Cost-Effective Integration of Distributed Solar Generation
A Utility-Centric View

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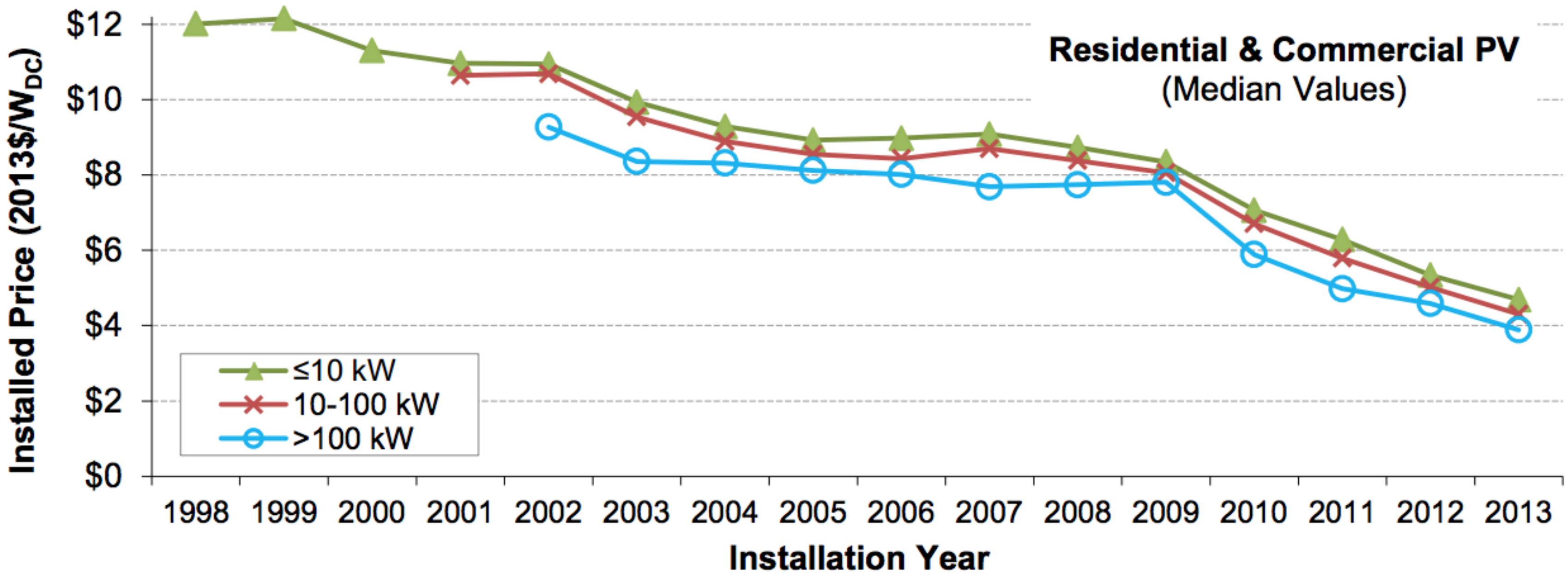
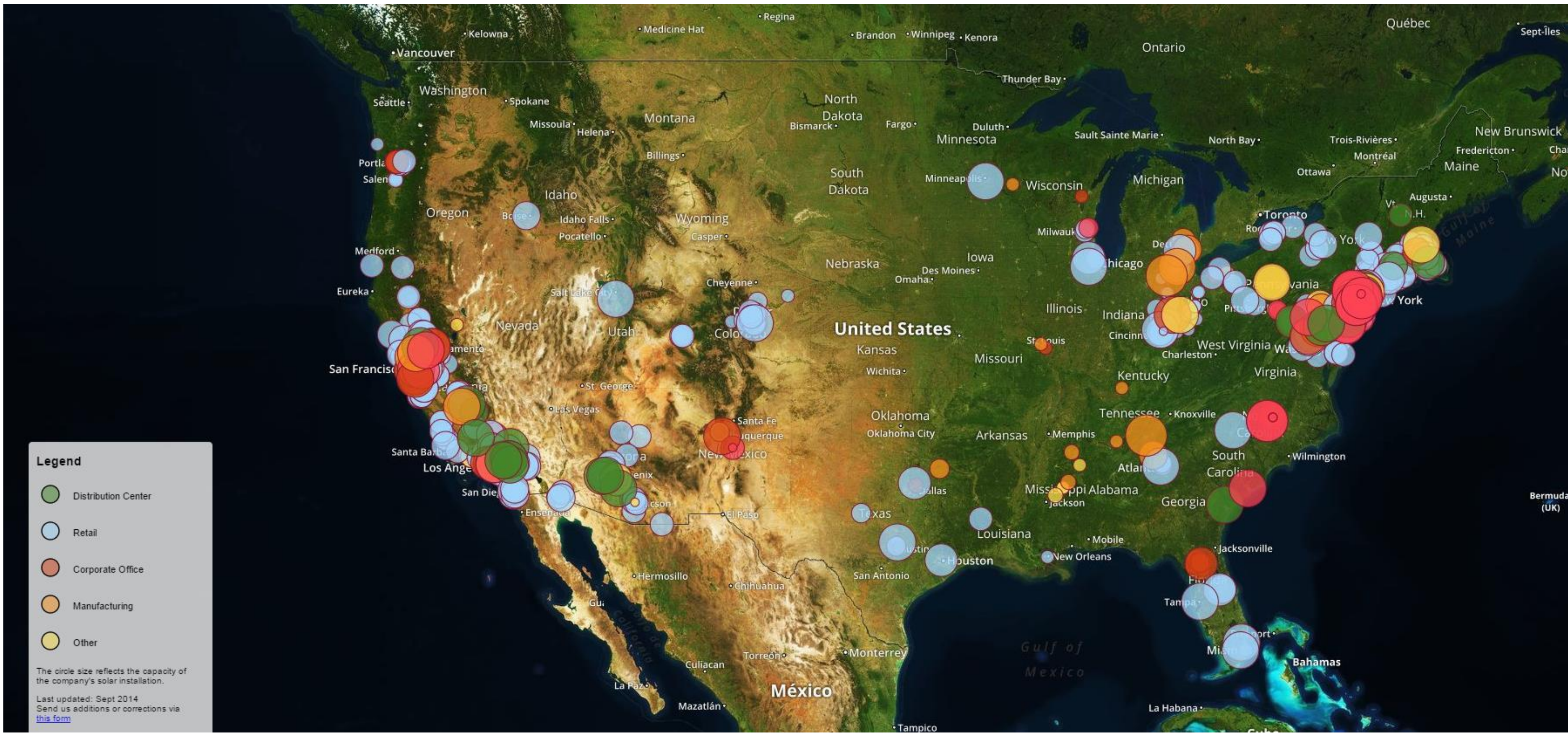
Steadily Falling Prices of Solar Power



