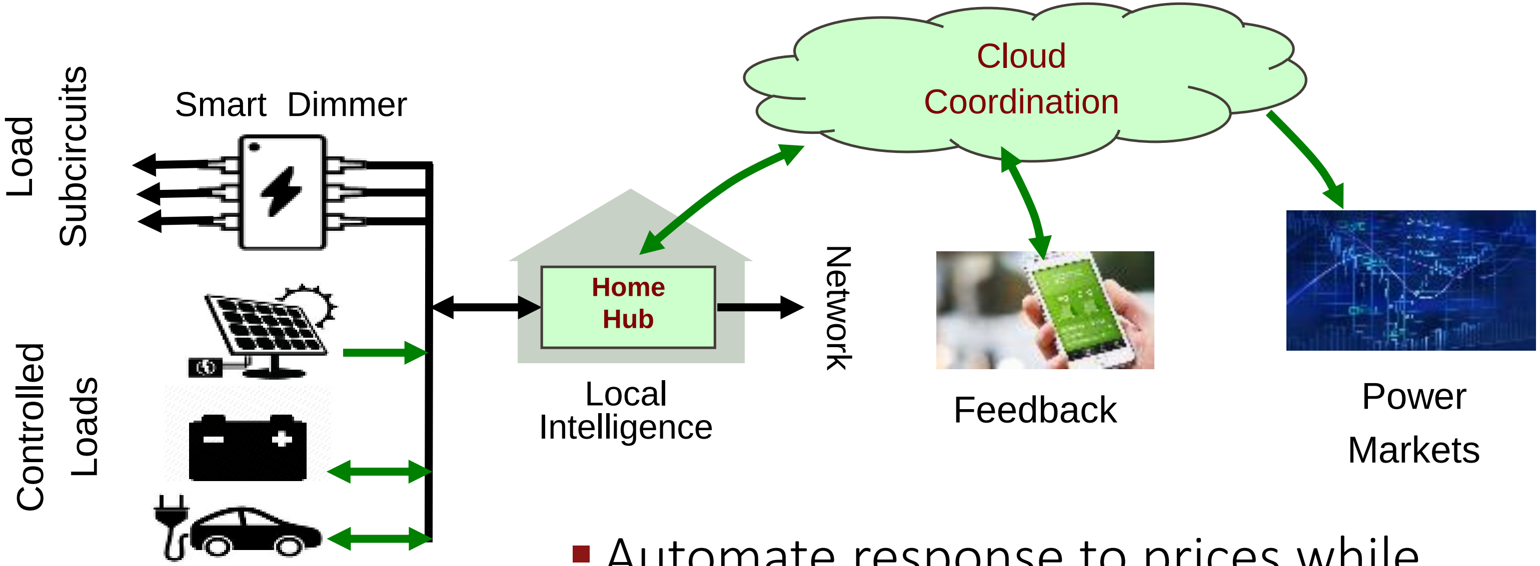
Powernet

RAM RAJAGOPAL, STANFORD UNIVERSITY

Powernet: coordinating from the cloud



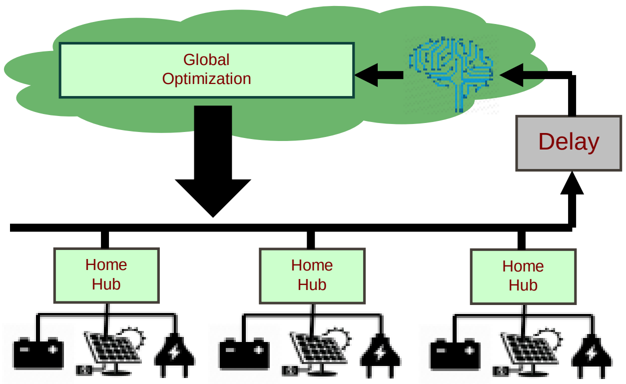
Stanford University

SLAC NATIONAL ACCELERATOR LABORATORY

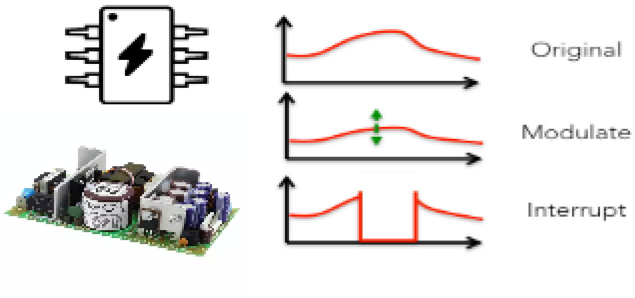
Google

- Automate response to prices while preserving privacy and reliability
- Coordinate homes to shave peaks and provide grid services
- Enable smart homes and buildings

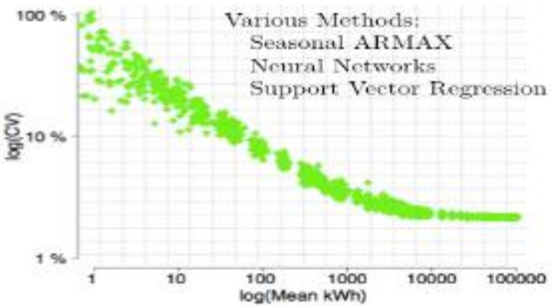
What is inside & why is it hard?



