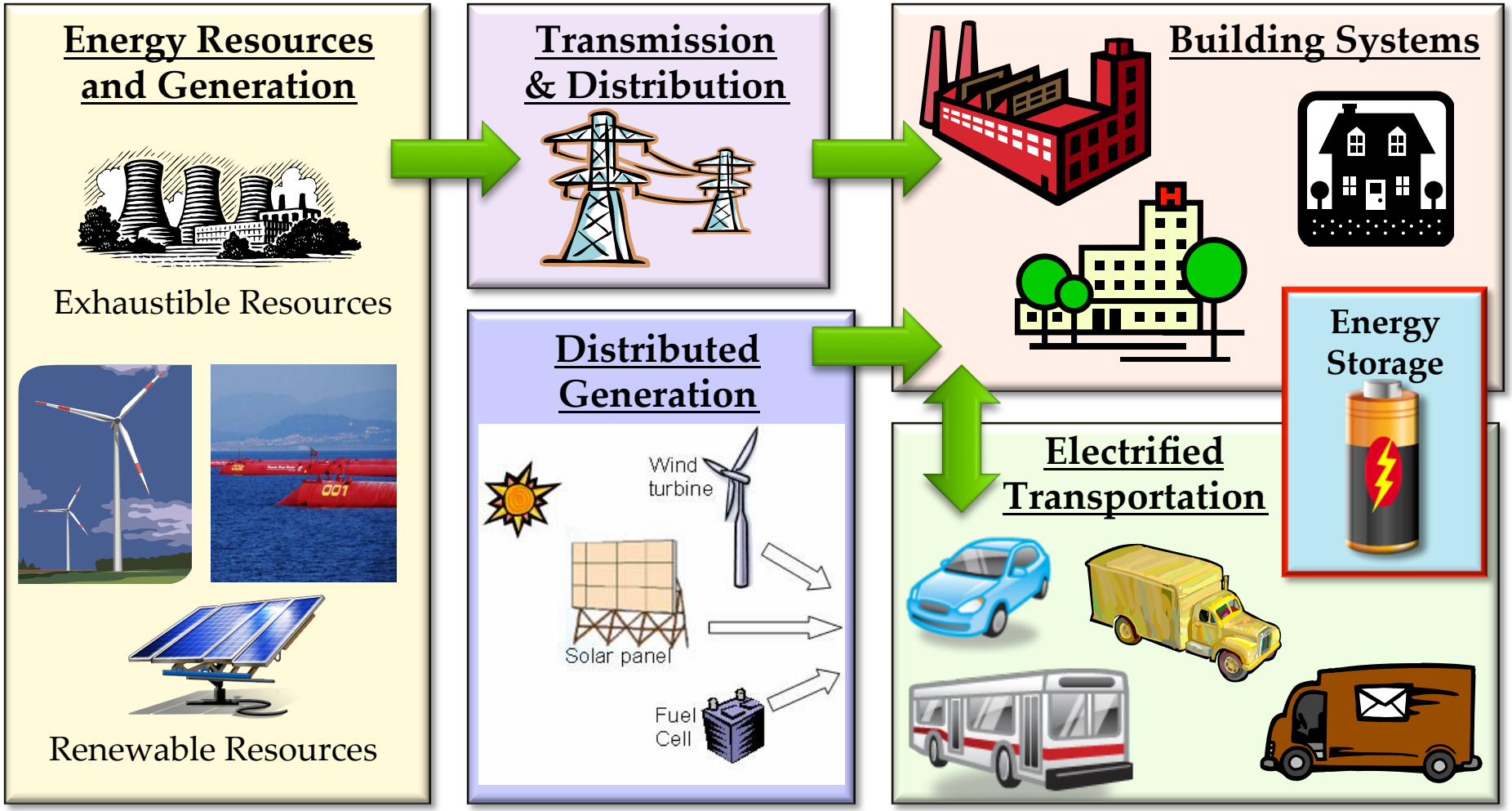
Smarter Cars, Homes, and Grids:
Case Studies in Optimal Energy Management

Prof. Scott Moura

Assistant Professor | eCAL Director
Civil & Environmental Engineering
University of California, Berkeley

E93 : Energy Engineering Seminar

Vision for Future Energy Infrastructure



Outline

The Battery Problem

Needs: Cheap, high energy/power, fast charge, long life

The Battery Problem

Needs: Cheap, high energy/power, fast charge, long life

Reality: Expensive, conservatively design/operated, die too quickly

The Battery Problem

Needs: Cheap, high energy/power, fast charge, long life

Reality: Expensive, conservatively design/operated, die too quickly

Some Motivating Facts

EV Batts	1000 USD / kWh (2010)*
	485 USD / kWh (2012)*
	125 USD / kWh for parity to IC engine
	Only 50-80% of available capacity is used
	Range anxiety inhibits adoption
	Lifetime risks caused by fast charging

*Source: MIT Technology Review, "The Electric Car is Here to Stay." (2013)

The Battery Problem

Needs: Cheap, high energy/power, fast charge, long life

Reality: Expensive, conservatively design/operated, die too quickly

Some Motivating Facts

EV Batts	1000 USD / kWh (2010)*
	485 USD / kWh (2012)*
	125 USD / kWh for parity to IC engine
	Only 50-80% of available capacity is used
	Range anxiety inhibits adoption
	Lifetime risks caused by fast charging

Two Solutions

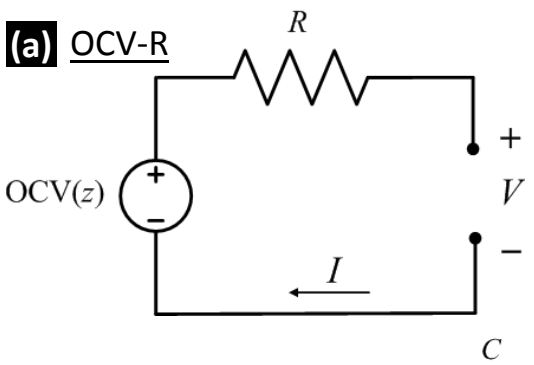
Design better batteries (materials science & chemistry)	Make current batteries better (estimation and control)

*Source: MIT Technology Review, "The Electric Car is Here to Stay." (2013)

