# Advanced Grid-Interactive Distributed PV and Storage

CSI RD&D Program – Progress Update

October 10th, 2012

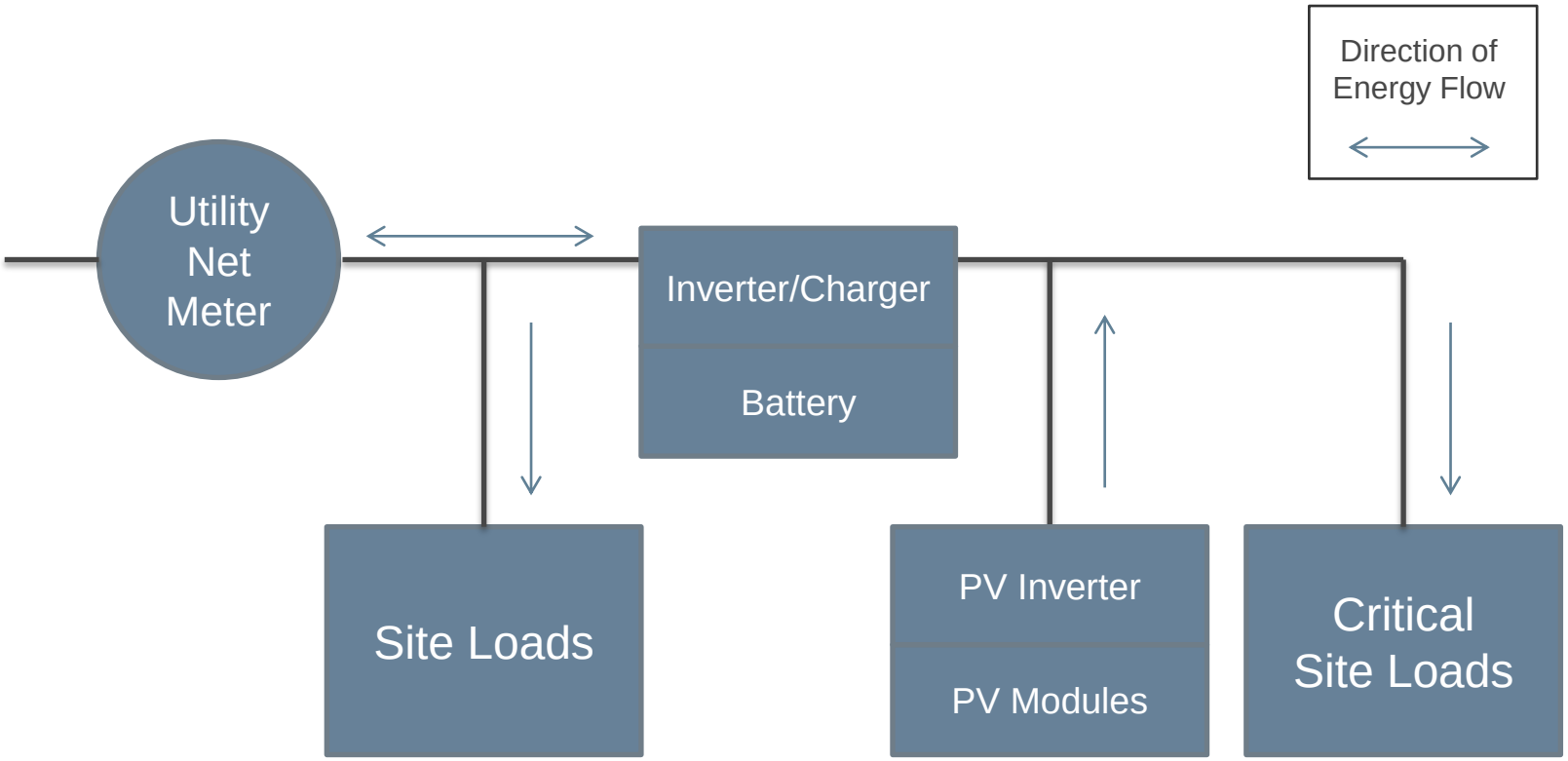
# Project Goals Overview

- **Objective :** Demonstrate integrated PV and battery storage technology that will enable cost effective load shifting, demand reduction and reduced needs for conventional ancillary services.
  - Demonstrate communication and control technology platform.
  - Demonstrate advanced lithium-ion (Li-ion) battery storage technology platform.
- **Objective:** Show that advanced, distributed, PV-coupled, grid-interactive storage solutions will reduce cost and carbon emissions and improve grid reliability and security.
- **Objective**: 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

- Task 1
  - Grant administration
- Task 2
  - Install lead-acid pilot systems
  - Internet-based storage control platform
- Task 3
  - Stationary Li-ion battery integration
  - Install Li-ion pilot systems
- Task 4
  - Marketing analysis of perceived customer benefits
  - PV variability analysis
  - Retail and distribution benefits analysis
  - Aggregate control methods
  - Balancing authority benefits
  - Storage financing methods

# PV and Storage System Components



# Task 2.1: Storage Pilots with Lead Acid Batteries

- Three residential installations

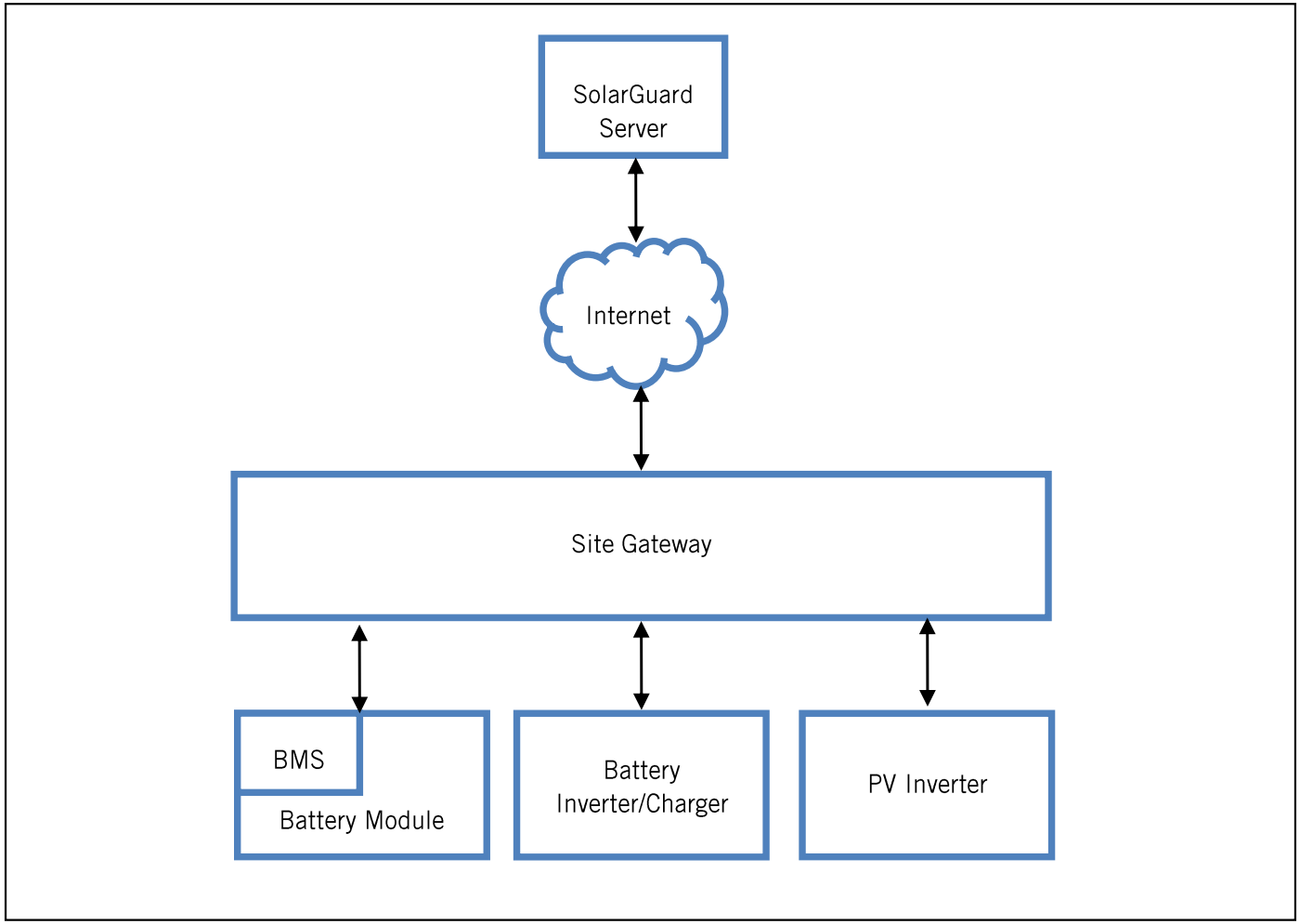
# Task 2.1: Key Lessons Learned From Lead-acid Pilots