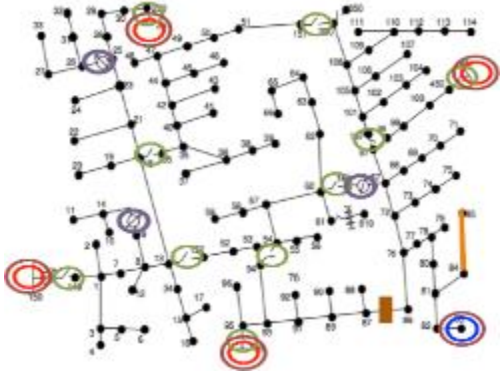
Distributed Intelligence and Optimization



Smart Dimmer



Predictive and Diagnostic Analytics



Hardware and Systems in the loop

Team

- Stanford

Architecture	Jon Gonçalves, Gustavo Cezar
Smart Dim Fuse	Aaron Goldin, Juan Rivas, Ram Rajagopal
Learning	Lily Buechtler, Yuting Ji, Ram Rajagopal
Coordination	Thomas Navidi, Matt Kiener, Abbas El Gamal, Ram Rajagopal
T2M:	Adhlok ,Arun Majumdar, Steven Chu

- SLAC

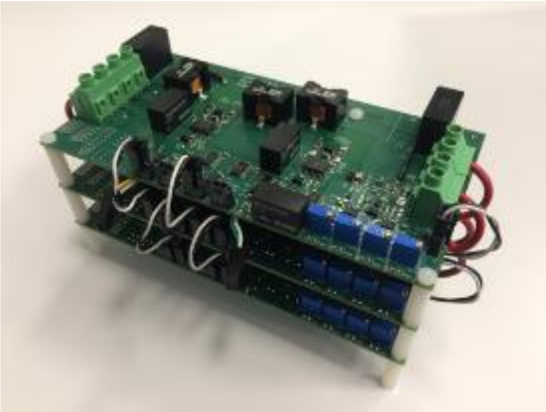
Validation	Sila Kiliccote
Simulation	Claudio Rivetta, David Chassin
Field deployment	Claudio Rivetta
Power electronics	Claudio Rivetta

- University of Florida

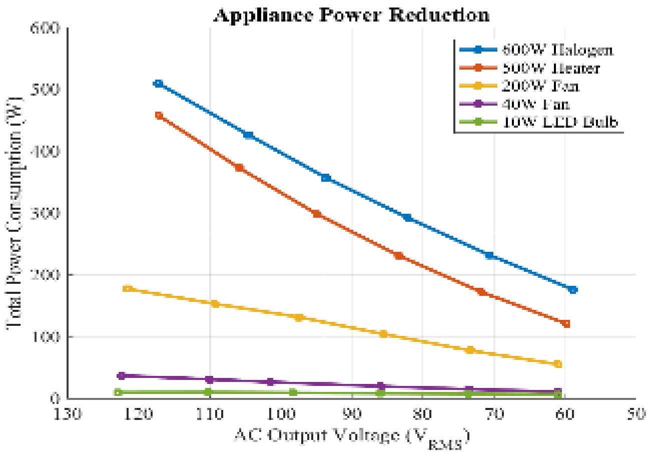
Markets	Neil Camaradella, Sean Meyn
Coordination (loads)	Ana Busic, Sean Meyn

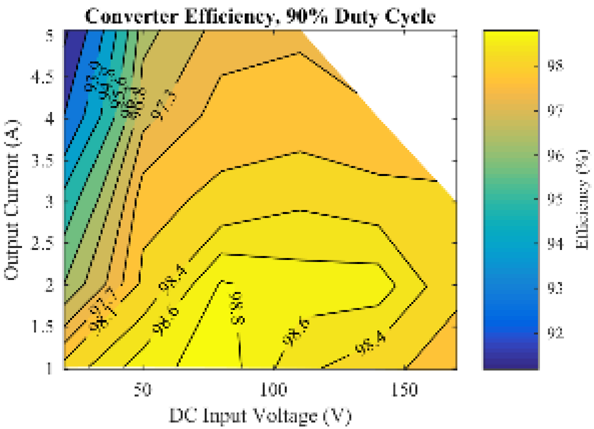
- Google — Ana Radovanovic

Smart Dim Fuse



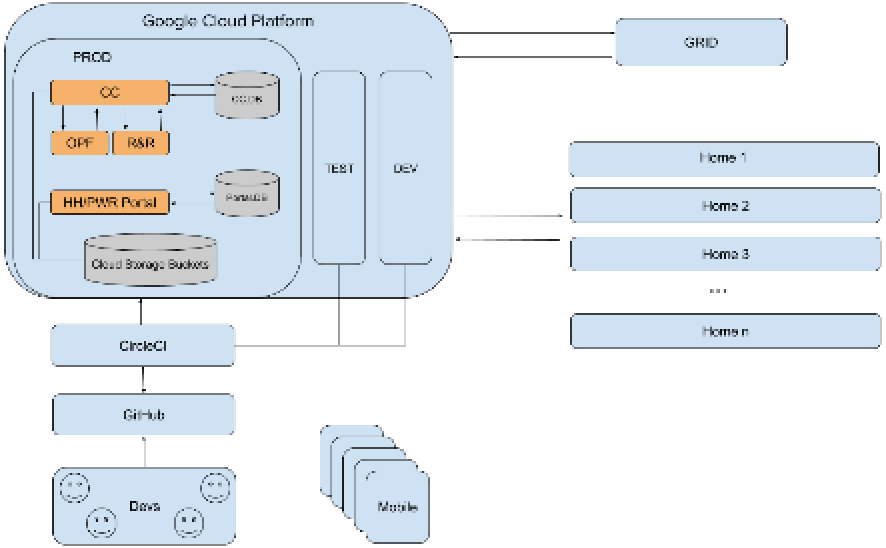
Prototype showing three
750W modules configured in parallel