Battery Models

Equivalent Circuit Model

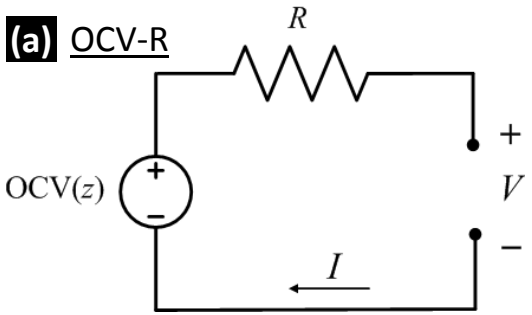
(a) OCV-R



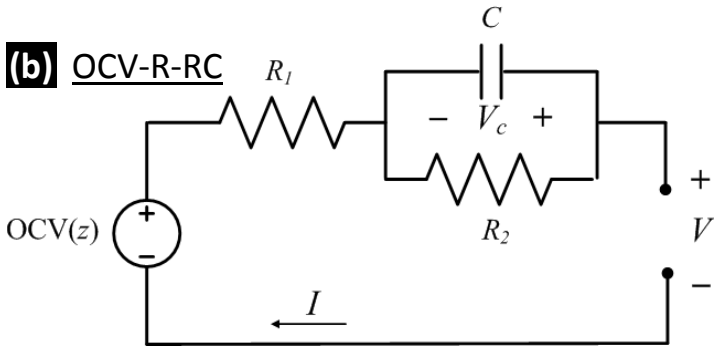
Battery Models

Equivalent Circuit Model

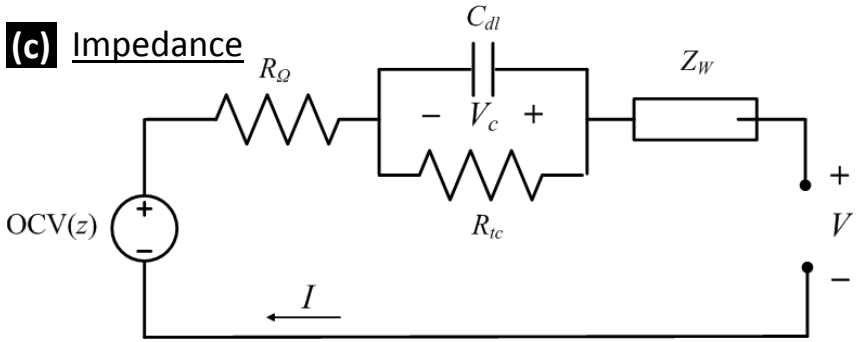
(a) OCV-R



(b) OCV-R-RC

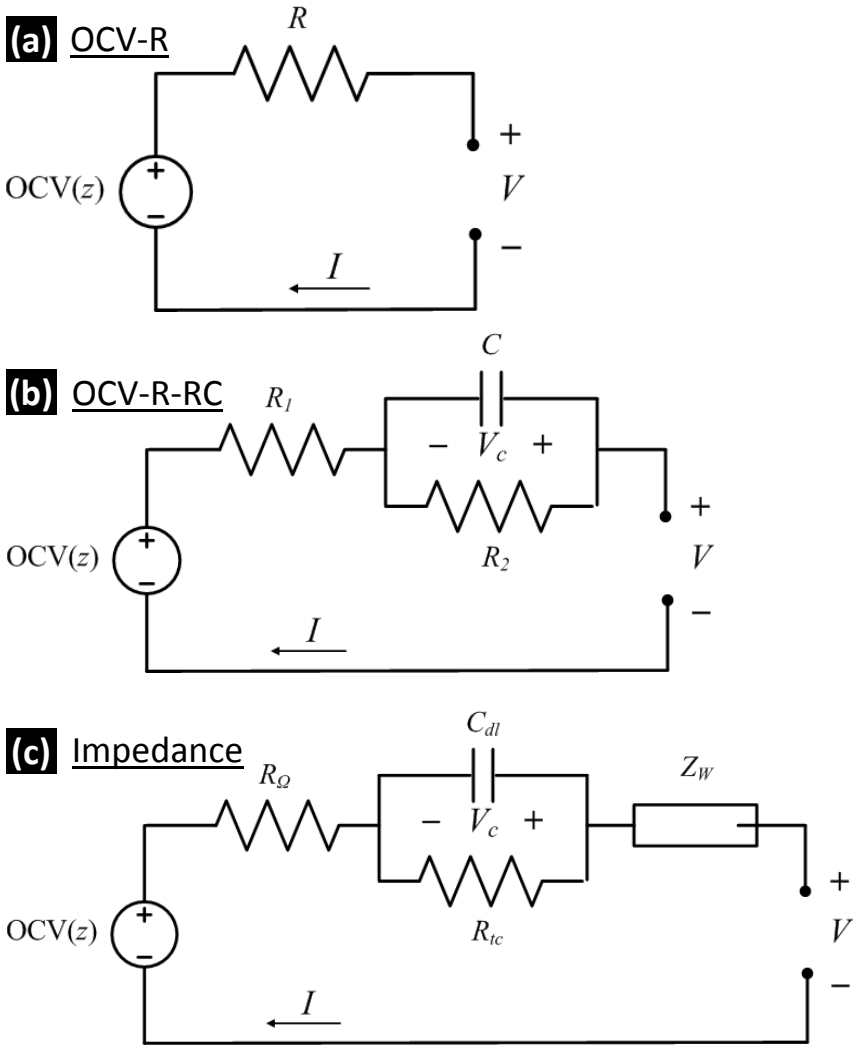


(c) Impedance

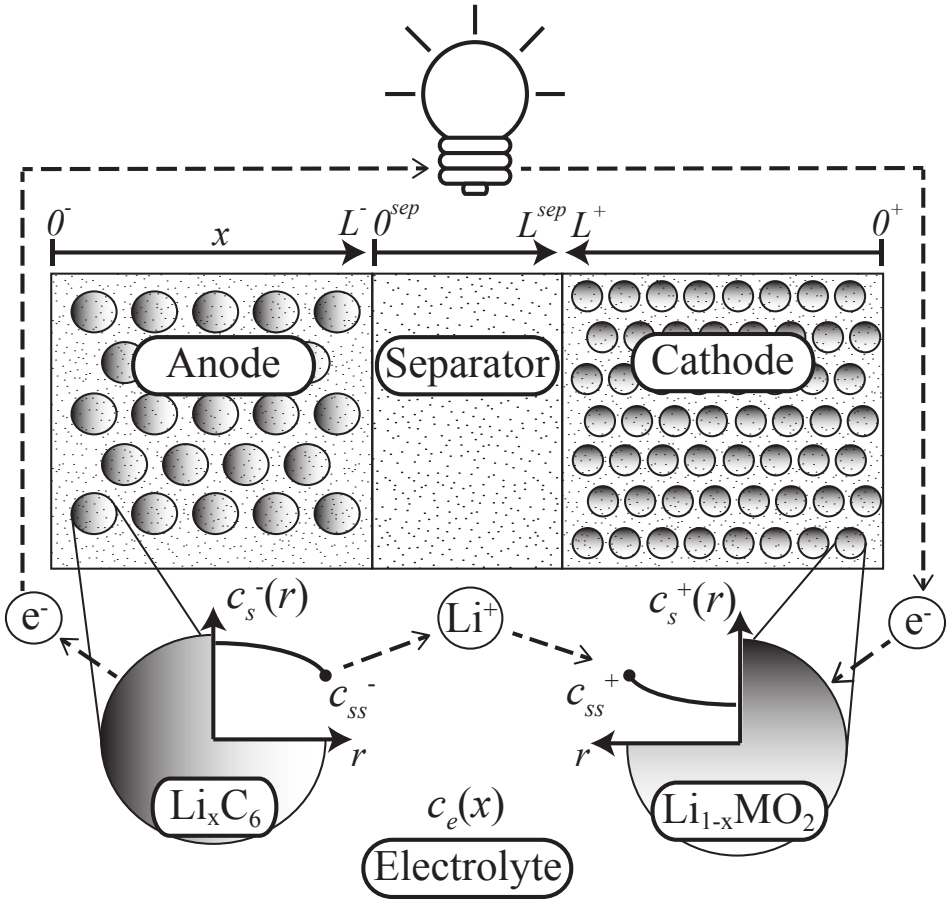


Battery Models

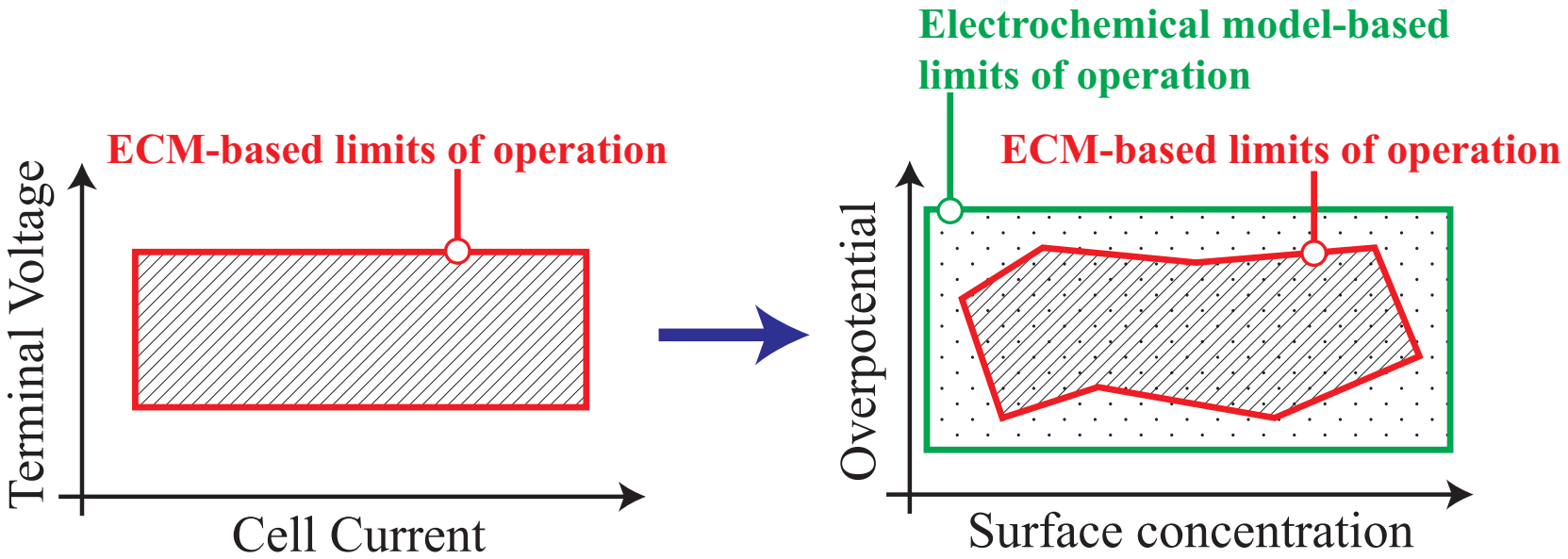
Equivalent Circuit Model



Electrochemical Model



Operate Batteries at their Physical Limits



Electrochemical Model Equations

well, some of them

Description	Equation
Solid phase Li concentration	$\frac{\partial c_s^{\pm}}{\partial t}(x,r,t) = \frac{1}{r^2}\frac{\partial}{\partial r}\left[D_s^{\pm} r^2 \frac{\partial c_s^{\pm}}{\partial r}(x,r,t)\right]$
Electrolyte Li concentration	$\varepsilon_e \frac{\partial c_e}{\partial t}(x,t) = \frac{\partial}{\partial x}\left[\varepsilon_e D_e \frac{\partial c_e}{\partial x}(x,t) + \frac{1-t_c^0}{F} i_e^{\pm}(x,t)\right]$