- **Space Constraints**
  - Wall and floor space are a premium
  - Floor mounted batteries in garages are a collision concern
  - Outdoor rated equipment options are extremely limited
- **Power Electronics**
  - Native 120/240 VAC split-phase power electronics outputs simplify interconnection
  - Power electronics with partial 120 VAC support require significant additional balance-of-system for many sites
- **Electrical Code Compliance**
  - UL Listing is incomplete for many components due to unpermitted “Off-grid” historical applications

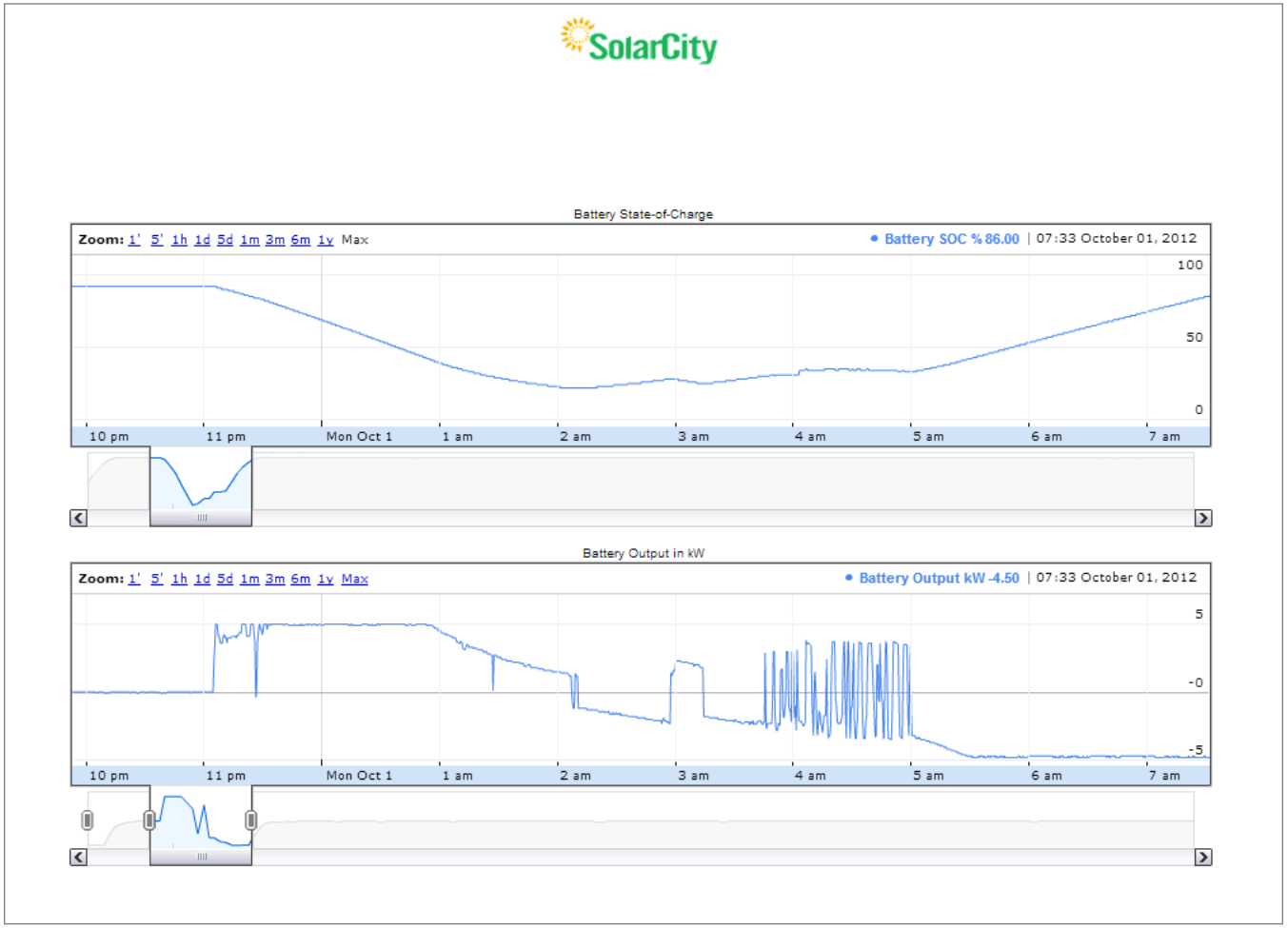
# Task 2.1: Lead-acid Pilots At Commercial Installations

- 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.

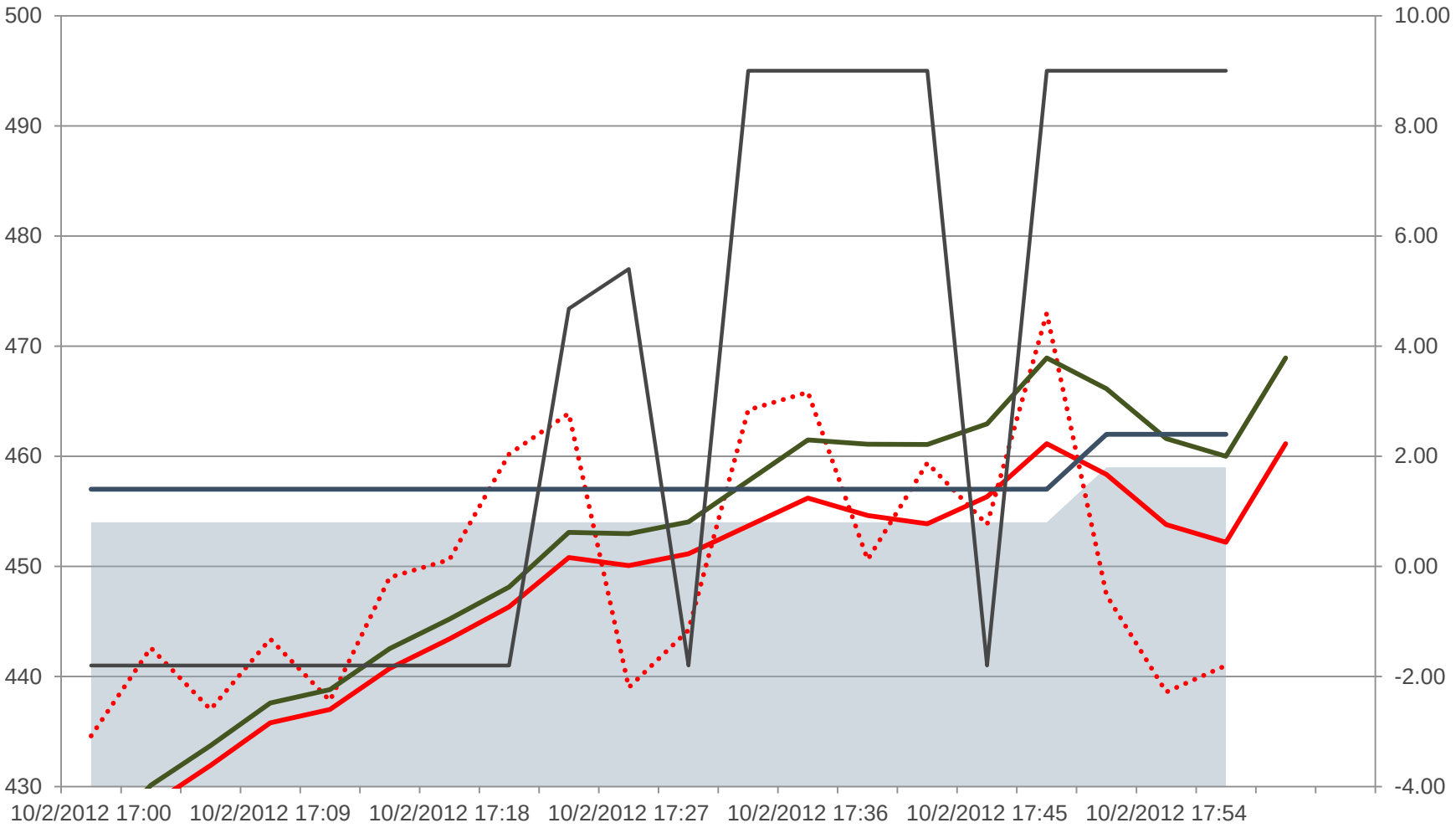
# Task 2.2: Storage Control System



# Task 2.2: Storage Control System Interface



# Task 2.2: Storage Control System Data



# Task 2.2: 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 intelligence** – Central, server driven control best optimizes a fleet of systems, but most data processing and decision making is best done locally

# Task 3.2: Li-ion Pilots - Commercial

- Three commercial sites
  - Site A: Construction completed. Awaiting final interconnection approval
  - Site B: Construction completed
  - Site C: Construction in progress

# Task 3.2: Li-ion Pilots – Commercial

# Task 3.2: Li-ion Pilots - Residential

# Task 3.2: Li-ion Pilots – Key Lessons

- **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 education is needed. Requirements are uncertain for fire and chemical safety documentation of energy storage.
- **Physical Space** – Even with high density Li-ion storage, indoor space in retail environments is extremely limited. Weatherized power electronics are needed.