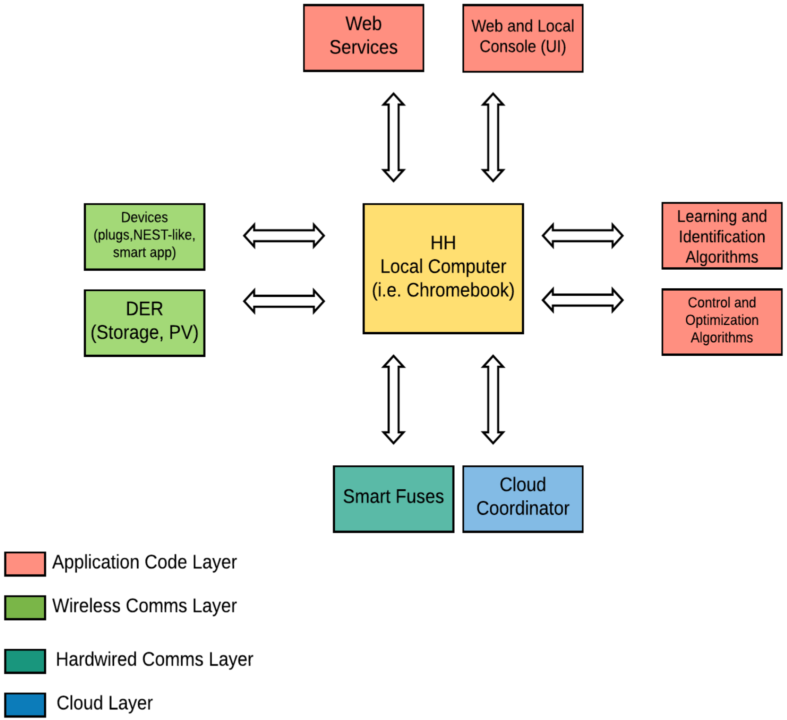




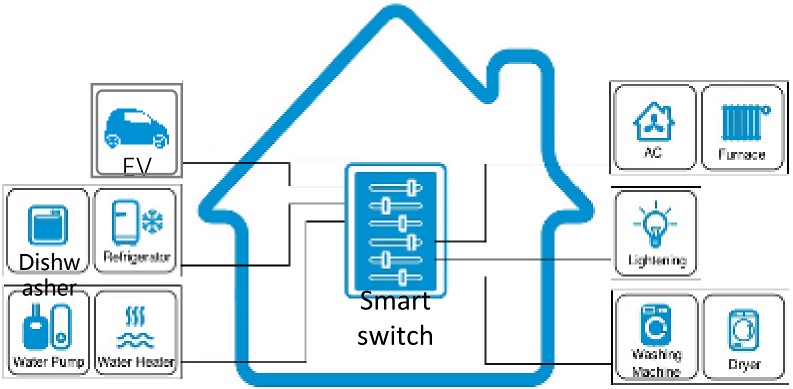
- Improved safety with fast response fault detection and current limiting
- Modular design for installation in different circuit current ratings
- High bandwidth voltage/current measurements for load characterization and data-driven load modeling