Solid potential	$\frac{\partial \phi_s^{\pm}}{\partial x}(x,t) = \frac{i_e^{\pm}(x,t) - I(t)}{\sigma^{\pm}}$
Electrolyte potential	$\frac{\partial \phi_e}{\partial x}(x,t) = -\frac{i_e^{\pm}(x,t)}{\kappa} + \frac{2RT}{F}(1-t_c^0)\left(1 + \frac{d\ln f_{c/a}}{d\ln c_e}(x,t)\right)\frac{\partial \ln c_e}{\partial x}(x,t)$
Electrolyte ionic current	$\frac{\partial i_e^{\pm}}{\partial x}(x,t) = a_s F j_n^{\pm}(x,t)$
Molar flux btw phases	$j_n^{\pm}(x,t) = \frac{1}{F} i_0^{\pm}(x,t)\left[e^{\frac{\alpha_a F}{RT}\eta^{\pm}(x,t)} - e^{-\frac{\alpha_c F}{RT}\eta^{\pm}(x,t)}\right]$
Temperature	$\rho c_P \frac{dT}{dt}(t) = h\left[T^0(t) - T(t)\right] + I(t)V(t) - \int_{0^-}^{0^+} a_s F j_n(x,t)\Delta T(x,t)dx$

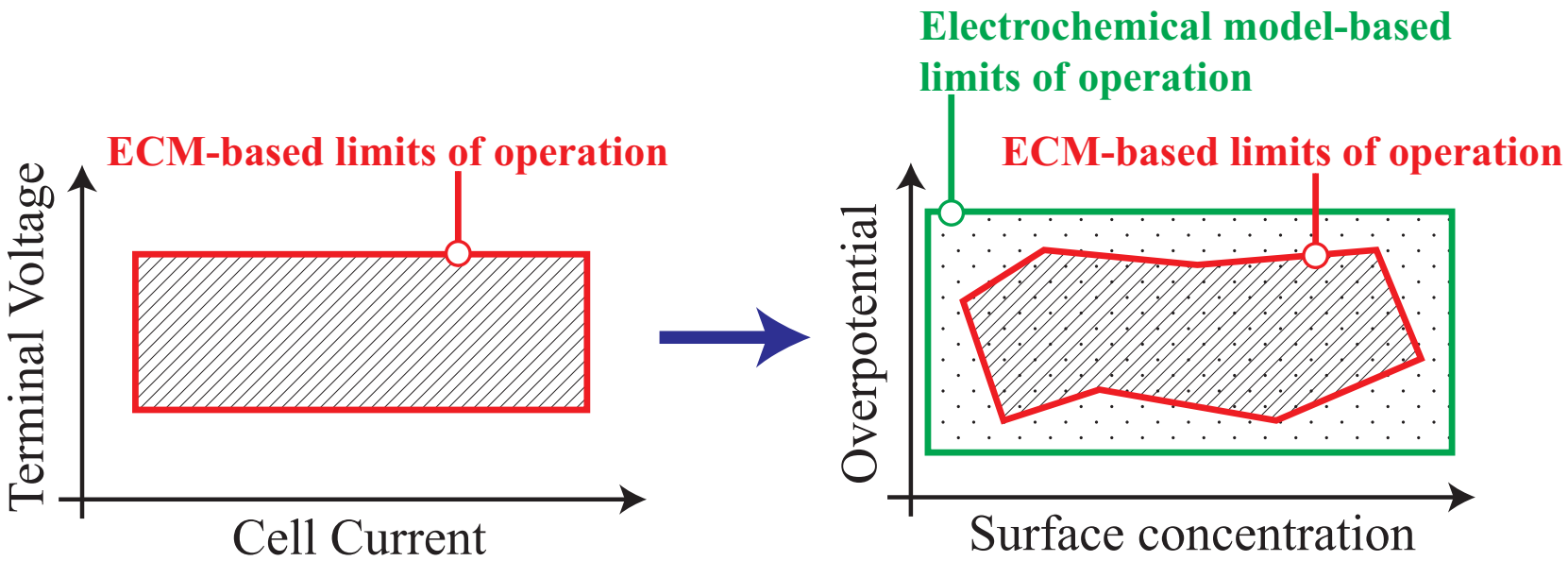
Animation of Li Ion Evolution

Operate Batteries at their Physical Limits

Operate Batteries at their Physical Limits

Problem Statement

Given accurate state estimates, govern the electric current such that safe operating constraints are satisfied.