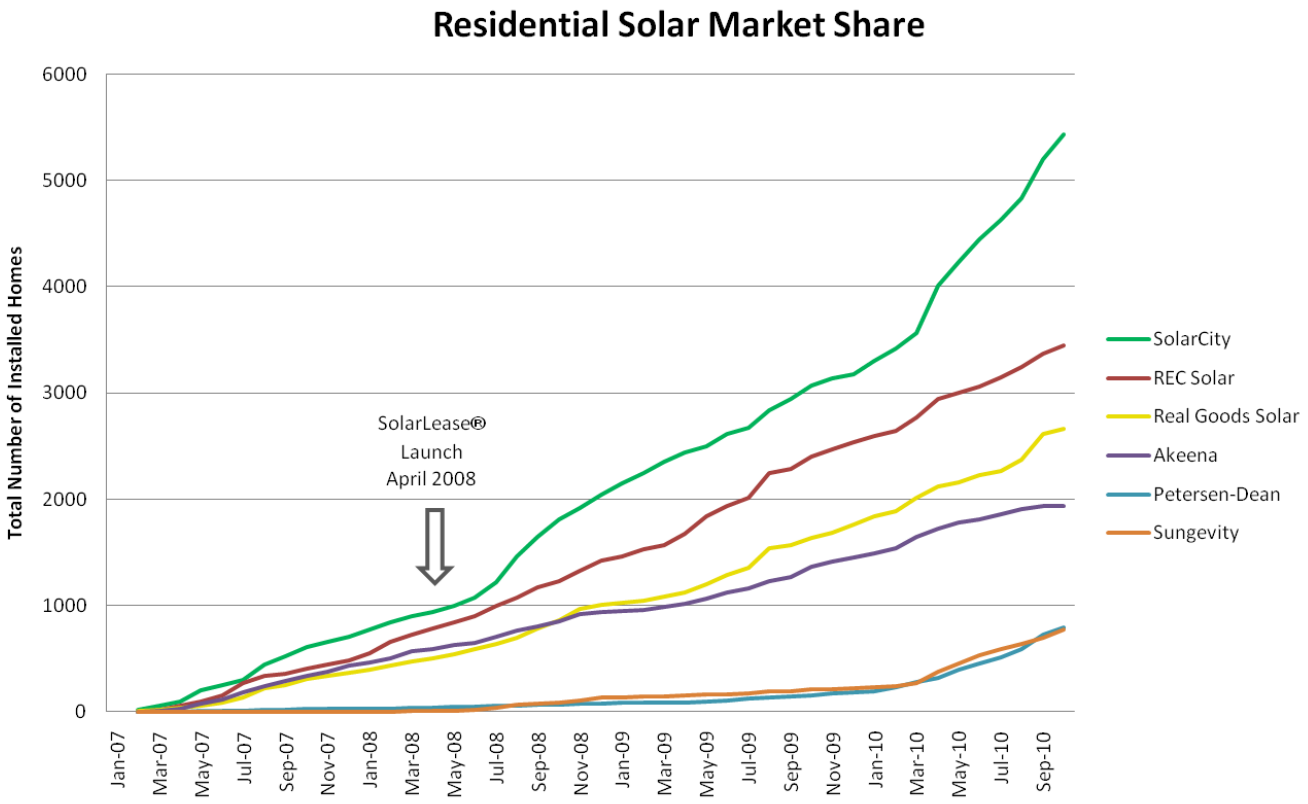
# Task 3.2: Interconnections

- Utility interconnection charges comprise a significant portion of installation costs for residential applications
  - PG&E requires technical review of individual UL 1741 listed inverter models when backup power features are included

| Interconnection Item | PV | Storage + PV |
|---|---|---|
| NEMMT NGOM Meter | - | $700+ |
| Rule 21 Interconnection Request Fee | - | $800 |
| Rule 21 Supplemental Review Fee | | Up to $2,500 |
| Departing Load Charges | - | To be determined |
| Standby Load Charges | | To be determined |
| **Total** | **$0** | **$1,500 – 4,000+** |

# Task 4.6: Finance Mechanisms for Storage

- High capital costs are a significant barrier to customer adoption of new technologies
  - Finance mechanisms reduce barriers to widespread deployment



# Task 4.6: Finance Income Sources

- Viability of financing dependent on reliable, long term income sources

| Value Proposition | Financing Challenge |
|---|---|
| **Renewable Integration** | • Amount and collectability of income is difficult to predict due to volatility of bidding prices<br>• Many states do not have regulations that require renewable integration |
| **Distribution Infrastructure Support** | • Regulatory environment needs to change before the infrastructure benefits can be efficiently realized and priced/financed |
| **Retail Energy and Power Management** | • Time-of-use energy rate differences have limited value<br>• Demand charges are limited to commercial tariffs |
| **Local Power Quality and Reliability** | • Determining the value of local energy management is difficult due to the lack of a large, well-developed and transparent marketplace |

# Task 4.6: Finance Structures

- Investors typically choose structures based on past experience and assessment of risks

| Finance Mechanism | Structure | Typical Criteria for Use |
|---|---|---|
| Sale Leaseback | • Investor retains ownership of asset<br>• Investor entitled to all cash and tax benefits | • Investor willing to consolidate asset on balance sheet<br>• Investor comfortable with longer term interest in project |
| Inverted Lease | • Developer retains ownership of asset<br>• Investor receives benefit of asset (i.e. use of asset or cash from sublease of asset) and tax credits if available | • Depreciation not valued by investor<br>• Investor more comfortable with operating risk |
| Partnership Flip | • Investor retains ownership of asset<br>• Investor entitled to share of benefits (i.e. use of asset, tax benefits, cash) | • Investor comfortable with longer term interest in project |
| Pure Debt | • Developer retains ownership of asset<br>• Debt secured by asset | • Investor only values cash benefits<br>• Significant, predictable, secure income |

# Stationary Energy Storage

October 2012

# Stationary Energy Storage

- Context & Applications
- Technology Development
  - Initial Prototype
  - Field Prototypes
  - Tesla GTB-X – 10kWhr Grid Tied Battery
- Current Work

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# Context & Applications

- Battery energy storage for:
  - Solar firming
  - Peak shaving
  - Ancillary Services
- Why Tesla?
  - Leverages high volume vehicle development and production designs, processes, and capability, with focus on HV battery module engineering and safety.
    - Tesla will have existing capacity for 1.5GWh of annual module production by 2013, with up to 5GWh by 2015.
  - Using these modules in new configurations and packaging, Tesla can address new stationary storage applications and markets.