System Architecture: Cloud Coordinator and Home Hub

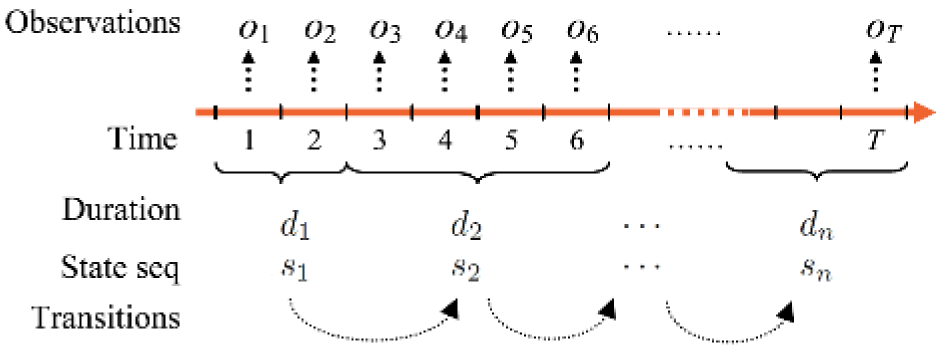


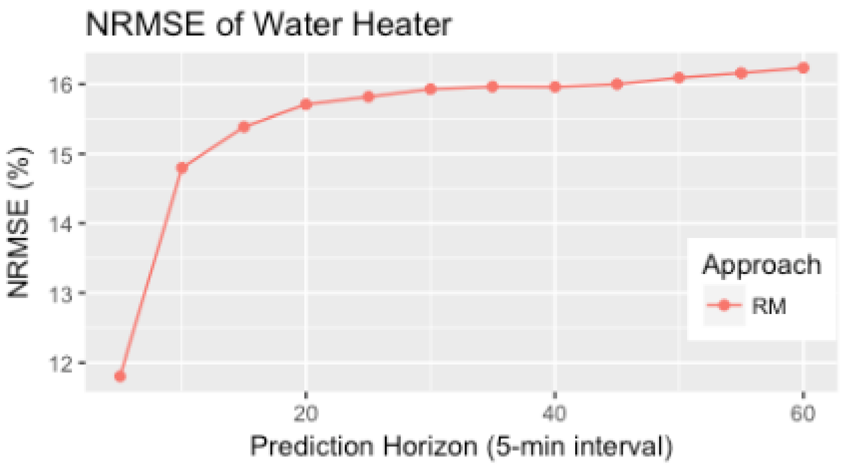


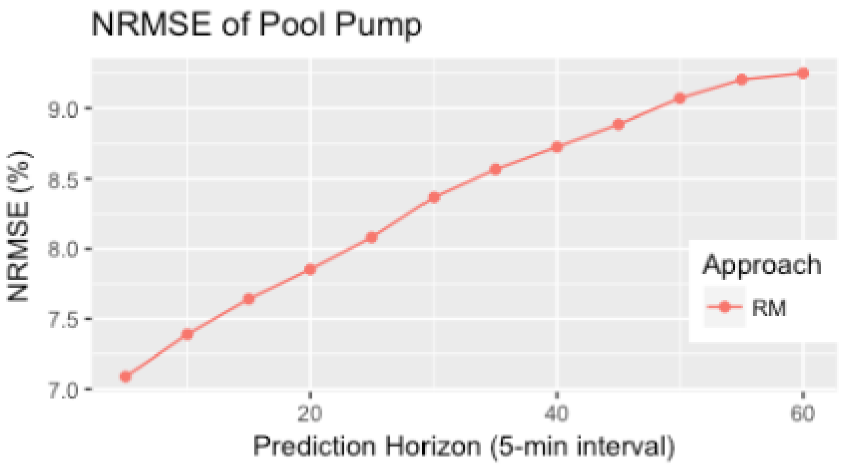
Learning Consumer Behavior and Preferences



Hidden semi-Markov model

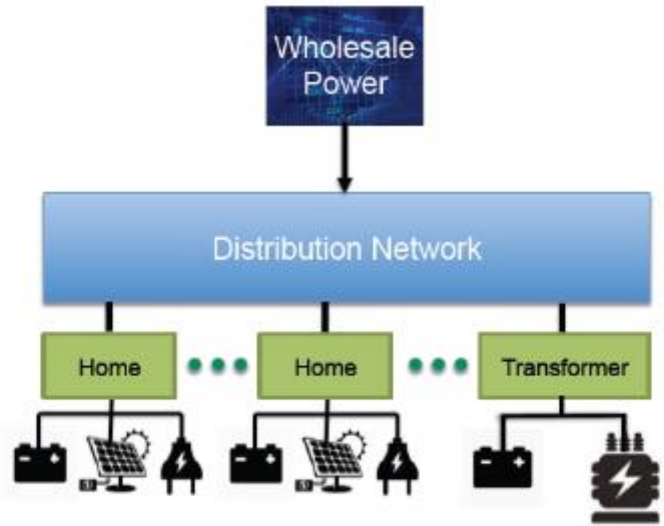






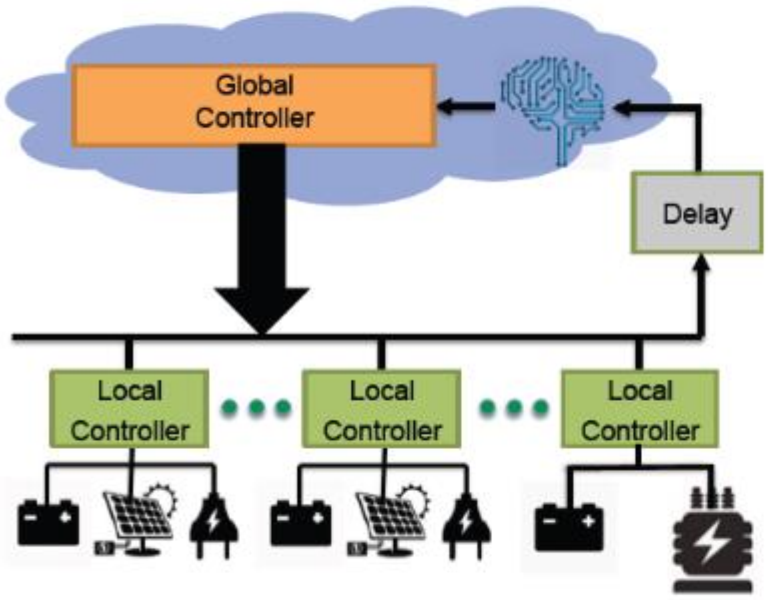
Who Should/Can Coordinate

- Network operator:
  - knows the network and collects smart meter data (delayed and buffered, cannot perform real time control)
  - Doesn’t own or operate behind meter resources
- DER providers:
  - Have private cloud to collect “behind the meter” data about their devices
  - Don’t know the network
  - Don’t know the loads or other DER providers’ data, cannot perform network coordination
- Third party:
  - All above problems in one