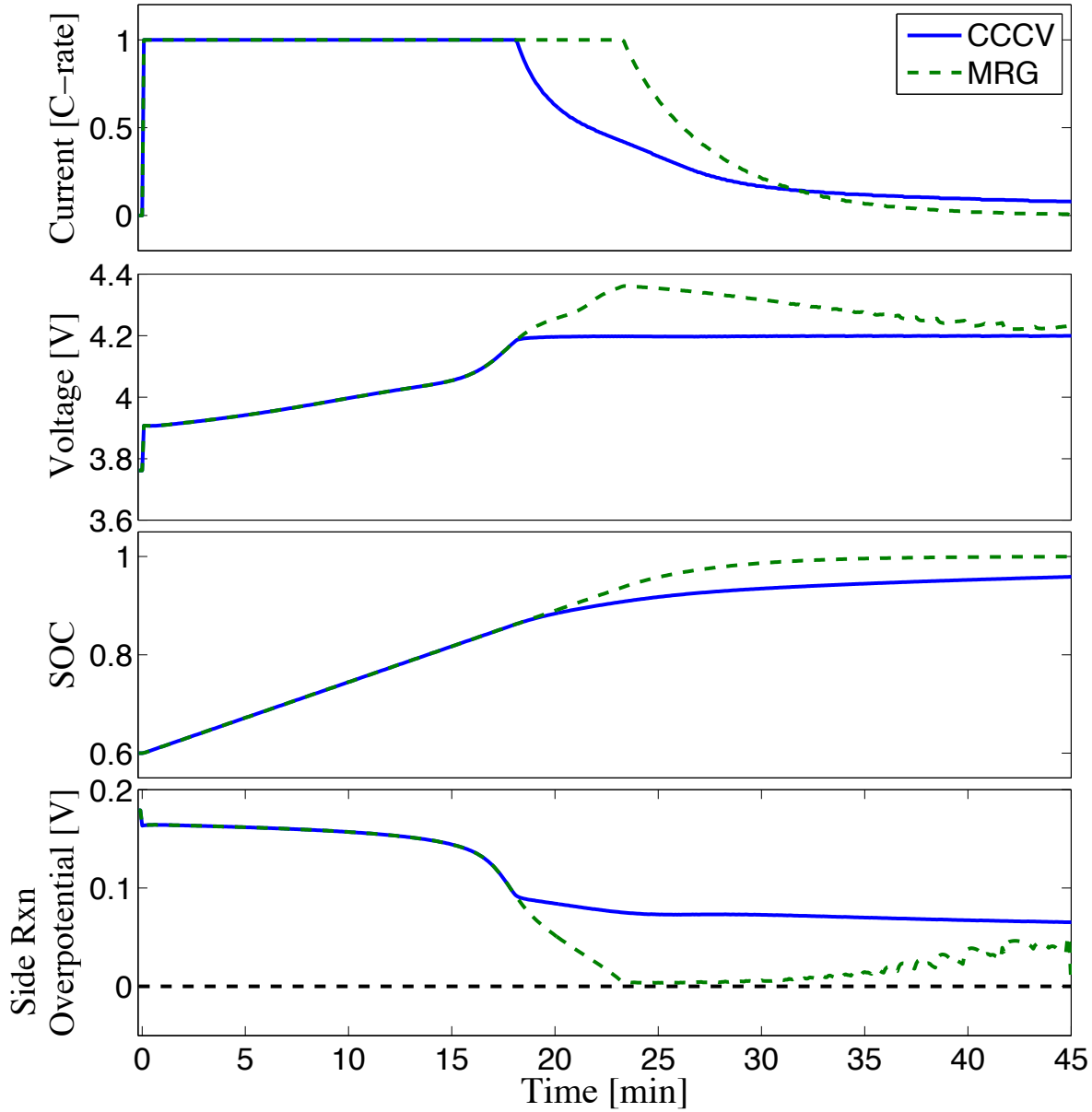


Constraints

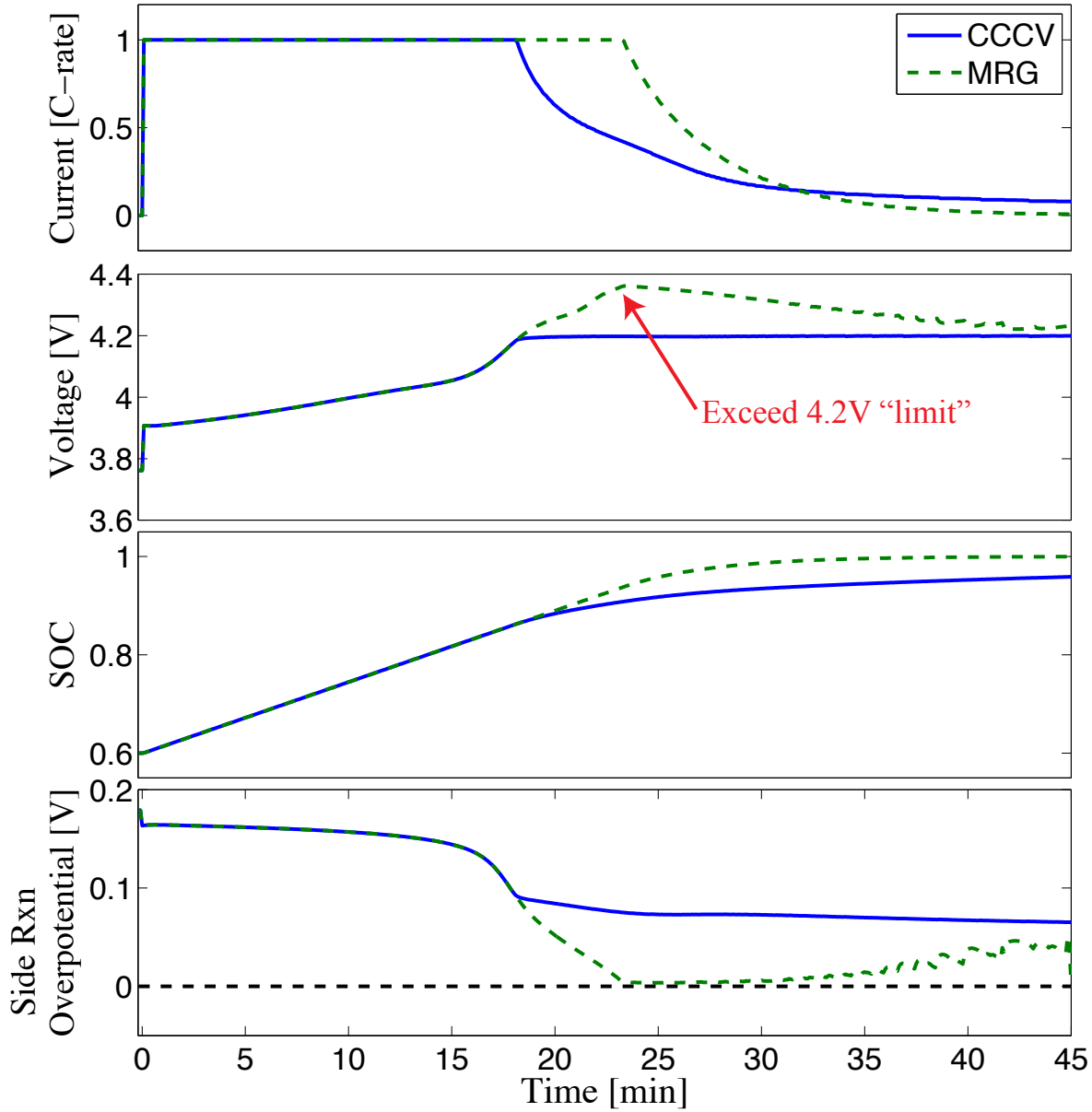
Variable	Definition	Constraint
$I(t)$	Current	Power electronics limits
$c_s^{\pm}(x, r, t)$	Li concentration in solid	Saturation/depletion
$\frac{\partial c_s^{\pm}}{\partial r}(x, r, t)$	Li concentration gradient	Diffusion-induced stress
$c_e(x, t)$	Li concentration in electrolyte	Saturation/depletion
$T(t)$	Temperature	High/low temps accel. aging
$\eta_s(x, t)$	Side-rxn overpotential	Li plating, dendrite formation

Each variable, y, must satisfy $y_{\text{min}} \leq y \leq y_{\text{max}}$.