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# Initial Prototype

- 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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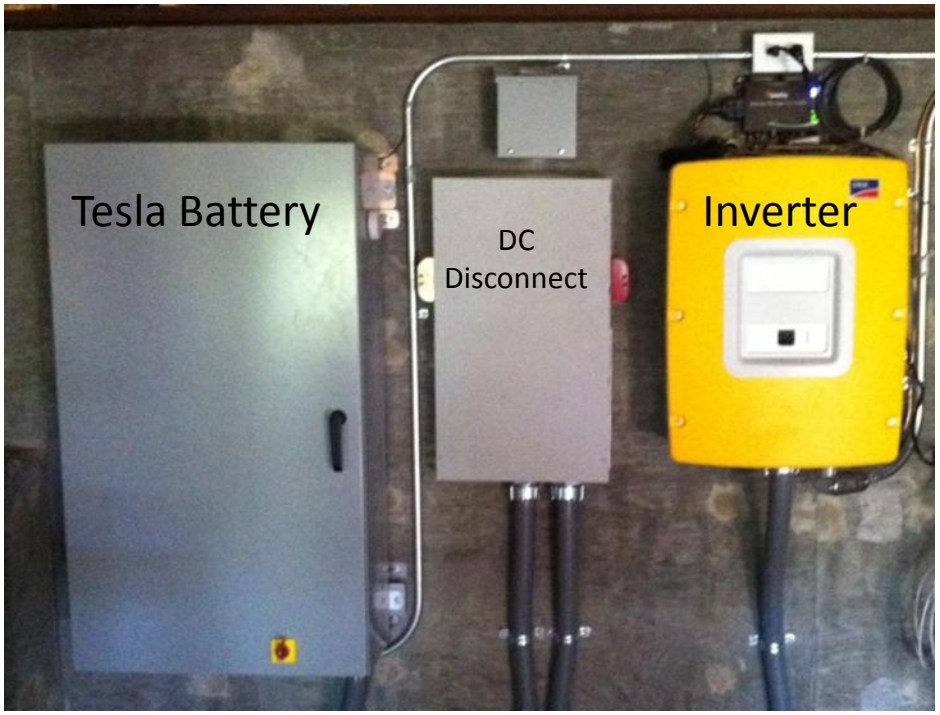
# Field Prototypes

- 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 Walmart 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
  - Listing expected Q4 2012
- 2 units to be delivered as part of Grant in October
- Initial production in Q4 2012

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# Tesla GTB-X Specifications

| Electrical | |
|---|---|
| Continuous power | 5 kW AC |
| AC Capacity @ 5kW (92.5% Inverter Eff) | 10 kWhr |
| Voltage, nominal | 56.25 V DC |
| Vmin | 40.5 V DC |
| Vmax | 63 V DC |
| Continuous current @ Vnom | 100 A DC |
| Peak current (55 sec) | 150 A DC |
| Peak current (30 sec) | 200 A DC |
| Peak current (15 sec) | 250 A DC |
| Max charge power | 3.3 kW AC |
| Max charge current @ Vnom | 65 A DC |

| Operating Temperatures | |
|---|---|
| Low Ambient Operating Temp | -20 C |
| High Ambient Operating Temp | 40 C |
| Derated operation above 40C | |

| DC Wiring | |
|---|---|
| DC wire gauge | 1/0 AWG |
| Integrated 125A DC breaker | |
| Separate DC wiring compartment | |

| Compatible Inverter/Chargers |
|---|
| Schneider/Xantrex XW6048 |
| SMA Sunny Island 5048U |

| Efficiency | E/2 \| E/4 |
|---|---|
| DC (battery only), roundtrip | 96% \| 98% |
| AC (including inverter), roundtrip | 81% \| 85% |

**Extended Capacity**

Multiple units can be paralleled on a common DC bus for greater capacity

**Backup / off-grid capability**

Automatic backup / off-grid functionality
Provides 1 week of backup power for an energy star refrigerator
Potentially unlimited backup capability if used with solar

**Communications**

Zigbee, GMS and CAN connectivity
Accepts instantaneous and scheduled charge/discharge

| Mechanical and Mounting | |
|---|---|
| Height x Width x Depth | 950x400x260 mm |
| Weight | 80 kg |
| Wall Mount | |
| Separate mounting bracket with clevis feature for easy installation | |
| NEMA 4 outdoor enclosure | |

**Regulatory**

UL listing to UL 1973 pending


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# Tesla GTB-X

- Design work included:
  - New electrical design to integrate battery modules based on Model-S
  - New module racking design for modules, scalable for larger units
  - Custom enclosure design for easy manufacturing, assembly and installation
  - Inverter control logic and wireless communications
  - UL compliance

Close up of wiring compartment and integrated DC branch protection (left) and Custom enclosures (right)

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# Advanced Grid-Interactive Distributed PV and Storage

CSI RD&D Webinar

October 10, 2012

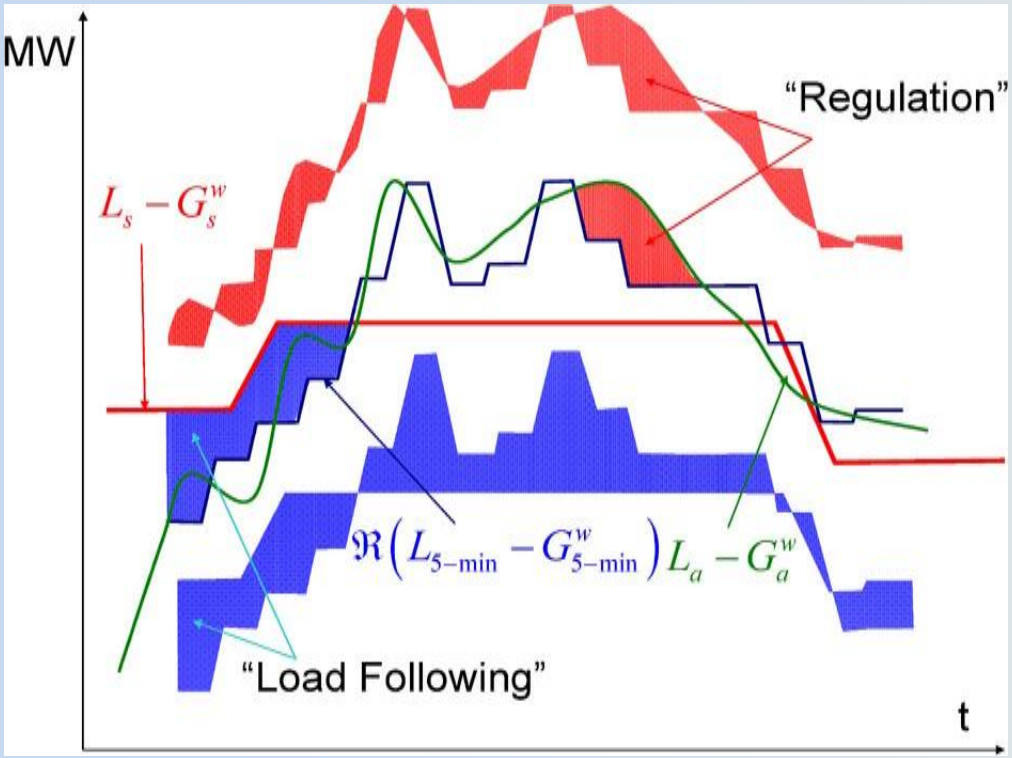
UC Berkeley:
PIs: Duncan Callaway and Dan Kammen

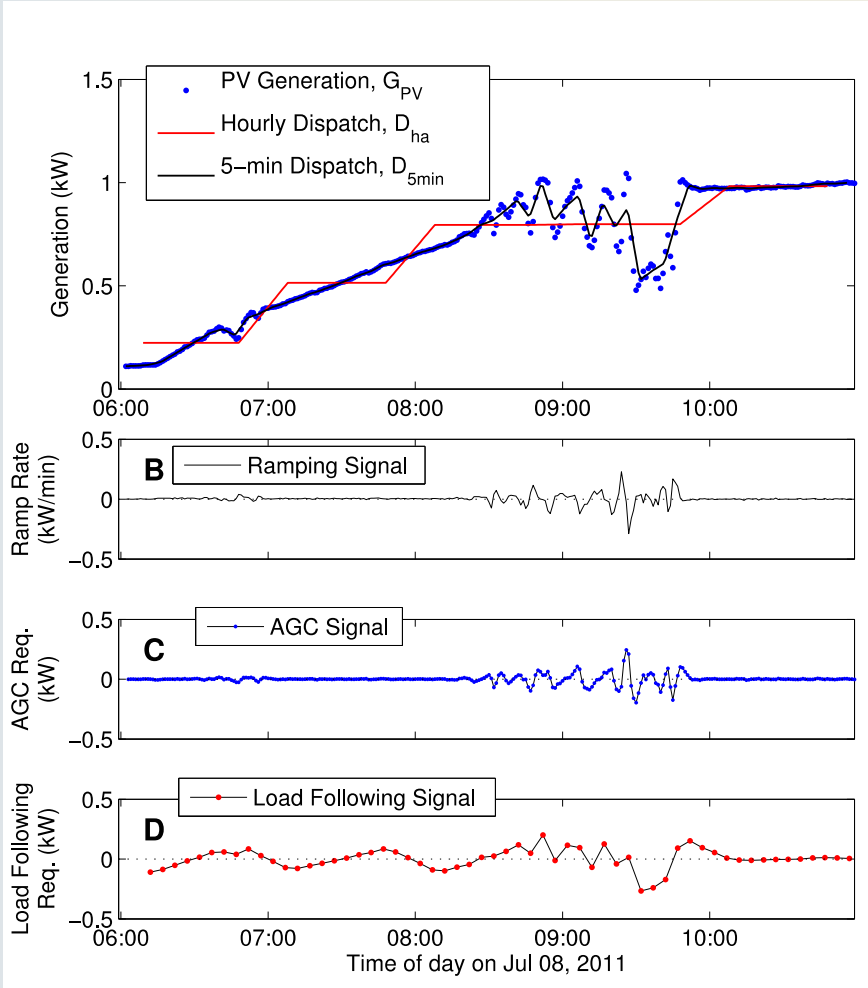
Students and Postdocs: Michael Cohen, Autumn Petros-Good, Michaelangelo Tabone, Josh Taylor