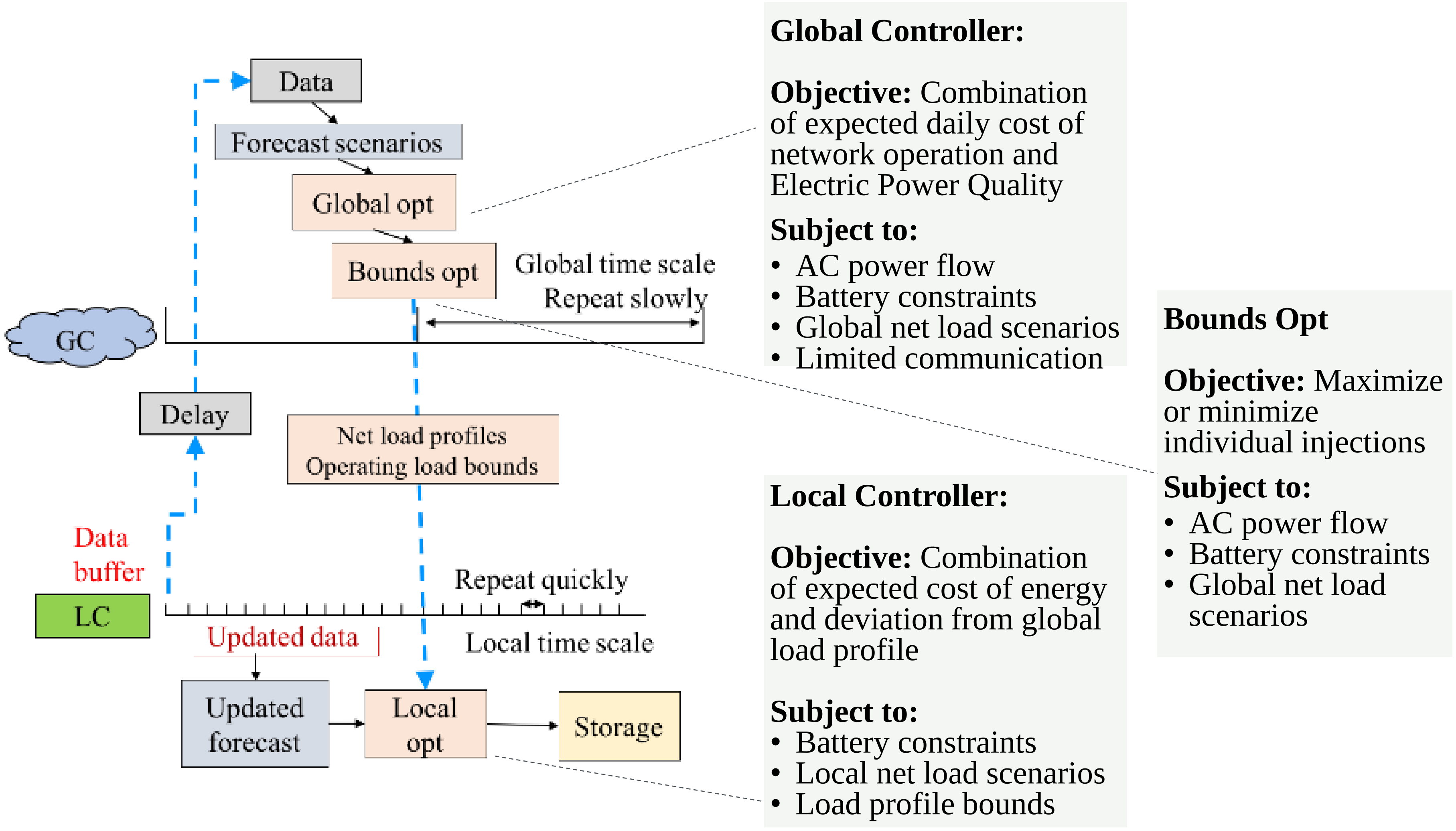


Our Proposed Approach

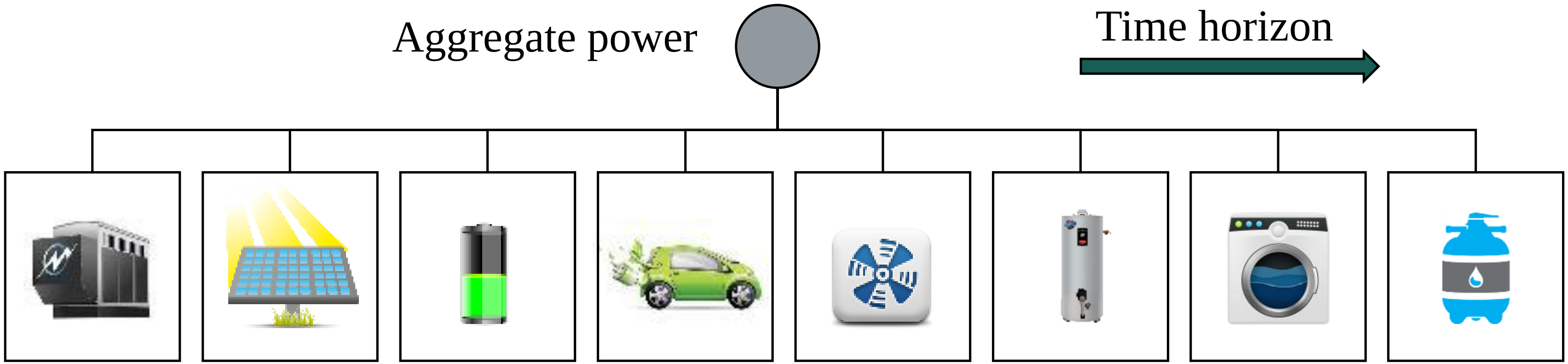
- Split coordination between:
  - Global controller (cloud)
  - Local controllers (home hub)
- Challenge: Spatial and temporal net load data asymmetry:
  - Each node has access only to its own load data and signals from global controller
  - Net load data is stochastic
  - Global controller has delayed net load data from smart meters
- How effective is this architecture (network reliability, arbitrage profit, aggregation)?



*K. Anderson, R. Rajagopal, and A. El Gamal, "Coordination of distributed storage under temporal and spatial data asymmetry," IEEE Trans. on Smart Grid.