source: Lawrence Berkeley National Laboratory, "Tracking the Sun VII: An Historical Summary of the Installed Price of Photovoltaics in the United States from 1998-2013", 2014

Corporate Solar Projects in USA



1,110 systems totaling 569 megawatts (MW)

source: http://www.seia.org/map/corporate-solar-projects.php

Corporate Solar Projects in USA

Solar energy makes financial sense!

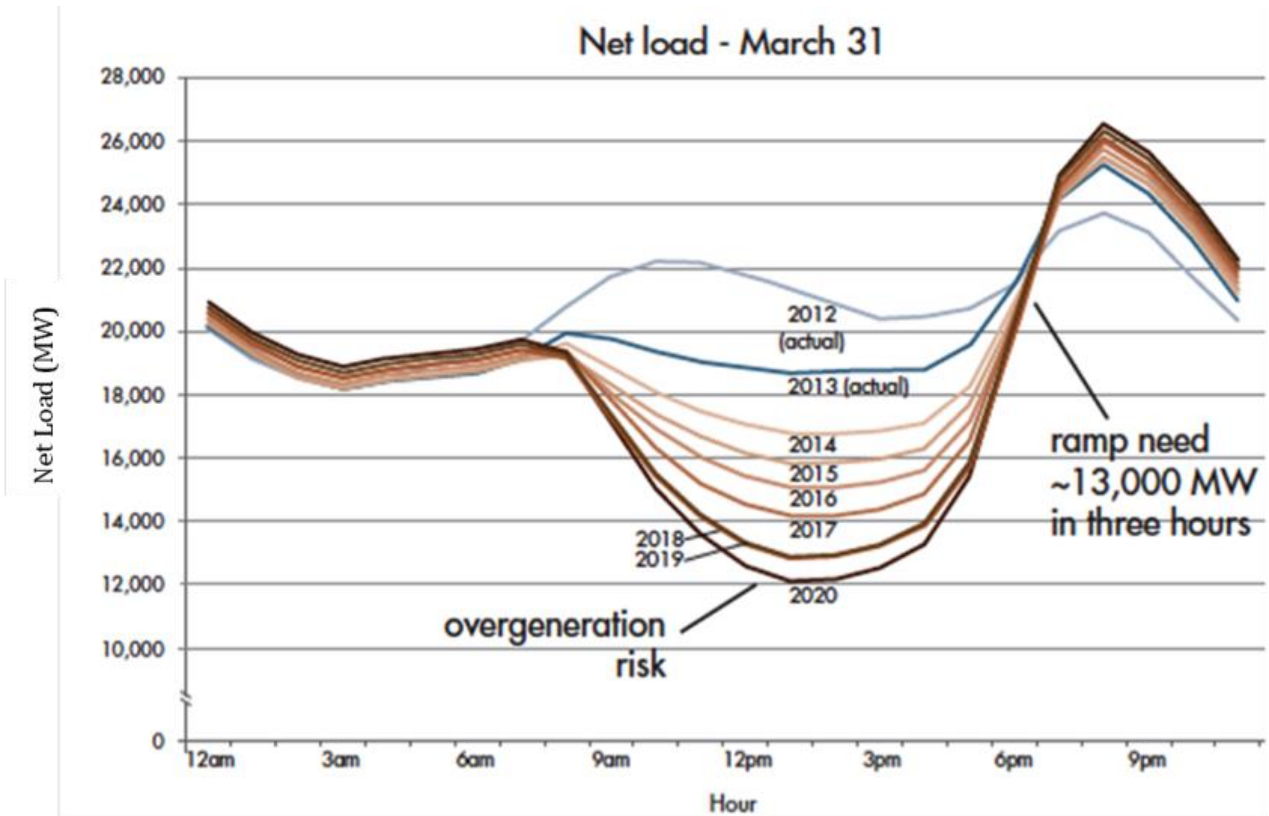
1,110 systems totaling 569 megawatts (MW)

source: http://www.seia.org/map/corporate-solar-projects.php

High Penetration of Residential Solar Power has Wide Ramifications

- System-wide impacts
  - Higher uncertainty in generation capacity
  - Increased need for ramping flexibility