# Work 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

# Task 4.2: Variability analysis

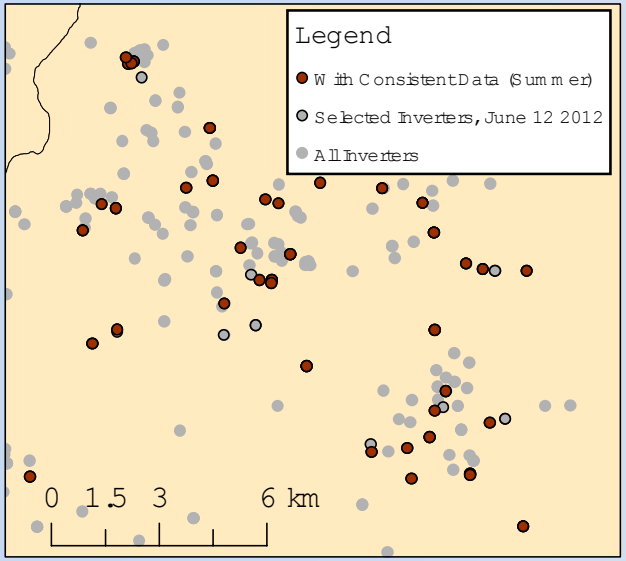


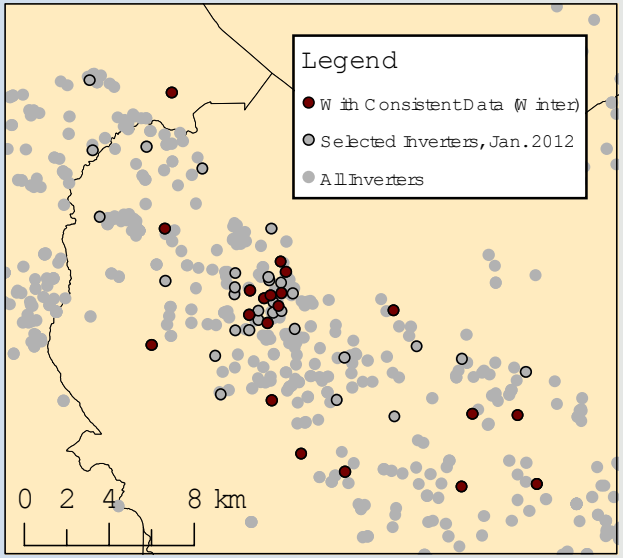
# Variability research question

- 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

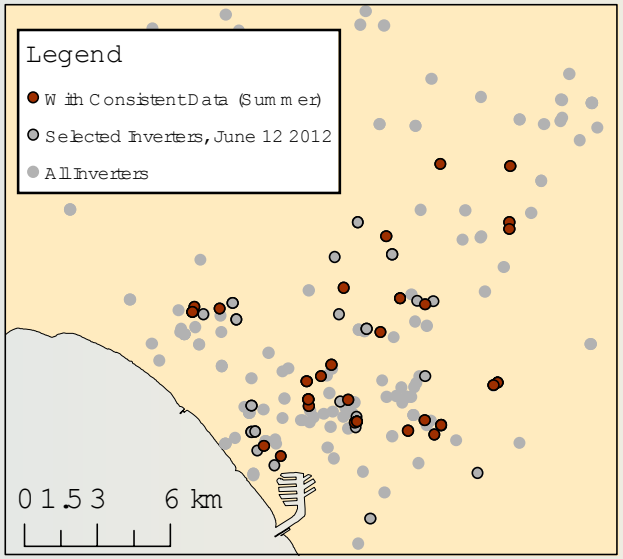
# Sites




Fresno




San Jose



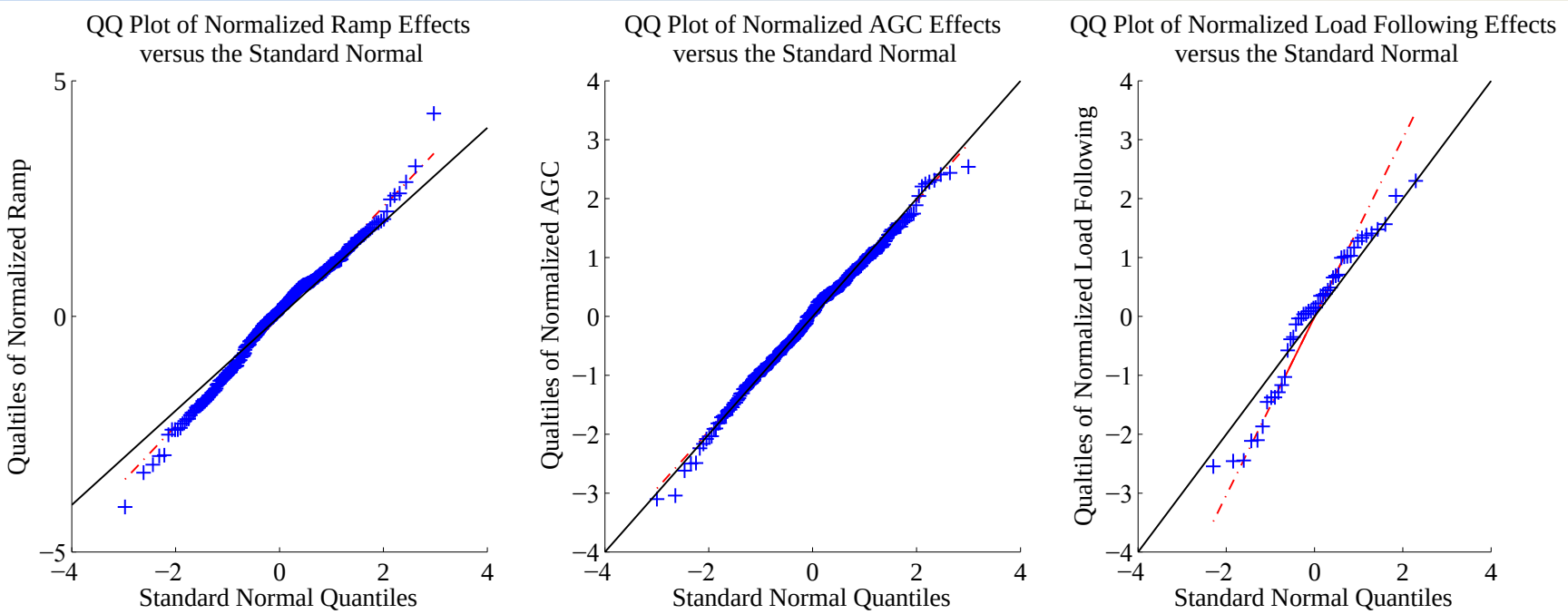

Los Angeles

- Stratified random sampling for distribution of pairwise distances
- Areas chosen to represent rough size of sub-load aggregation point