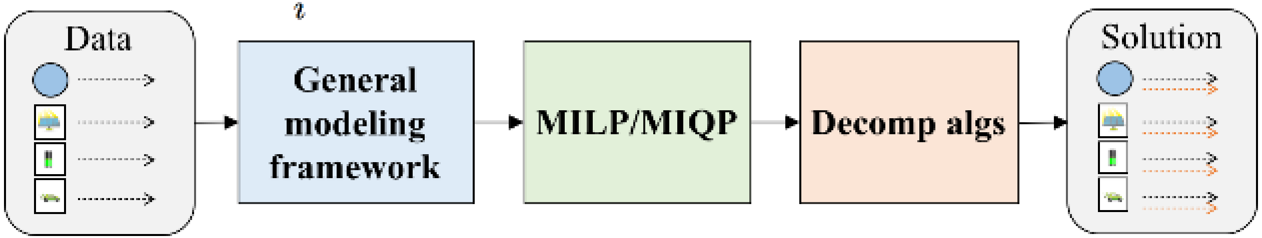

Data
Forecast scenarios
Global opt
Bounds opt
Global time scale
Repeat slowly
GC
Delay
Net load profiles
Operating load bounds
Data
buffer
LC
Repeat quickly
Updated data
Local time scale
Updated
forecast
Local
opt
Storage
Global Controller:
Objective: Combination of expected daily cost of network operation and Electric Power Quality
Subject to:
• AC power flow
• Battery constraints
• Global net load scenarios
• Limited communication
Bounds Opt
Objective: Maximize or minimize individual injections
Subject to:
• AC power flow
• Battery constraints
• Global net load scenarios
Local Controller:
Objective: Combination of expected cost of energy and deviation from global load profile
Subject to:
• Battery constraints
• Local net load scenarios
• Load profile bounds

Home Hub General Load Algorithms

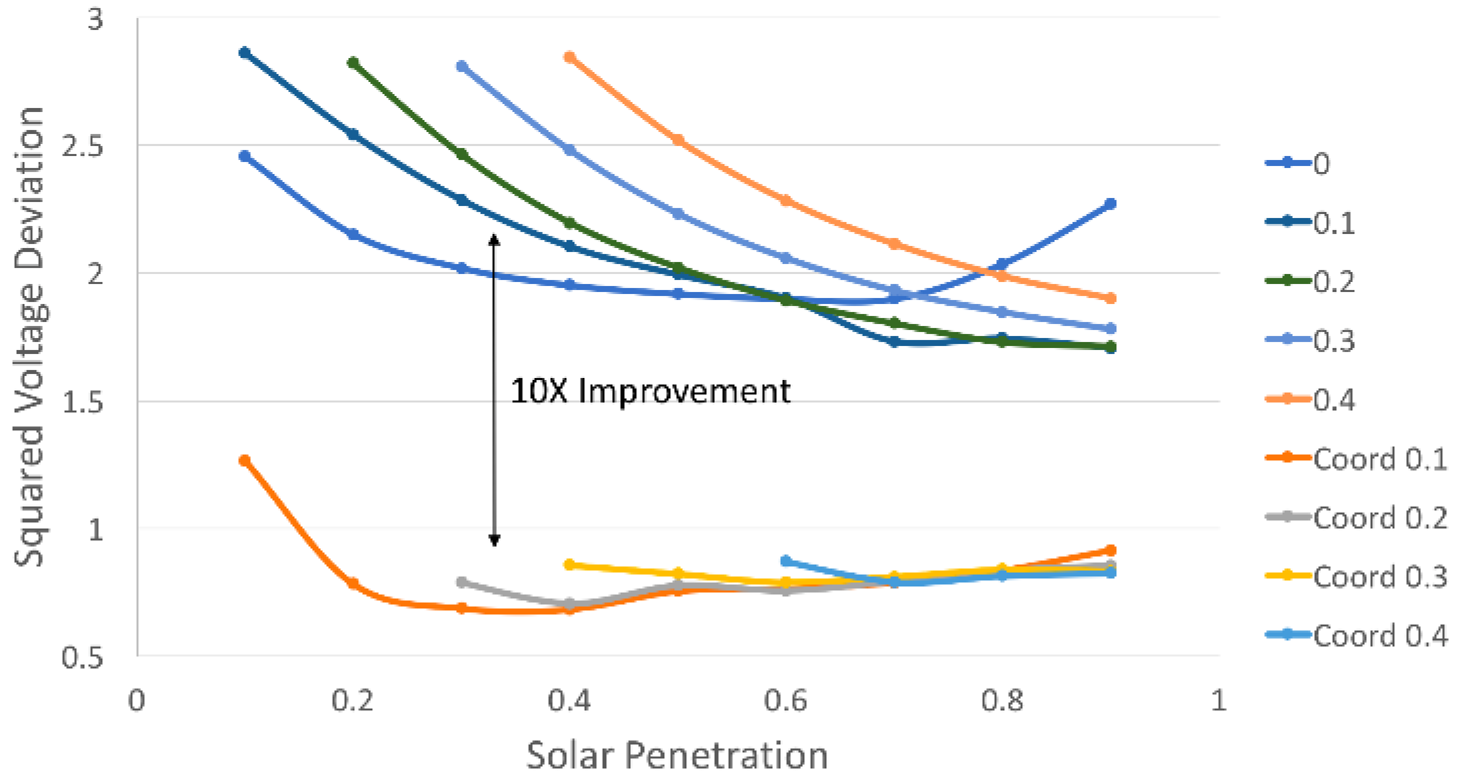


$$\min \quad \text{Cost}\left(\sum_i \text{power}_i\right) + \sum_i \text{cost}_i(\text{resource}_i)$$