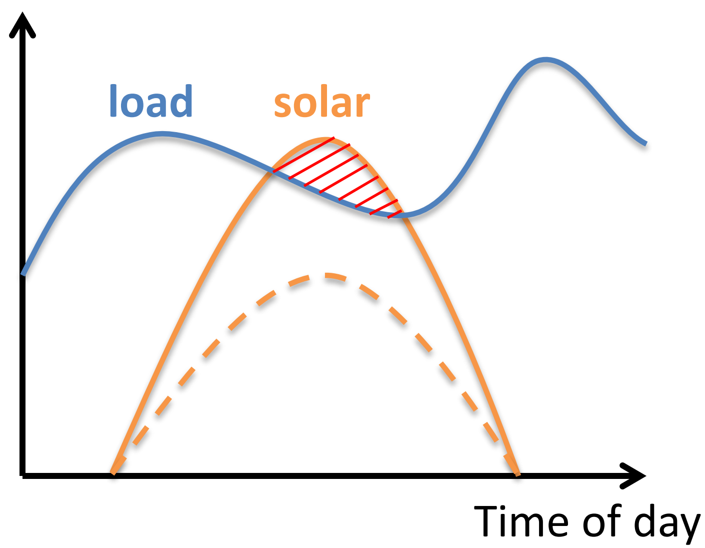
High Penetration of Residential Solar Power has Wide Ramifications



source: http://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf

High Penetration of Residential Solar Power has Wide Ramifications

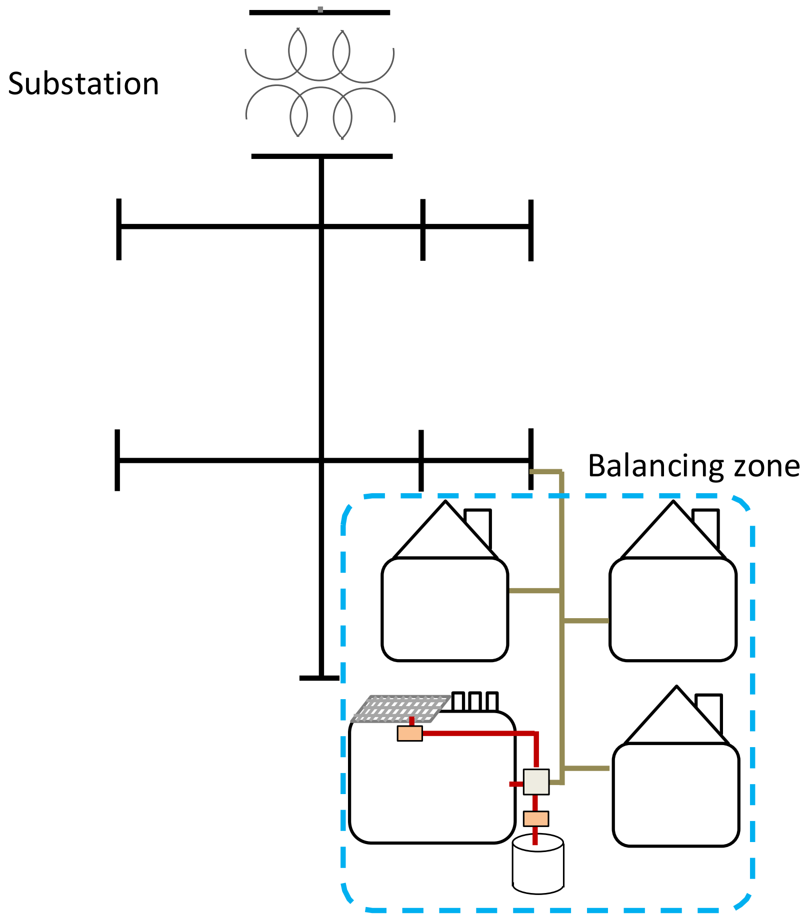
- Distribution network issues
  - Voltage variability on distribution feeders
  - Reverse power flow and protection problems



Mitigating Solutions for Utilities

- Upgrading the network (*e.g.*, install dynamic VAR control)
  - is a costly long-term solution
- Curtailing inexpensive solar power
  - is a forfeiture of inexpensive green energy that utilities have paid for
- Balancing supply and demand where and to the extent that is possible using new technologies
  - requires optimal operation of storage systems and elastic loads within *balancing zones*

What is a Balancing Zone?



Storage and elastic loads are enabling technologies for balancing the grid in sub-seconds

Today’s Grid Controls are Insufficient!