# Variability analysis process

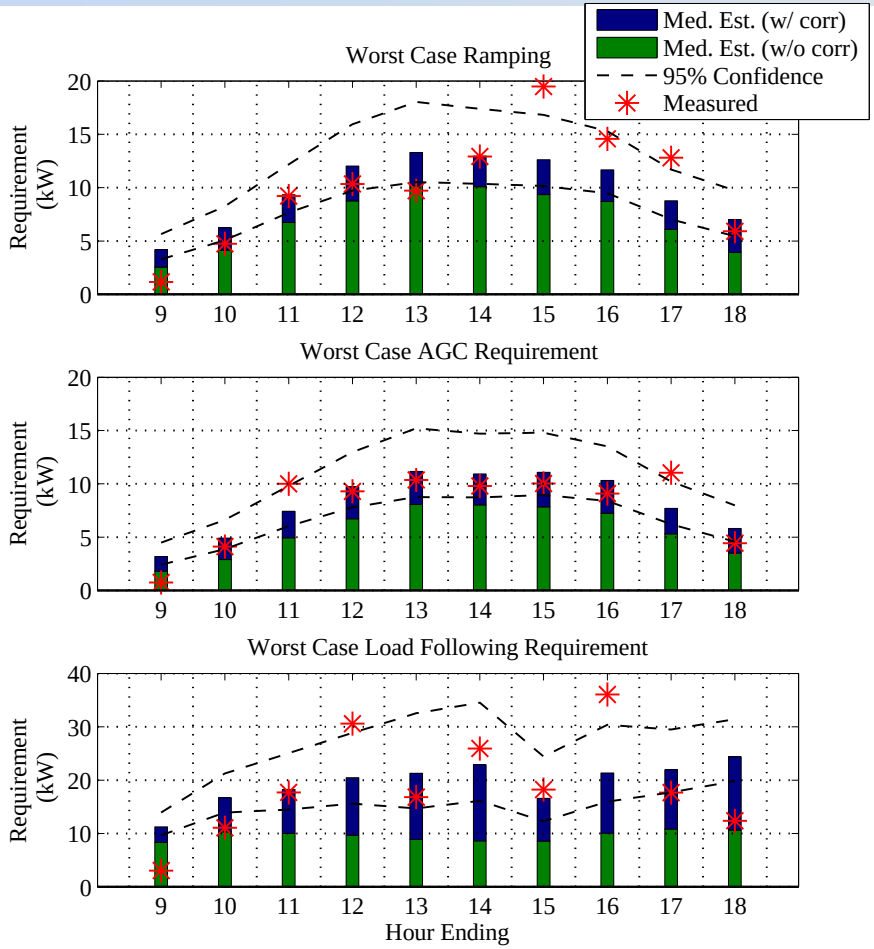
- Assume correlation of impact metric as function of distance goes as $\rho_{ij} = ae^{-dij/\tau}$, where a and τ are fit from the data
- Condition the distribution of worst case impacts only on the number of systems in the volatile regime.
- (For now) Use historical data on number of sites in volatile regime to predict impacts out of sample
- (In process) Hidden Markov model to estimate process of transitioning from one regime to another.

# Variability analysis results: qq plot




- Residuals for highly volatile (>95th percentile variance) effects during hours ending 10 to 15.
- Residuals are calculated from LA-summer dataset, the model is estimated using the SJ-winter dataset.
- The volatility regime of each inverter at each realization is assumed to be known.

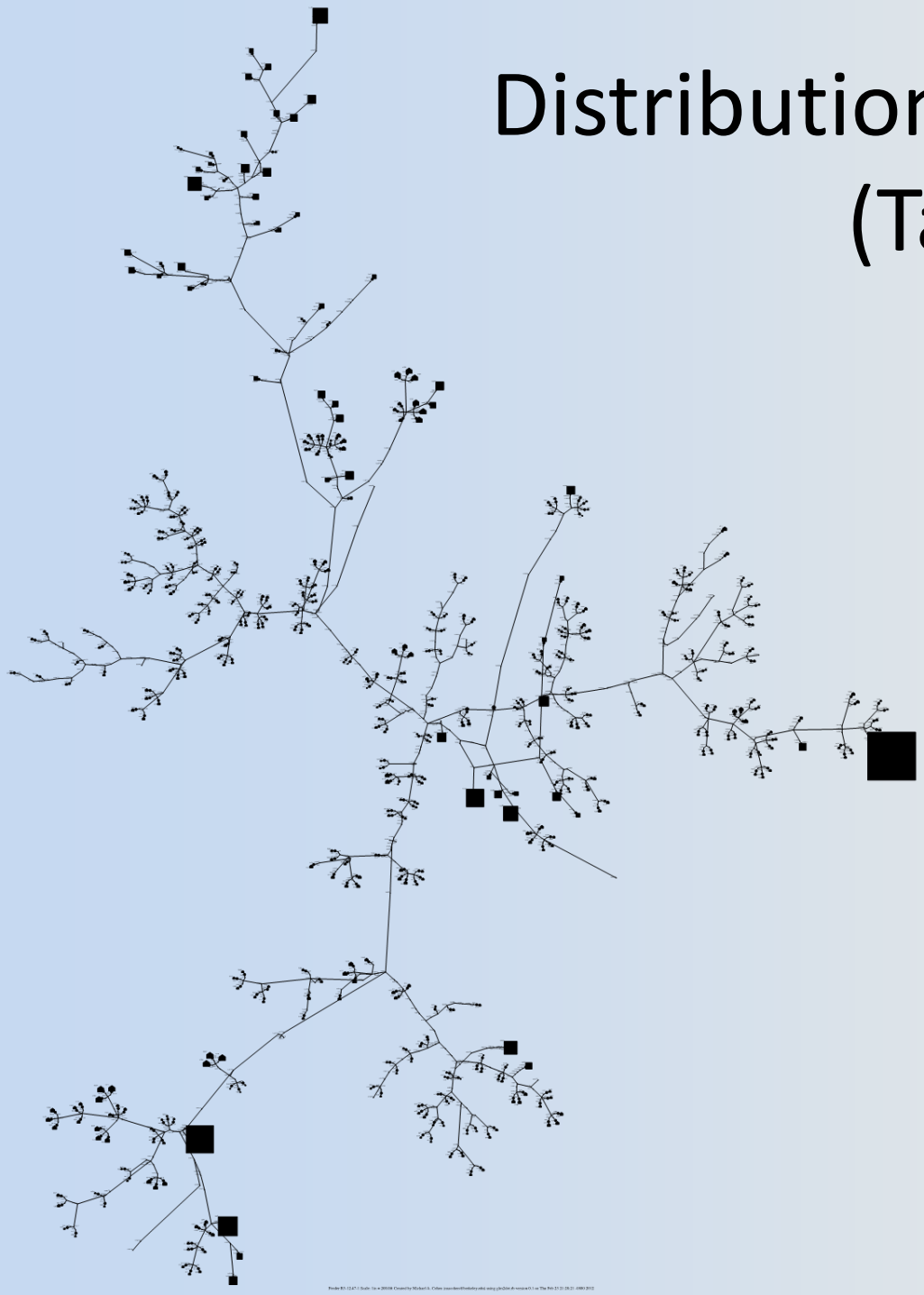
# Variability analysis: impact prediction




- Parameters estimated from San Jose winter data
- Actual estimates made using LA volatility regimes and location
- Bar is the *expected* maximum impact over 30 days
  - Blue portion of bar: added variability due to spatial autocorrelation
  - Dashed lines: 95% confidence interval
- Red asterisk: worst case impact observed in 30 days in LA

# Variability analysis: interpretation

- Given forecasts of time in regime, this tool can be used to estimate flexibility needs
  - Forecasts from satellite data, or historical averages
- Sum of 95% confidence interval for AGC and LF is 50 kW in summer for LA network of sites
  - This is for approx 170 kW total capacity → 30%!
  - If this scales, need ~4 GW capacity for 12 GW PV
    - This only covers 10% of the 33% RPS
  - However spatial autocorrelation less important for larger spatial scales, so impact likely to be less.
  - (anti-)correlation with load variability still needs to be assessed