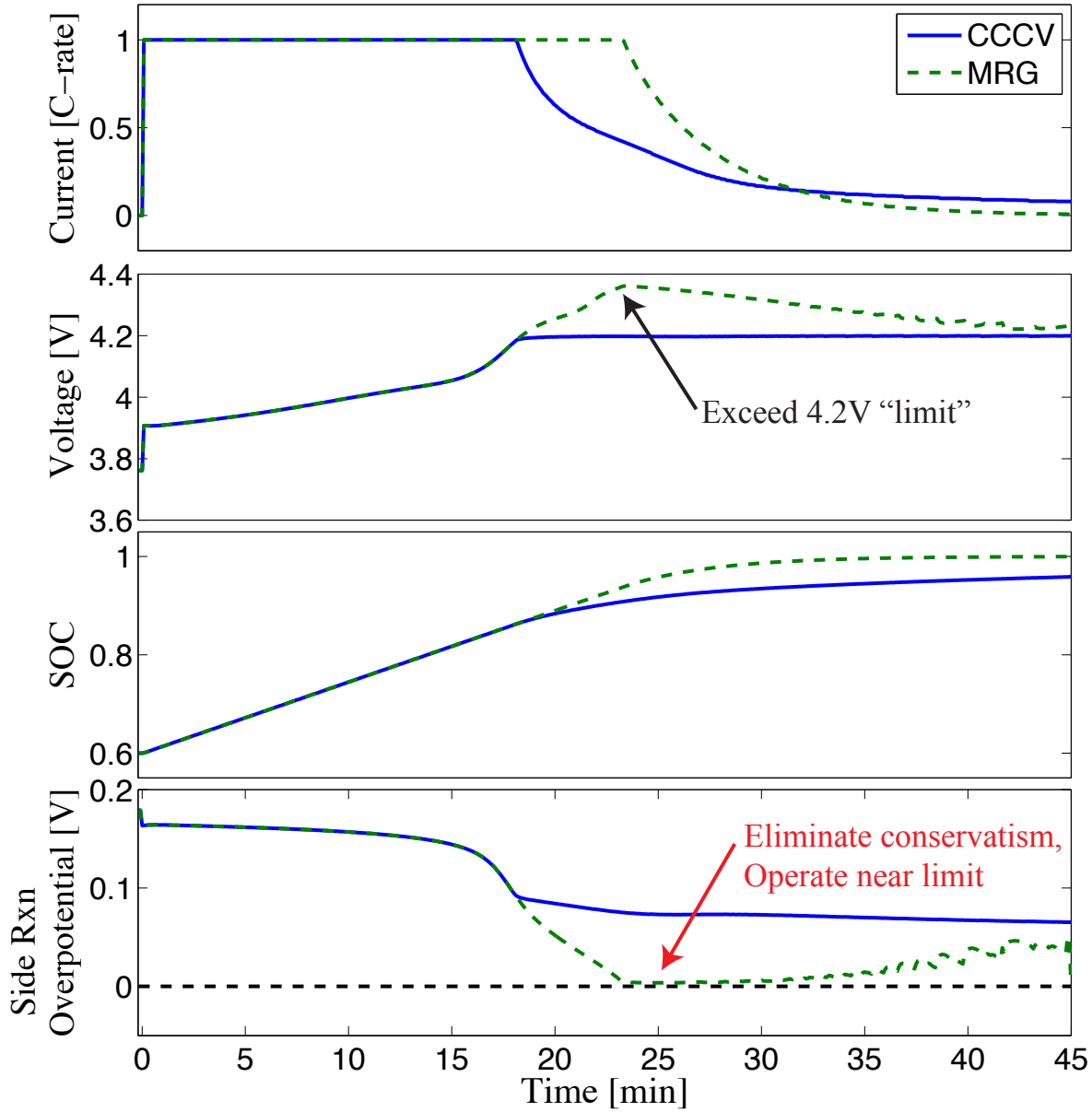
Application to Charging



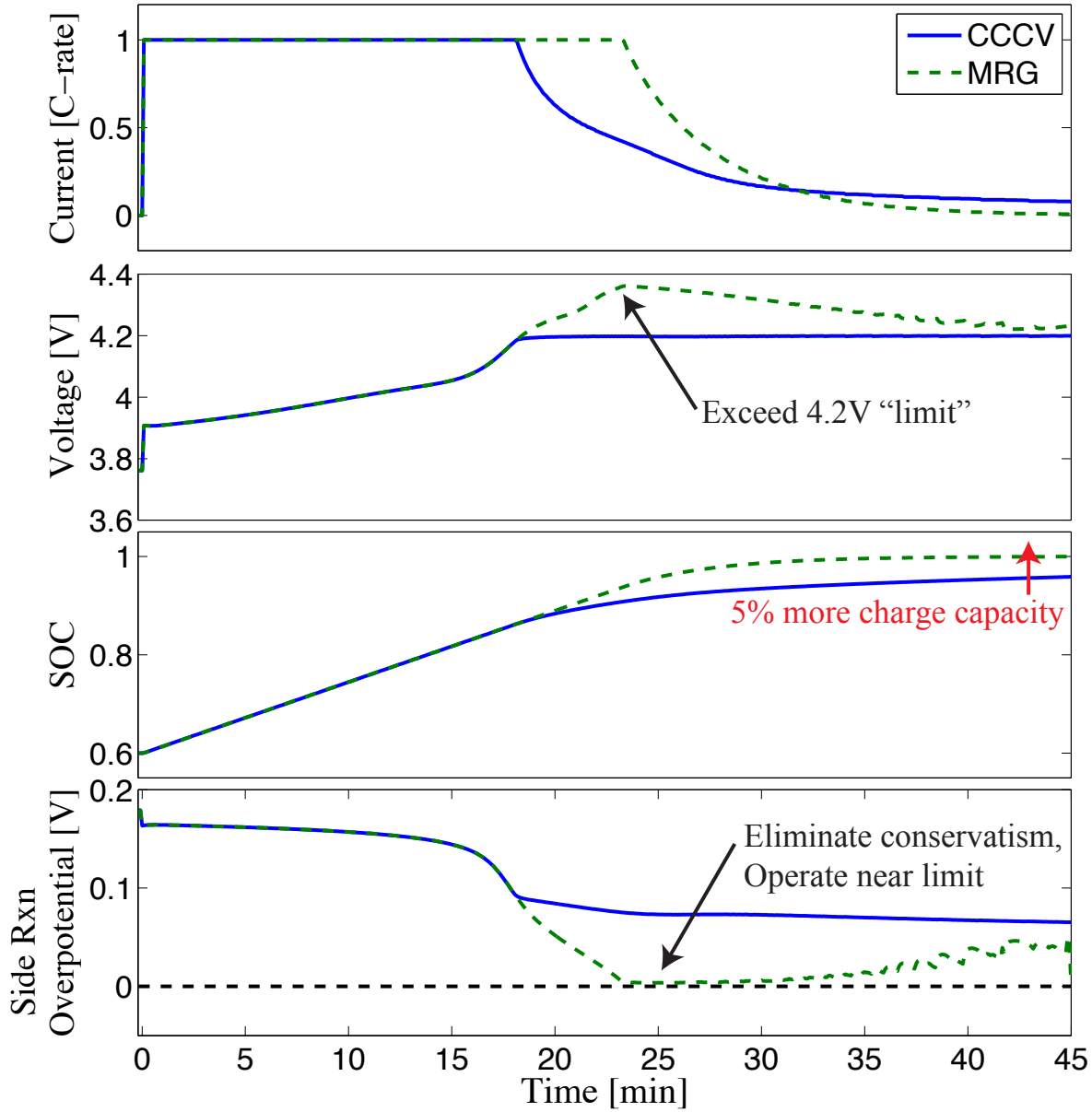
Application to Charging



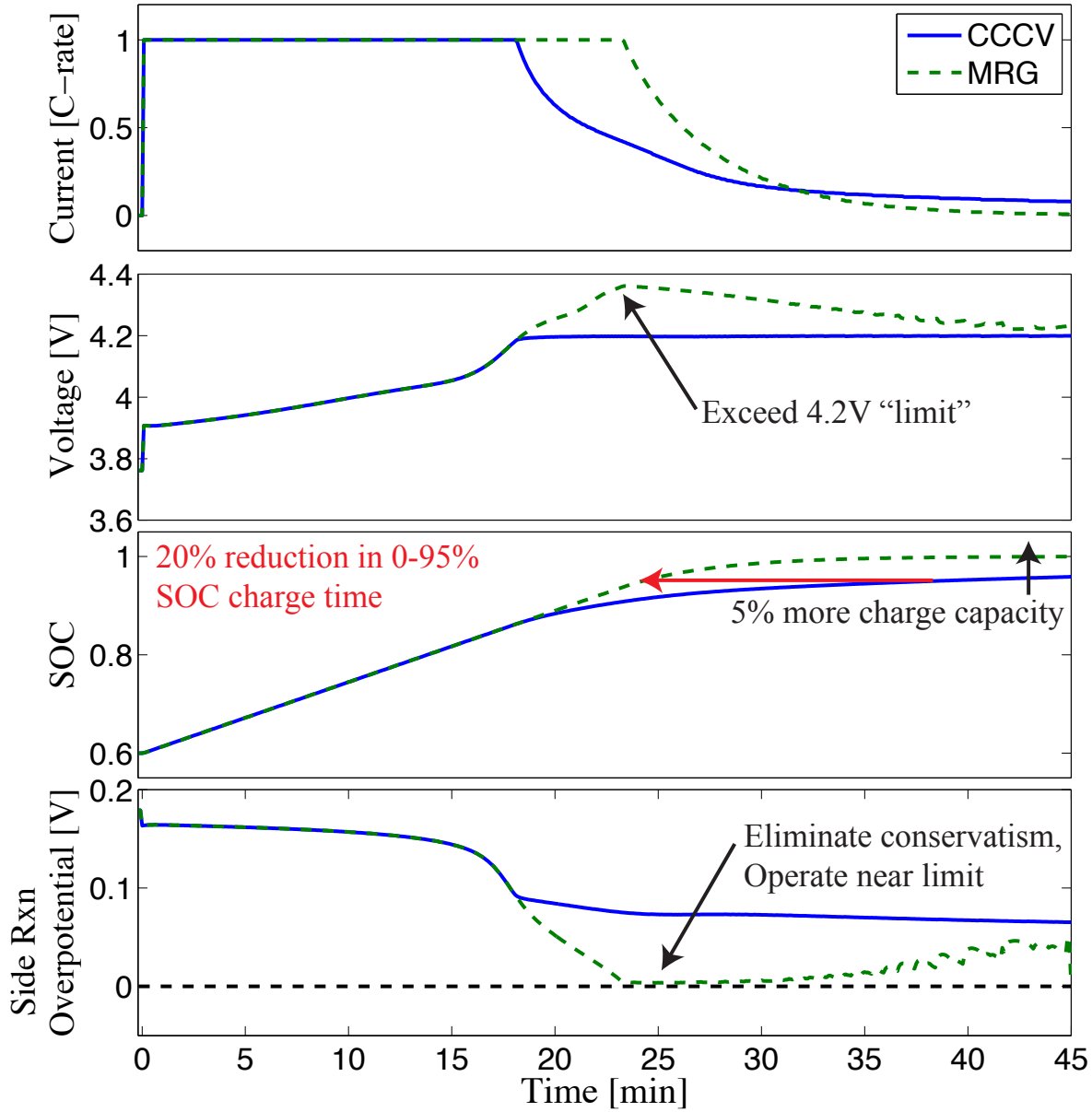
Application to Charging



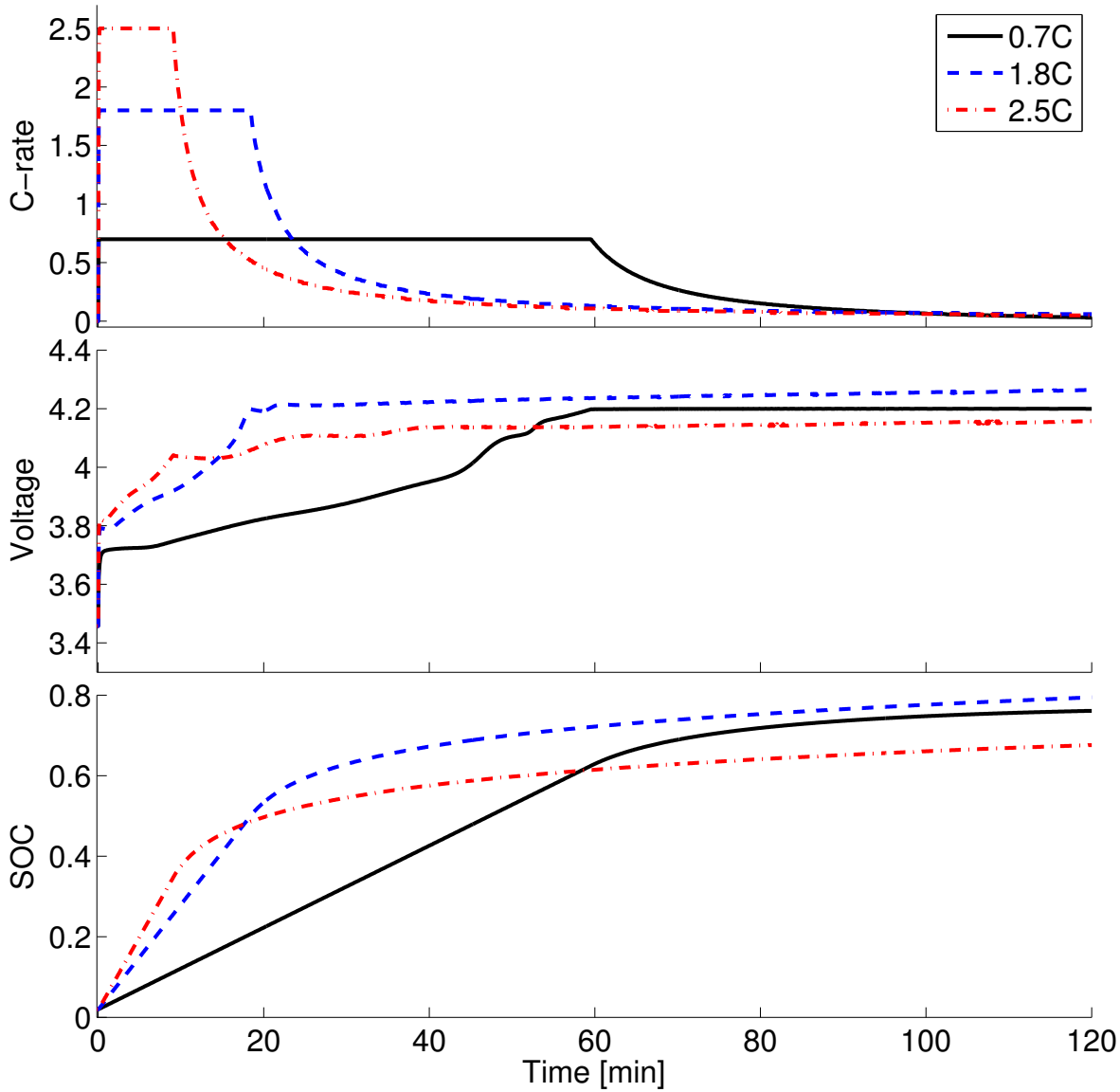