We Need…

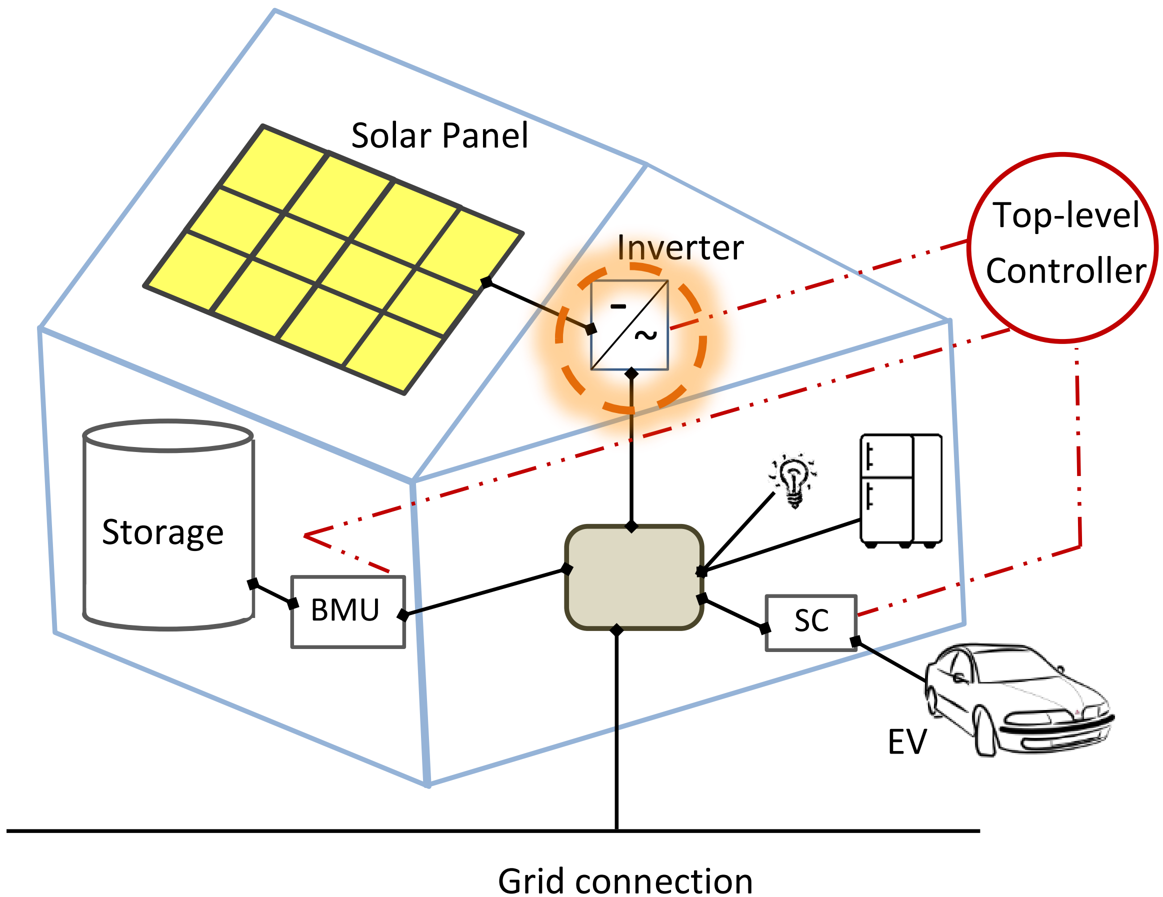
- Coordinated, real-time control of solar inverters, storage systems, and EV chargers
  - calls for the design of a legacy-compatible, scalable, decentralized overlay architecture for real power control

- Optimal control mechanisms to achieve multiple system-wide and local objectives

Our Approach

- Utility-centric
- Myopic
  - *Due to the lack of accurate predictive models for PV energy, EV mobility, and load*
- Based on real-time measurements
- Decentralized
  - *For scalability and robustness*

Context: Small Businesses



Constraints

- Demand and supply must be in balance in every time slot

  $S_{Grid}(t) + S_{Solar}(t) \pm S_{Storage}(t) = D_{inelasticLoads}(t) + D_{EVs}(t) + D_{SolarCurtailment}(t)$

- No network congestion in every time slot

  line loading (t) ≤ line setpoint
  transformer loading (t) ≤ transformer setpoint

- Unidirectional power flow outside balancing zones in every time slot

  $S_{Grid}(t) \geq 0$ *for each balancing zone*

- All storage systems within a balancing zone must be charging or discharging in a given time slot
  - to avoid energy transfer between storage systems

Objectives (in descending order of importance)

- Revenue-Maximizing Fair Power Allocation
  - $\max \sum_e \log D_{EV\_e}(t)$
- Minimizing Solar Curtailment
  - $\min \sum_i D_{SolarCurtailment\_i}(t)$
- Minimizing the Use of Conventional Power
  - $\min \sum S_{Grid}(t)$

Revenue-Maximizing Fair Allocation with Minimum Solar Curtailment

- The first two objectives are not conflicting
  - can be optimized at the same time
- Cast as a nonlinear convex optimization
  - gives us the fair power allocation to EVs and an optimal curtailment strategy
- Solved at the substation