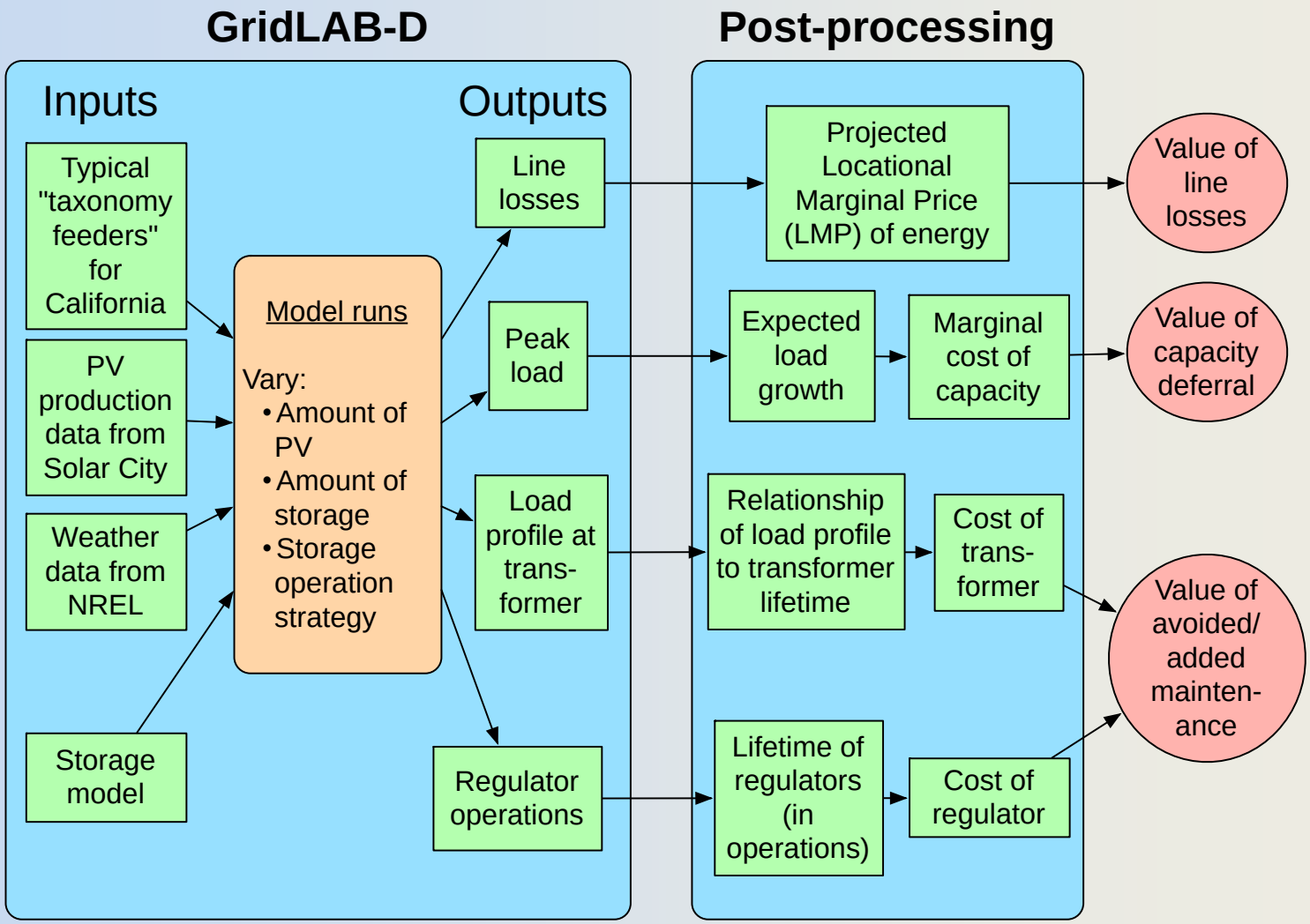


# Distribution system impacts (Task 4.3)

Research questions

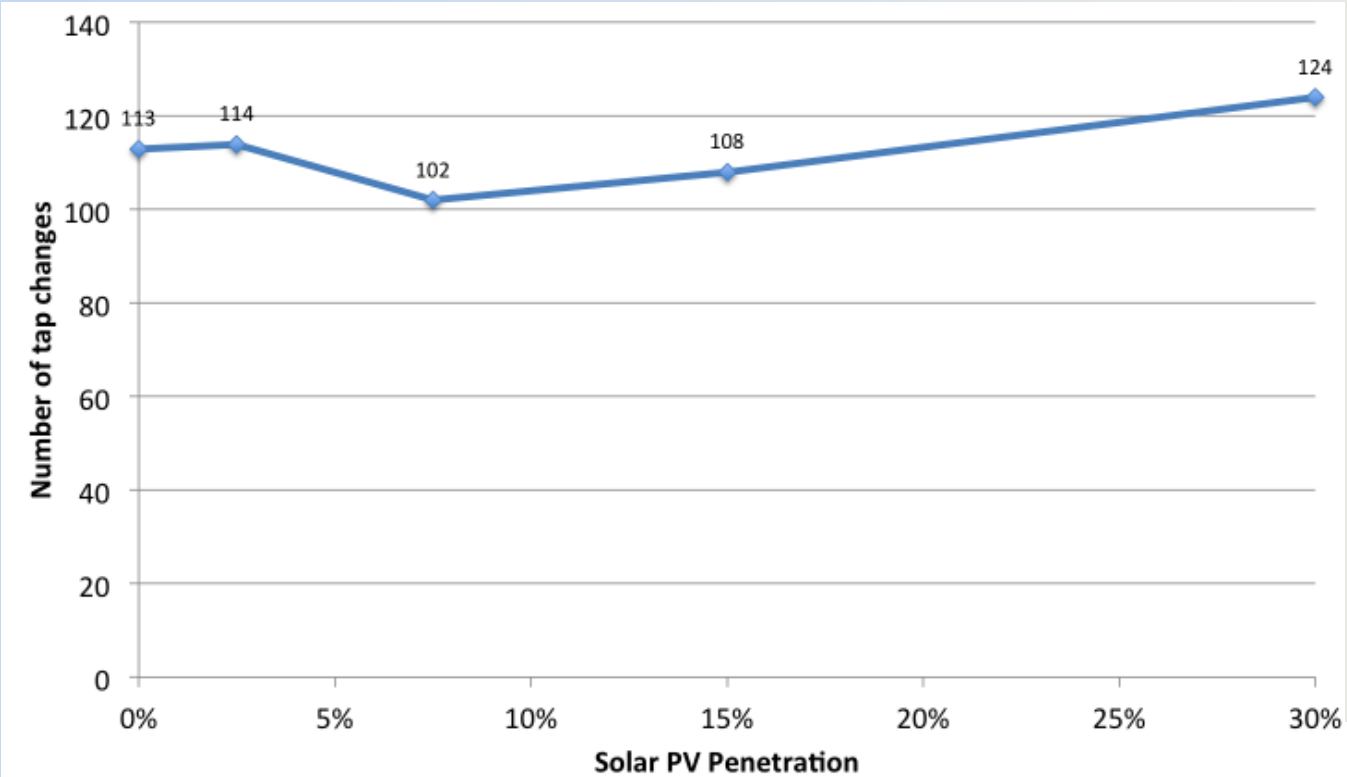
- How do physical impacts of distributed PV and storage vary with PV penetration?
  - Substation capacity
  - Resistive losses
  - Transformers
  - Voltage regulation
- What are the economic implications, in the context of load serving entity costs?

# Basic analysis framework



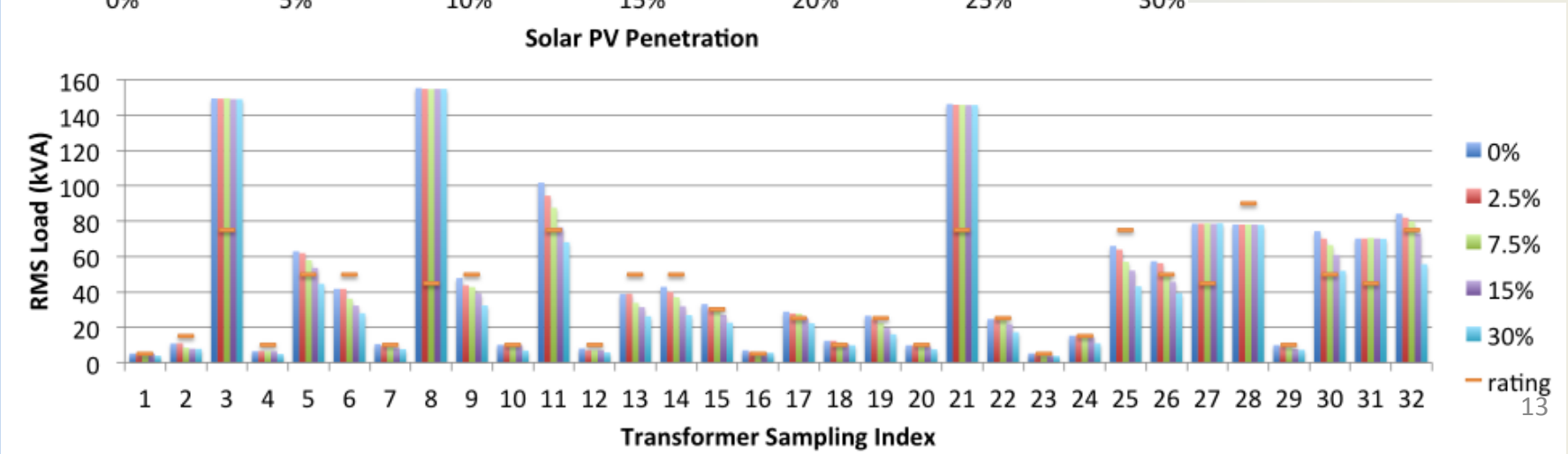
# Site selection example

# Physical modeling: Example results




Left: number of tap changer operations in 1 week as a function of PV penetration

Below: RMS loading on secondary distribution transformers as function of PV penetration