Application to Charging



Application to Charging



Fast Charging



Fast charge your smartphone/EV while getting coffee

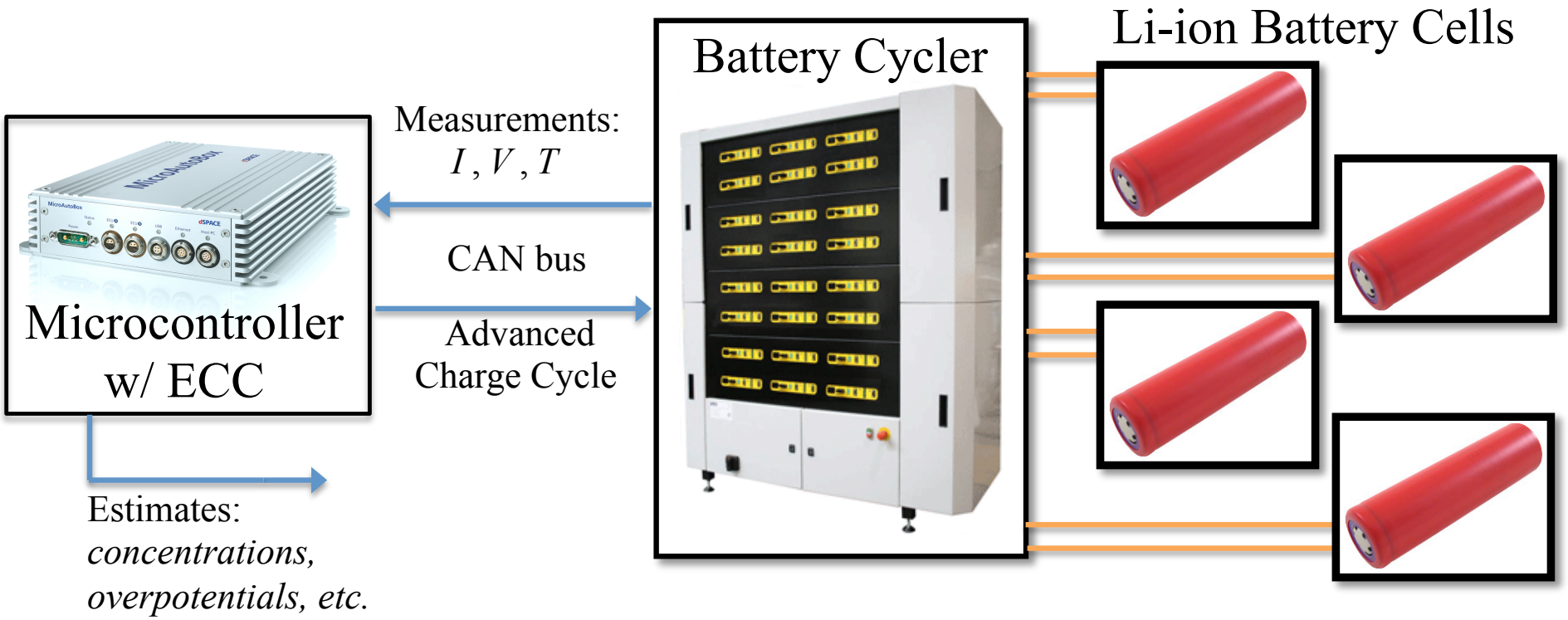
Table: Simulated fast charge times for various C-rates