Minimizing the Use of Conventional Power

- The last objective, $\min \sum S_{Grid}(t)$, is separable
  - can be decomposed to several optimization problems, one for each balancing zone

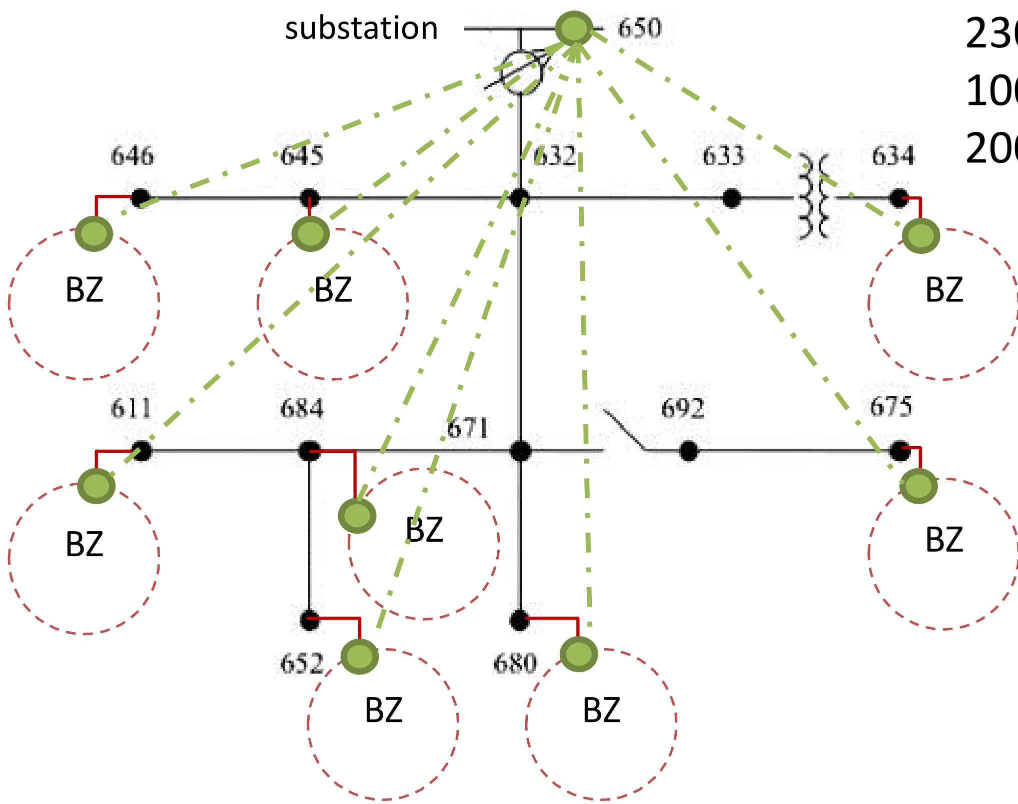
- The linear program can be solved at the edge of every balancing zone

Benchmark Scenarios

- Local control with no energy exchange within balancing zones
  1. local use of solar power without storage
  2. local use of solar power with storage