# Feeder analysis: status of research

- New transformer lifetime model that explicitly considers non-thermal causes of failure
- GridLAB-D model built, with extensive modifications to source code with PNNL engagement and development of new tools
- PG&E data on distribution system upgrade costs in-hand and analysis in progress
- Very large database management tools built for handling PV input data and GridLAB-D output data
- Preliminary results indicate deferred transformer bank capacity upgrades dominate benefits → motivates use of storage to balance PV variability

# 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

# Storage control algorithms

Results to date

- "Affine" (linear) control policies based on inventory control theory, includes storage inefficiency
- Application of basic concept to the problem of managing peak demand charges

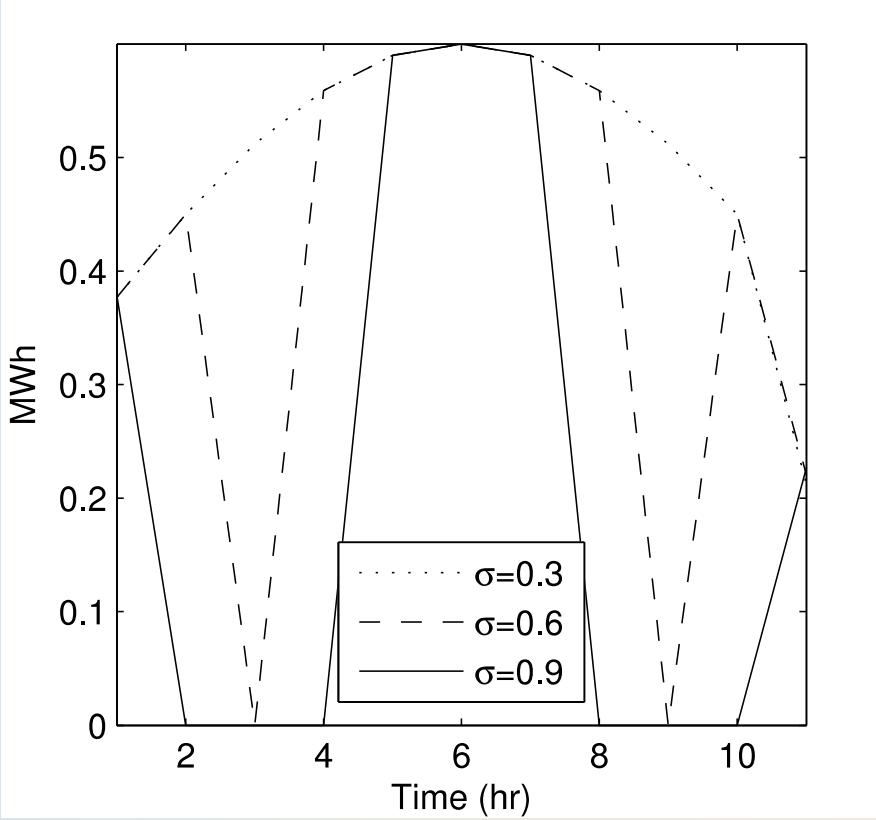


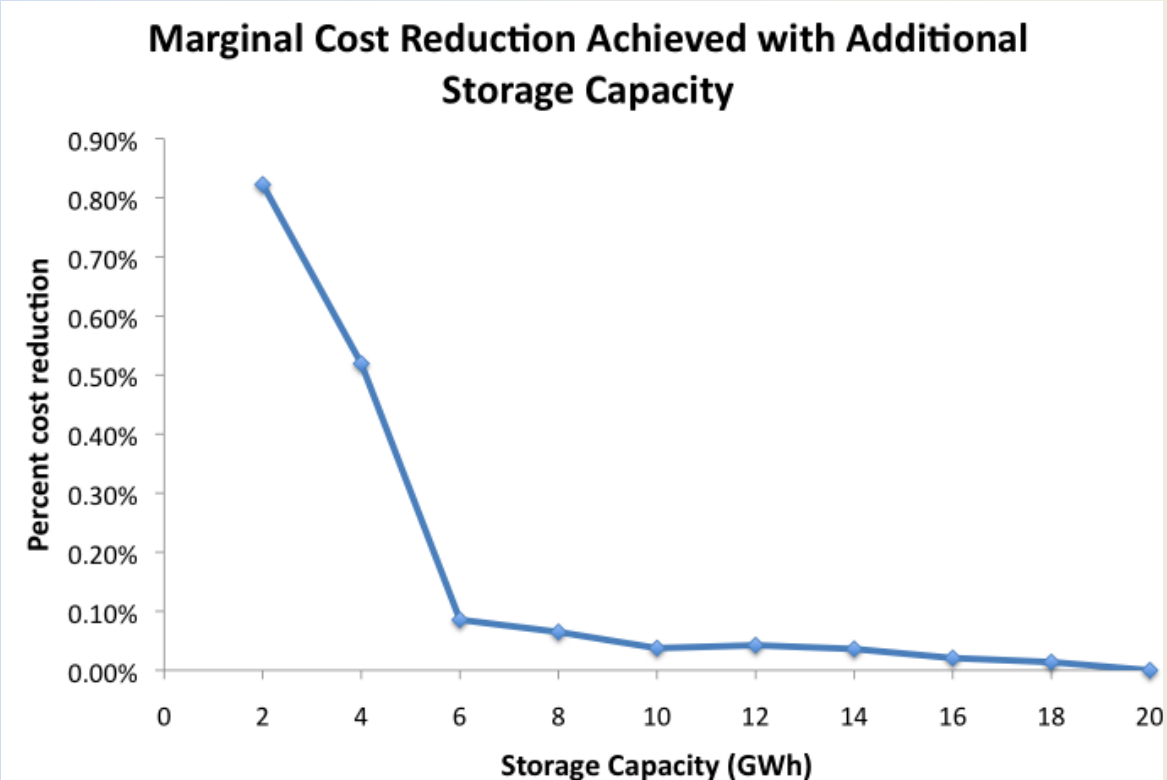

Fig. 4. The optimal $z_t$ for storage both absorbing deviations from solar and arbitraging over market prices as a function of arbitrage opportunity, $\sigma$.

# Storage value at transmission level

Main result: CAISO model (including WECC on periphery)

- Optimizes storage location
- DC load flow + unit commitment, evaluates 1 year of operating costs
- Varying amounts of storage, PV, wind, gas prices

Sample result, taken from a single day of operations



# Evaluating market products (Task 4.5)

- Analysis has focused on CAISO's new regulation energy management product for non-generator resources
  - Game theoretic approach to understanding how energy-limited market participants will behave strategically
  - Examines competition for
    - payments for each unit of unforecasted energy absorbed or discharged (energy payments), versus
    - payments for capacity
- Central result: When comparing "energy" vs. capacity payments, *energy payments* lead to
  - slightly more predictable NGR capacity commitment
  - reduced regulation energy prices

# Future work

- Task 4.2:
  - Expand analysis to state-level
  - Study impact of storage on variability
- Task 4.3
  - Complete physical & economic analysis of PV impacts on prototypical feeders
  - Evaluate benefit of storage control

# Future work

- Task 4.4
  - Apply storage control algorithms to manage demand charges
  - Complete marginal storage value curves for WECC
- Task 4.5
  - Study marginal value of storage in new applications, e.g. flexiramp
  - Complete and apply non-generator resource market theory analysis

This project is funded in part by a grant from California Solar Initiative Research, Development, Deployment and Demonstration Program. The Program is administered by Itron, Inc. under the oversight of the California Public Utilities Commission.

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