Charge range	**0.7C** | Traditional	**1.8C** | ECC	**2.5C** | ECC
0-10%	7.92 min	3.17 min	2.33 min
0-20%	17.83 min	7.00 min	5.08 min
0-50%	47.33 min	18.42 min	20.50 min

S. J. Moura, N. A. Chaturvedi, M. Krstic, “Constraint Management in Li-ion Batteries: A Modified Reference Governor Approach,” 2013 American Control Conference, Washington, D.C., 2013. (Invited Paper)

Battery-in-the-Loop Test Facility

611 Davis Hall



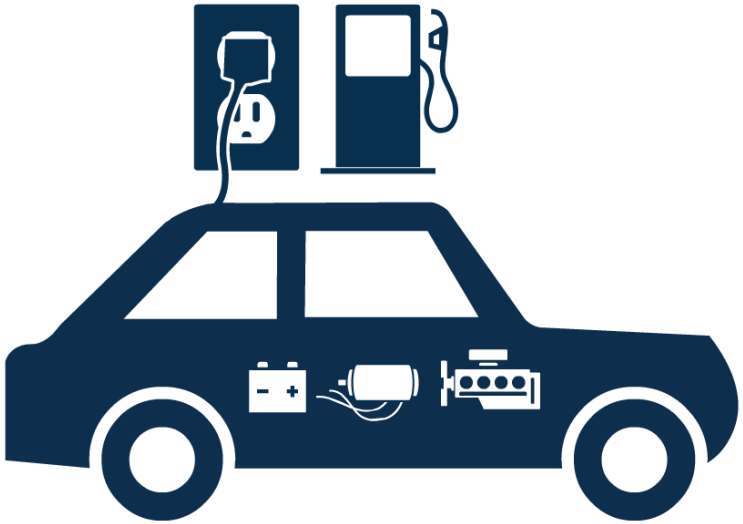
Motivation in Mobile Communication:

6.7B subscription accounts, 5.2B handsets in use,
1.7B sold worldwide in 2012

Outline

PHEV Energy Management Background

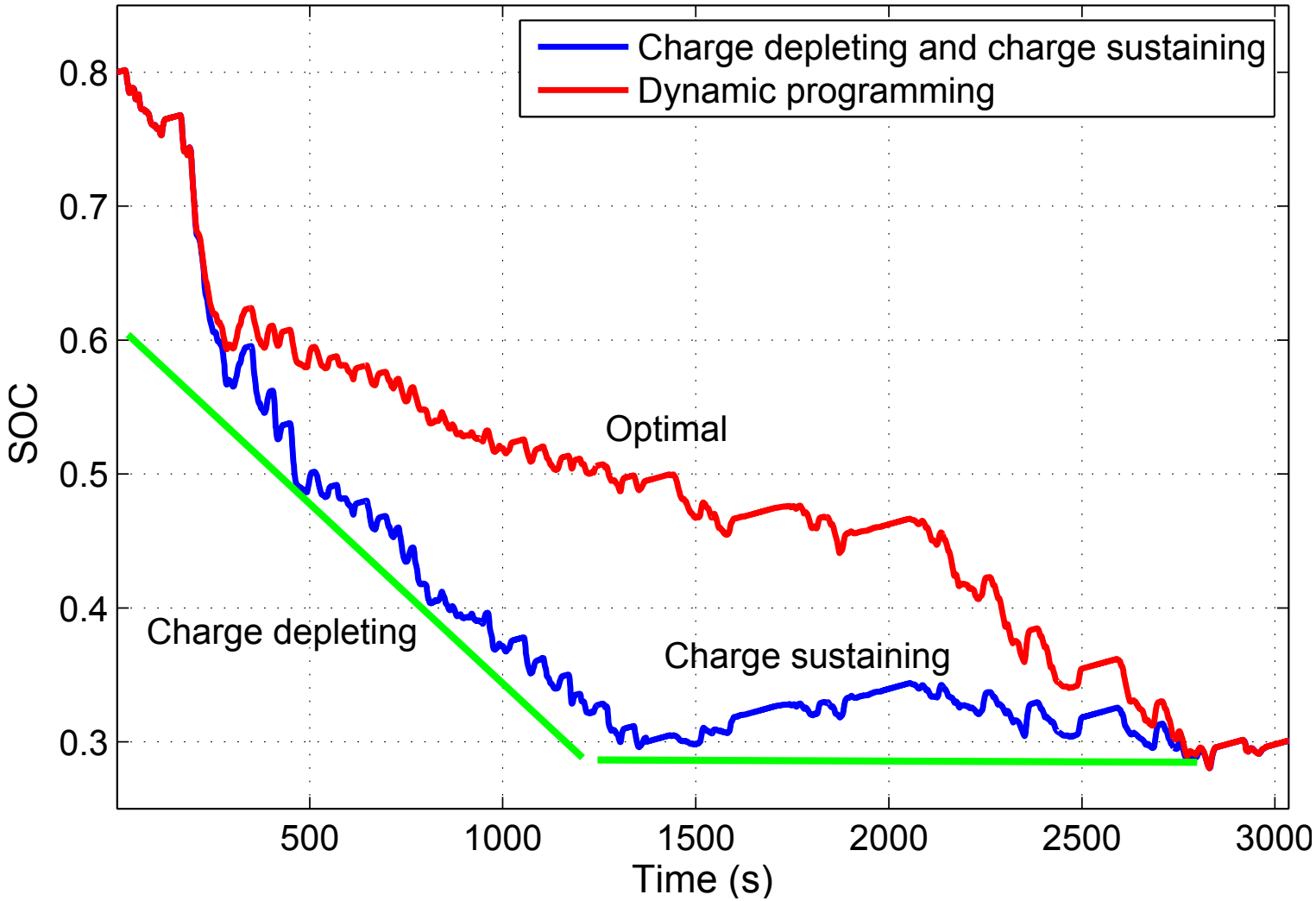
Plug-in Hybrid Electric Vehicles (PHEV)



- Fuel tank AND battery are depletable stores
- Fuel at gas station AND charge w/ plug