- Control at the level of balancing zones, assuming no storage

Test Distribution Network

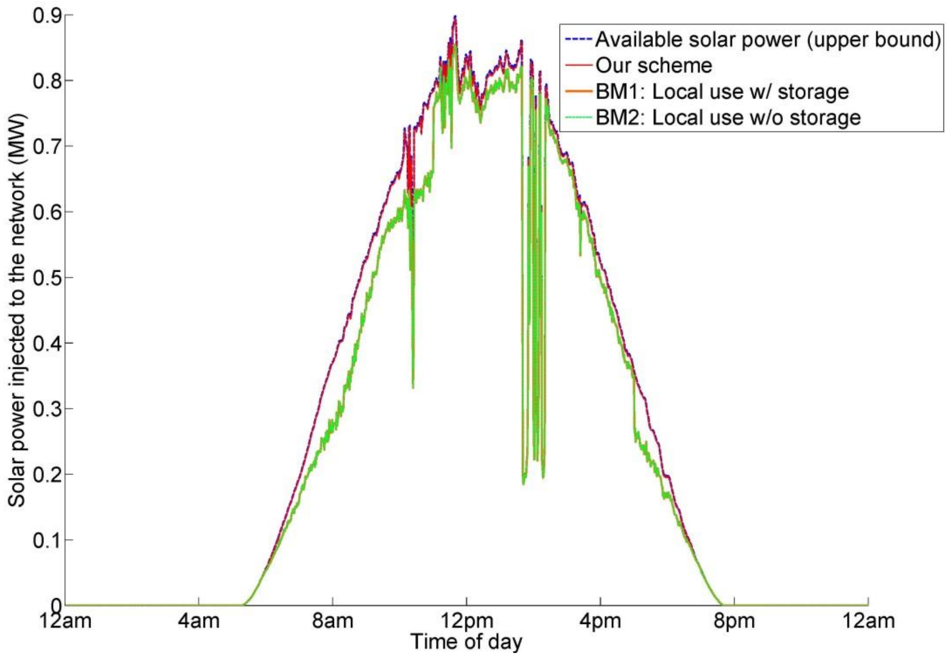


2300 households
1000 small businesses
200 EV chargers

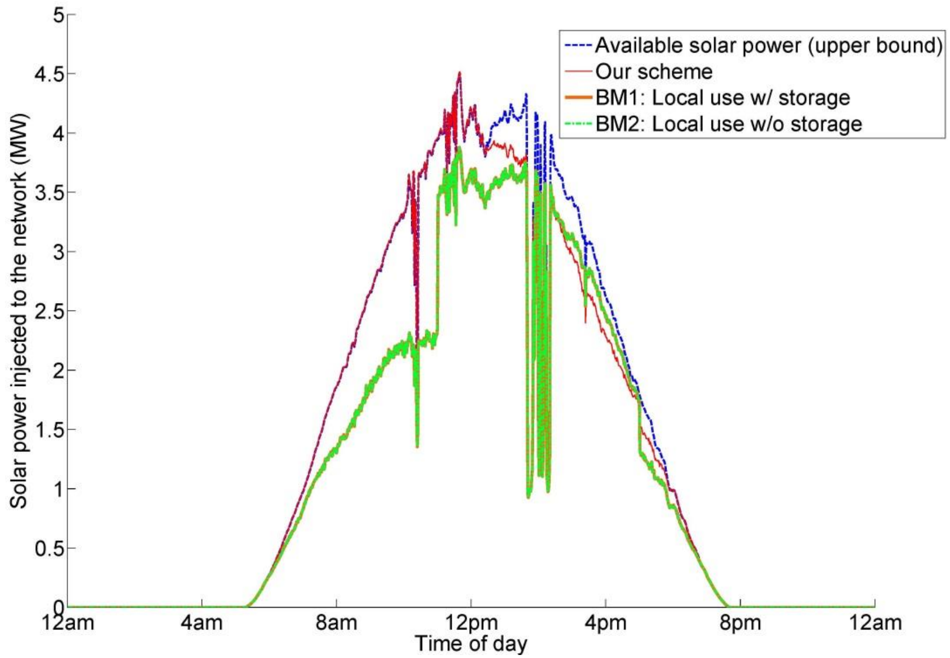
Bus	680			634			675			645		646		684		652	611
Phase	a	b	c	a	b	c	a	b	c	b	c	b	c	a	c	a	c
Num of homes	350	350	350	0	0	0	250	250	250	0	0	150	150	0	0	100	100
Num of small businesses	100	100	100	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Num of EV chargers	20	20	20	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Storage systems (% of total)	10%	10%	10%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
PV installations (% of total)	10%	10%	10%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%