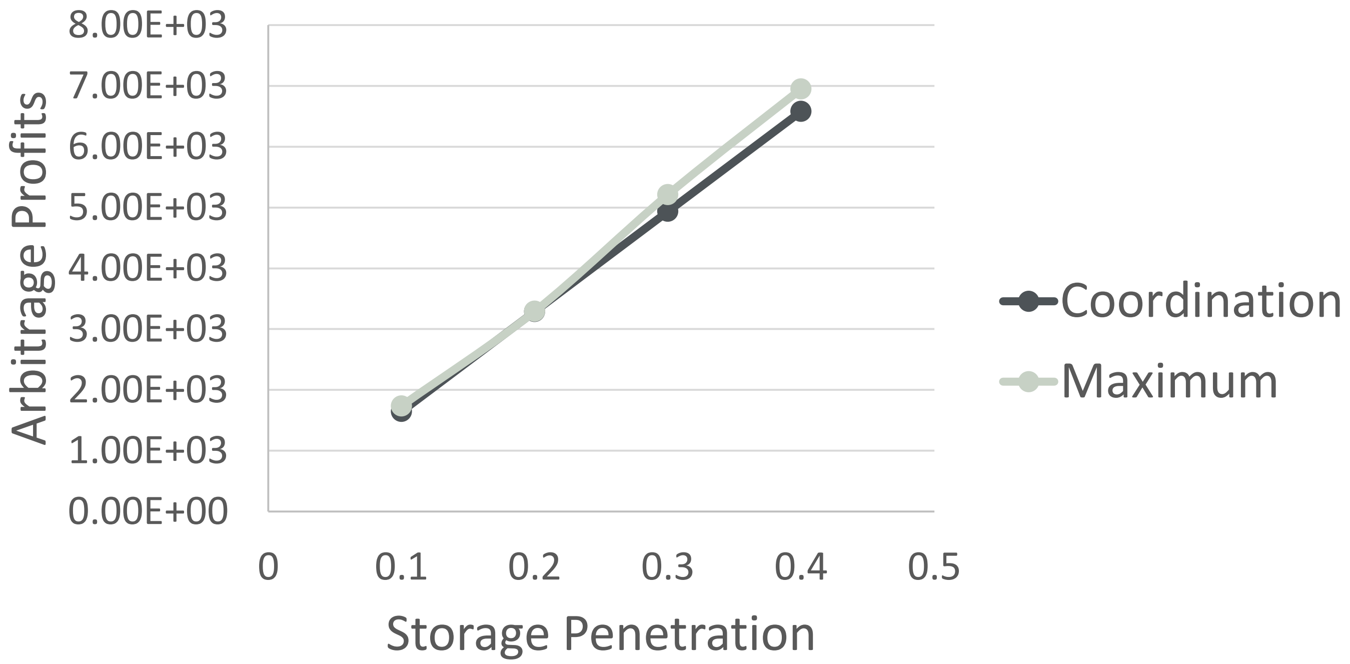
$$\text{s.t.} \quad \sum_i \text{power}_i \in \text{Set}, \quad \text{resource}_i \in \text{set}_i, \quad \forall i.$$



Squared Voltage Deviation vs. Solar and Storage Penetrations



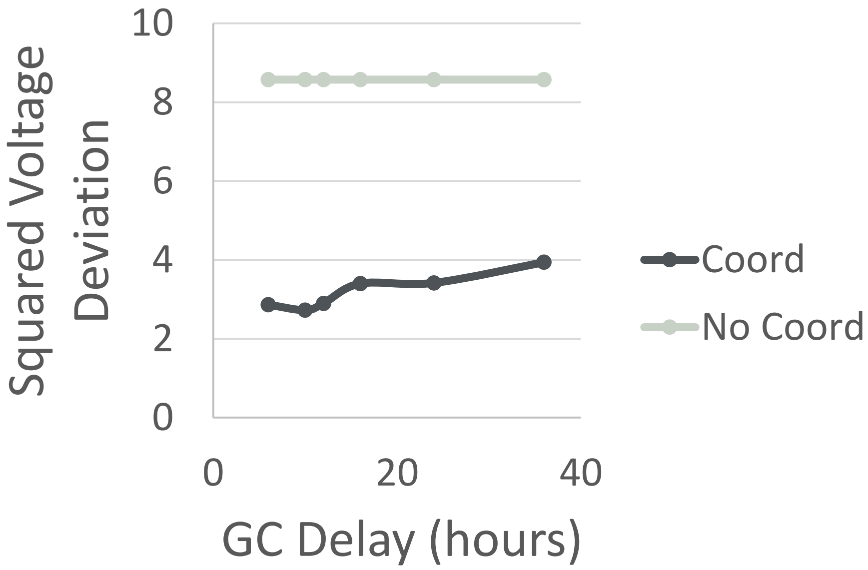
Arbitrage Profits vs. Storage Penetration at 40% PV Penetration

