarding SolarCity's customer and market growth opportunities, the future development, impact and benefits of energy storage technology, and assumptions relating to the foregoing.

Forward-looking statements should not be read as a guarantee of future performance or results, and will not necessarily be accurate indications of the times at, or by, which such performance or results will be achieved, if at all. Forward-looking statements are subject to risks and uncertainties that could cause actual performance or results to differ materially from those expressed in or suggested by the forward-looking statements. You should read the section entitled "Risk Factors" in our registration statement on Form 10-Q, which has been filed with the Securities and Exchange Commission and identifies certain of these and additional risks and uncertainties. We do not undertake any obligation to publicly update or revise any forward-looking statement, whether as a result of new information, future developments or otherwise, except as otherwise required by law.

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