Evaluation

200 PV panels, 100 storage systems each 20kWh with initial SOC 20%

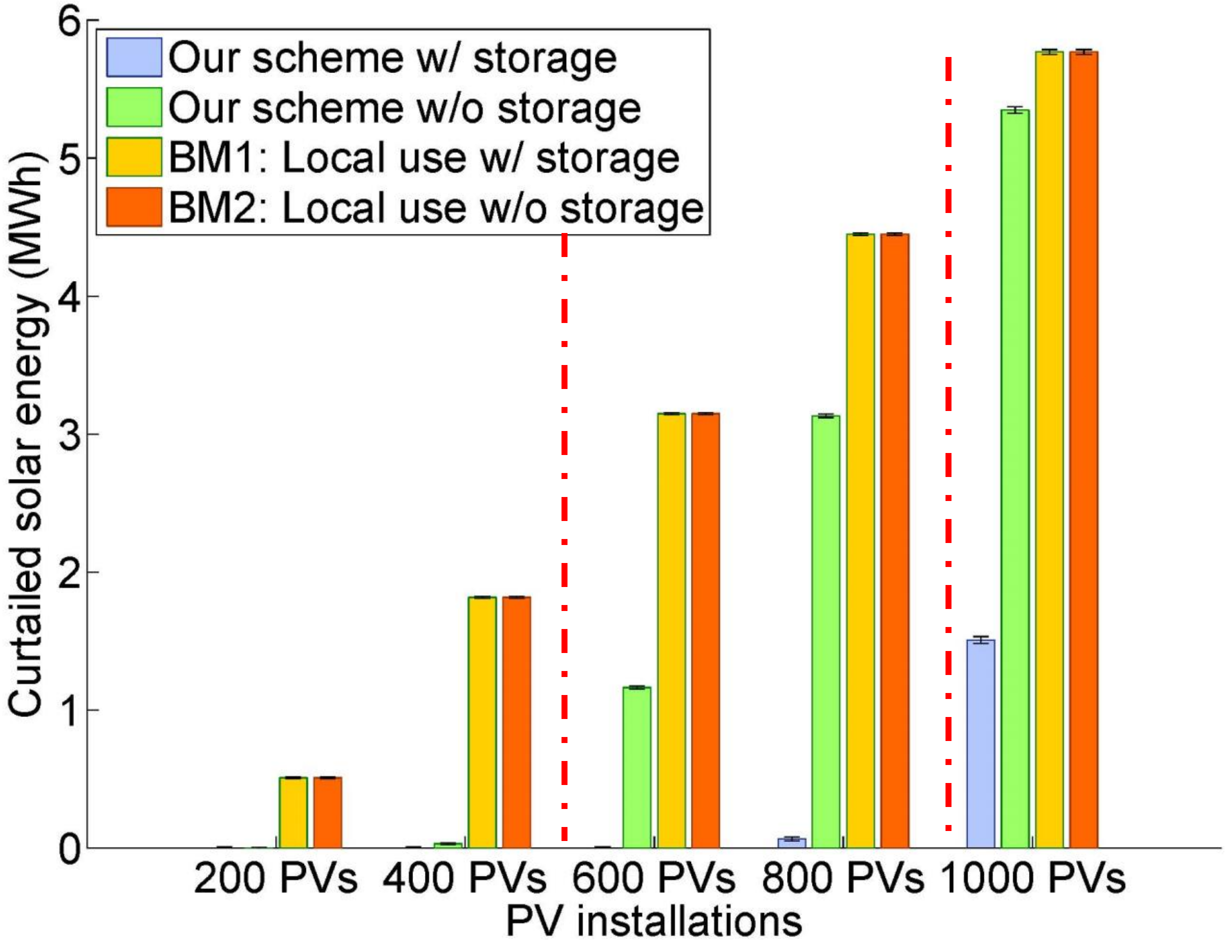


1000 PV panels, 500 storage systems each 20kWh with initial SOC 20%

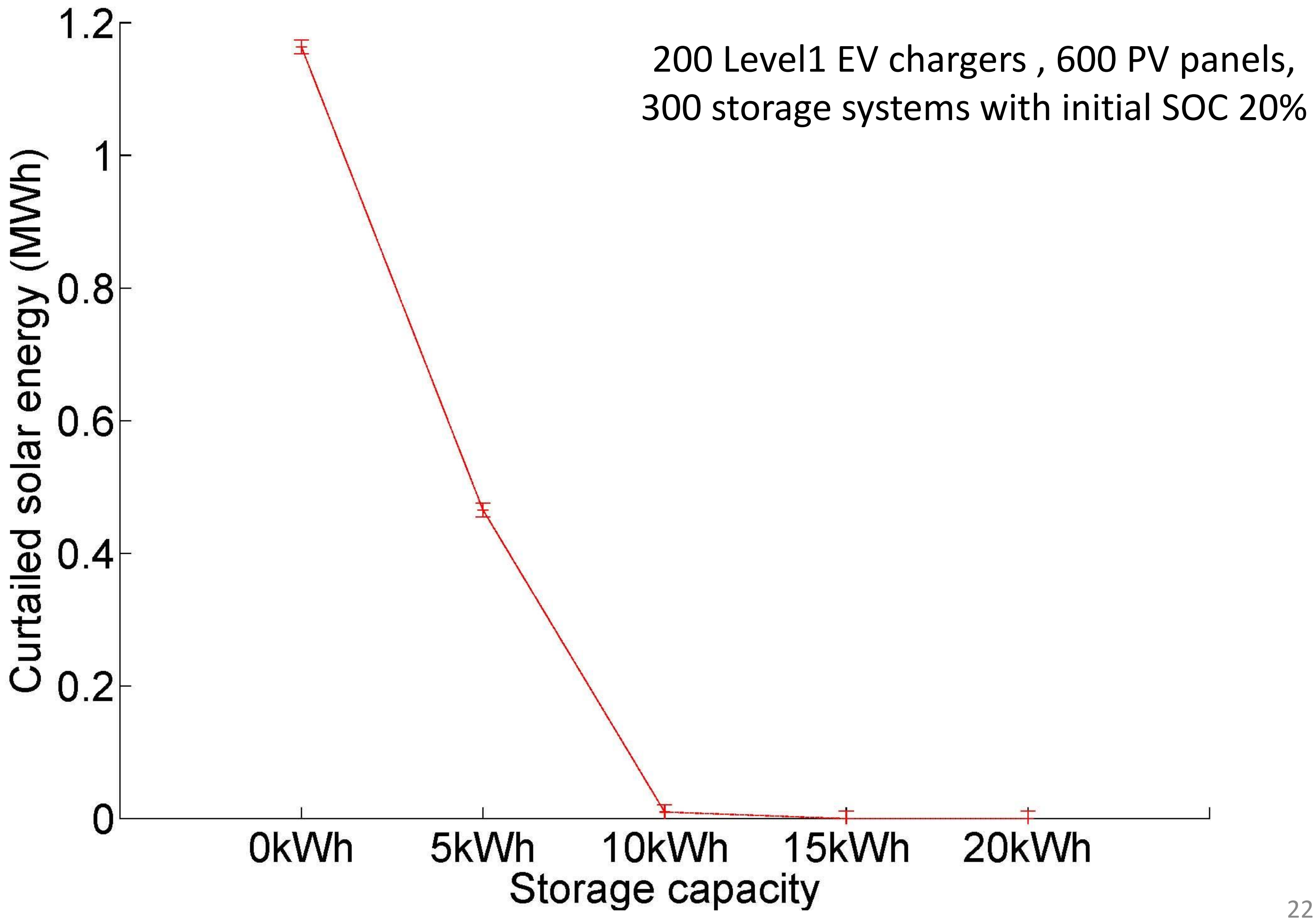


200 Level1 EV chargers, 2300 homes, 1000 small businesses, and the demand of EVs is 12kWh

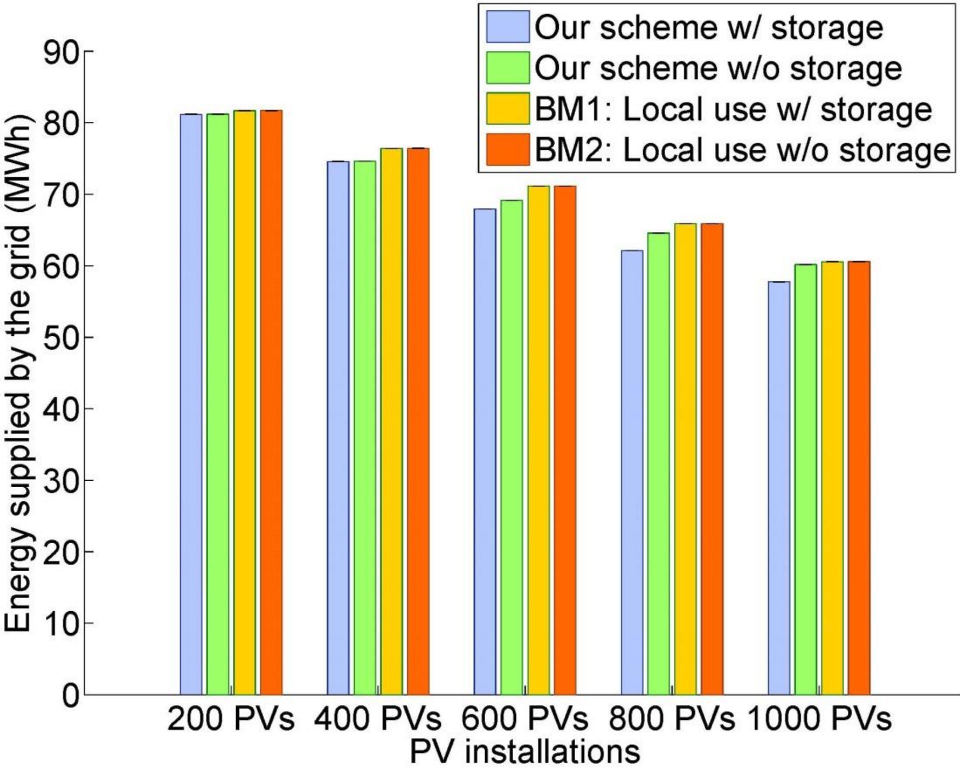
Evaluation - cont'd

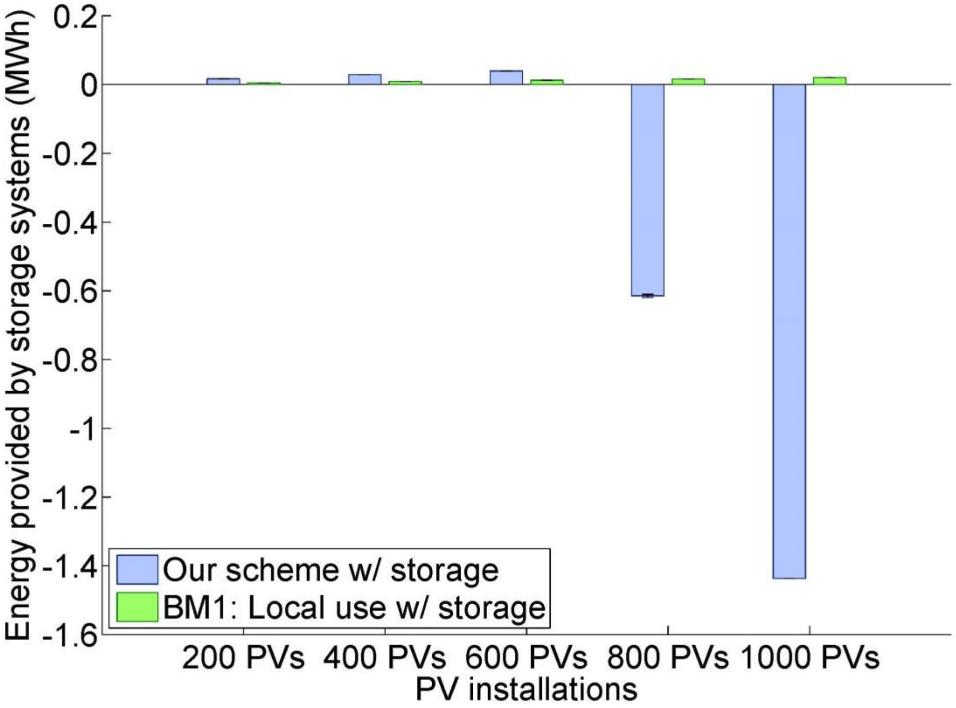


Evaluation - cont'd



Evaluation - cont'd





Conclusion

- Large-scale integration of solar photovoltaic systems, EVs, and storage systems will impair the reliability of the network
- Today’s best practices reduce the cost-effectiveness of solar installations
- Scalable myopic control algorithms developed on a decentralized control architecture enable the utility to simultaneously achieve different objectives