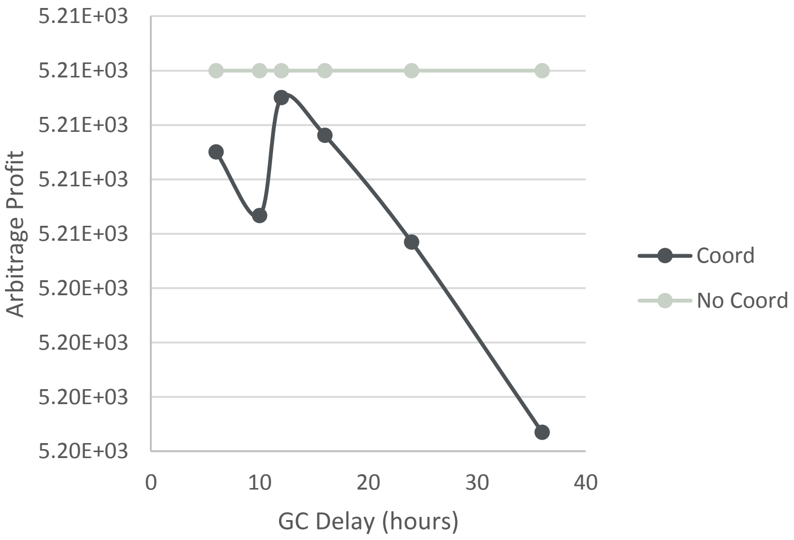


- Coordination is able to achieve nearly maximum arbitrage profits

Maximum is using Perfect Foresight Controller

Effects of Communication Delay (Solar = 50%, Storage = 30%)





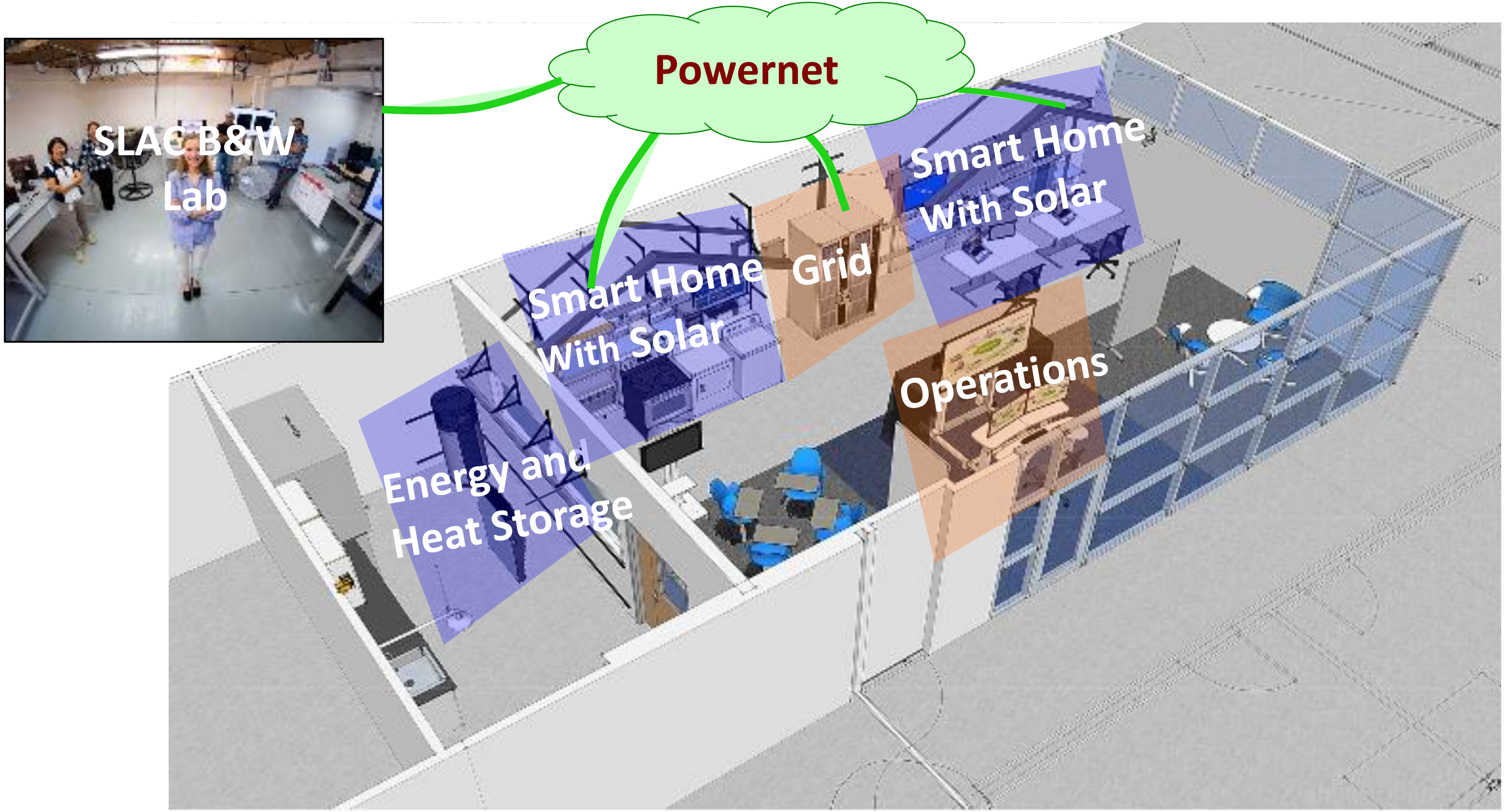
Ramp Following Results Overview

	Stochastic Ramps	Deterministic Ramps	Cost Min
Average Arbitrage Profit	599	2916	4441
Average Voltage Violation	0.011	0.004	0.011
Ramp Availability	93%	100%	-

- Ramp following does not increase the number of voltage violations
- Detracts from energy arbitrage capability
- Therefore, compensation from ramp following must be sufficiently high

Bits and Watts Labs

Powernet in the Lab



Powernet in the field

- 24 homes arranged in 13 units (2 single / 11 Duplex duplex side-by-side, equipped with PVs and A/C and individual power metering