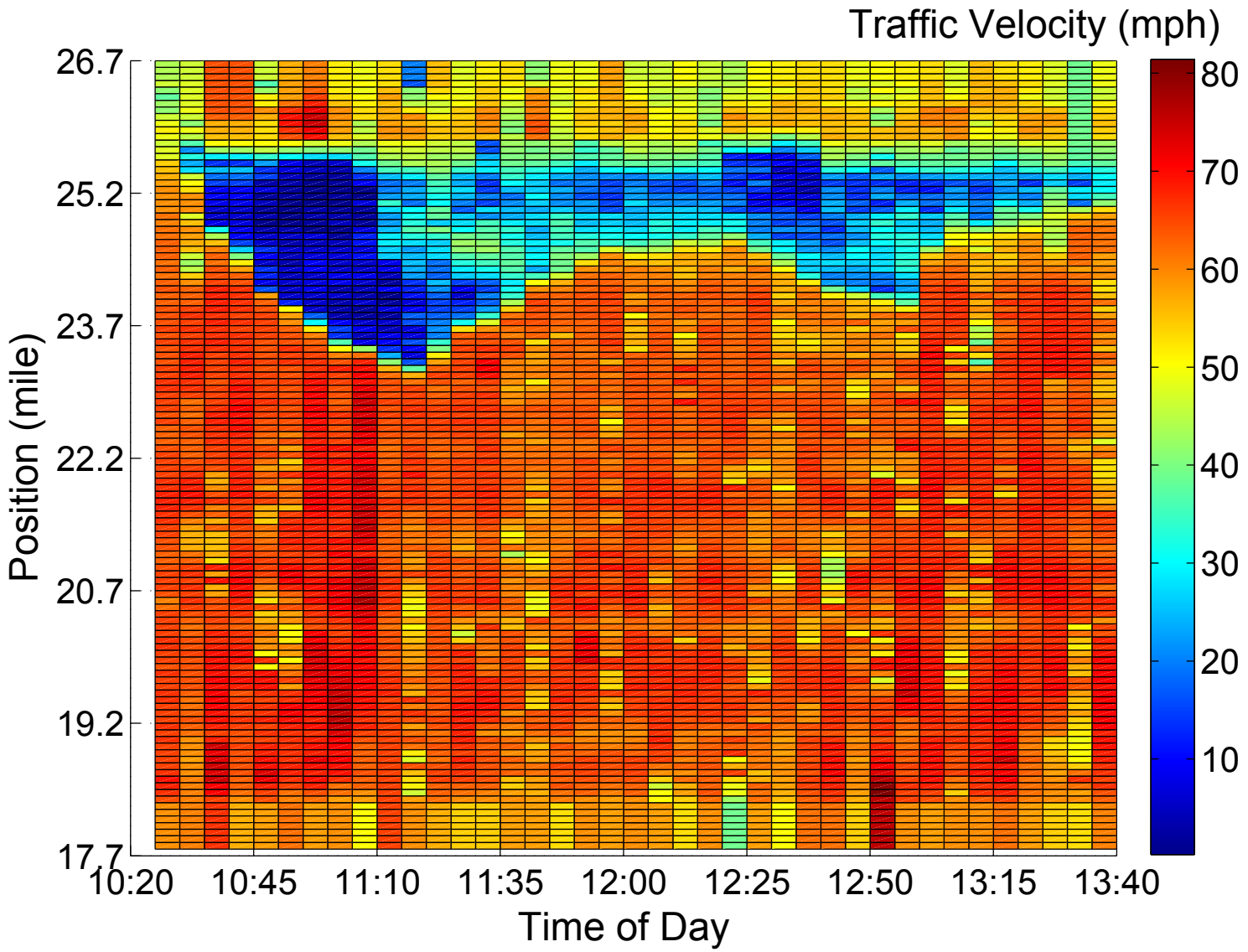
Ex: Chevy Volt, Prius PHEV, Fusion Energi, C-MAX Energi

PHEV Energy Management Background



Traffic Congestion

Traffic velocity on I-880 between 10:20 AM and 13:40 PM and between Hayward and Union City



Why Care?

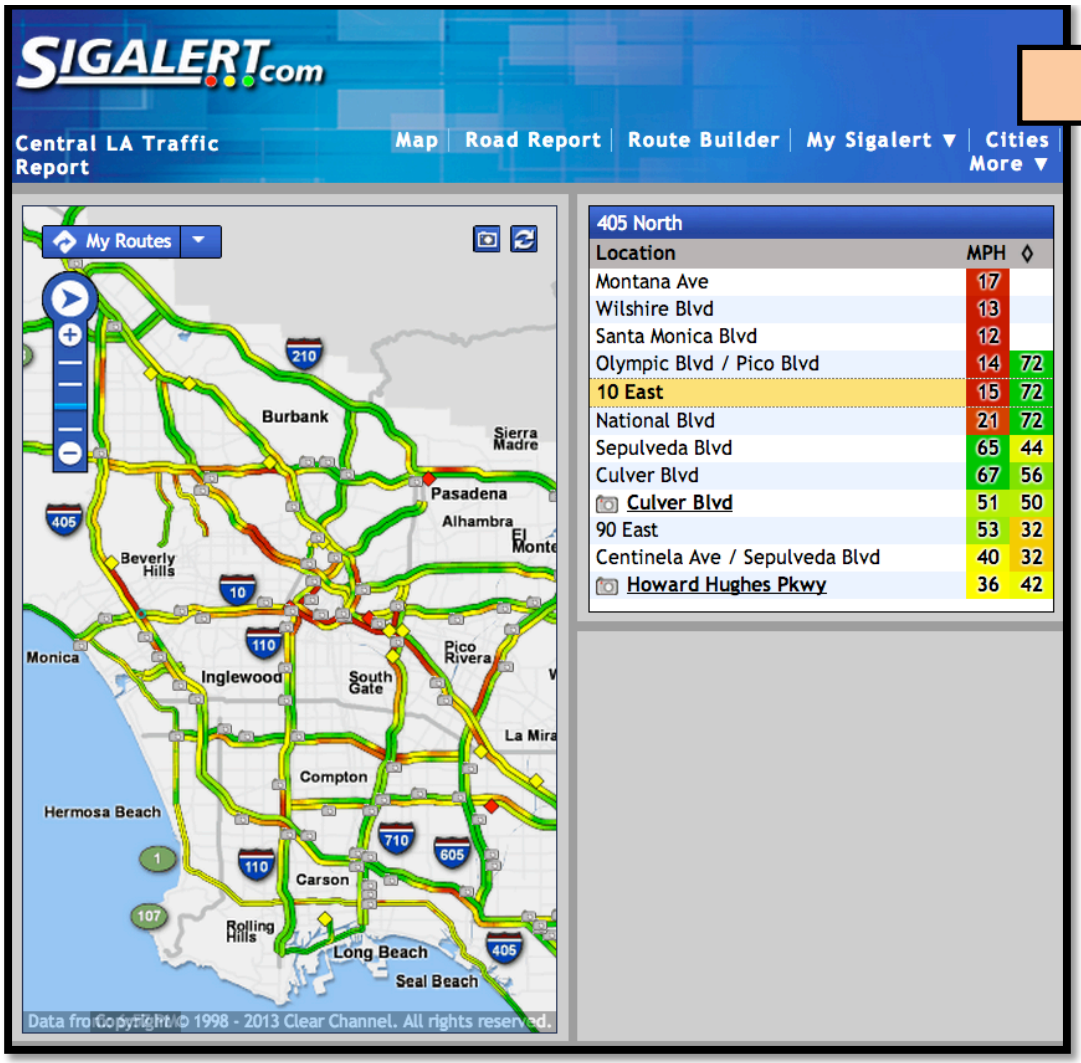
The Problem

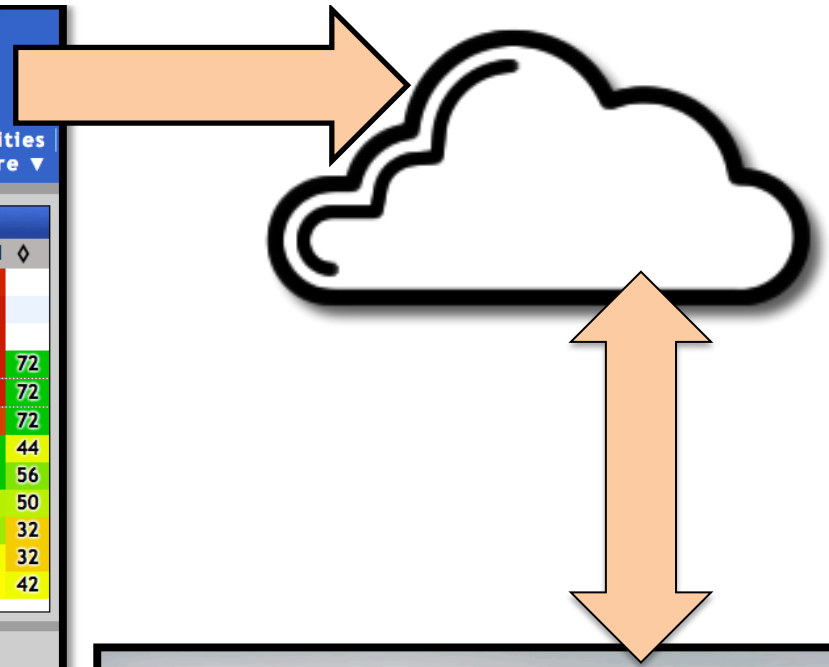
- 54.5 MPG CAFE by 2025
- Increased CAFE $\rightarrow$ Increased powertrain tech costs
- Urbanization $\rightarrow$ traffic $\rightarrow$ lower MPG

An Interesting Solution

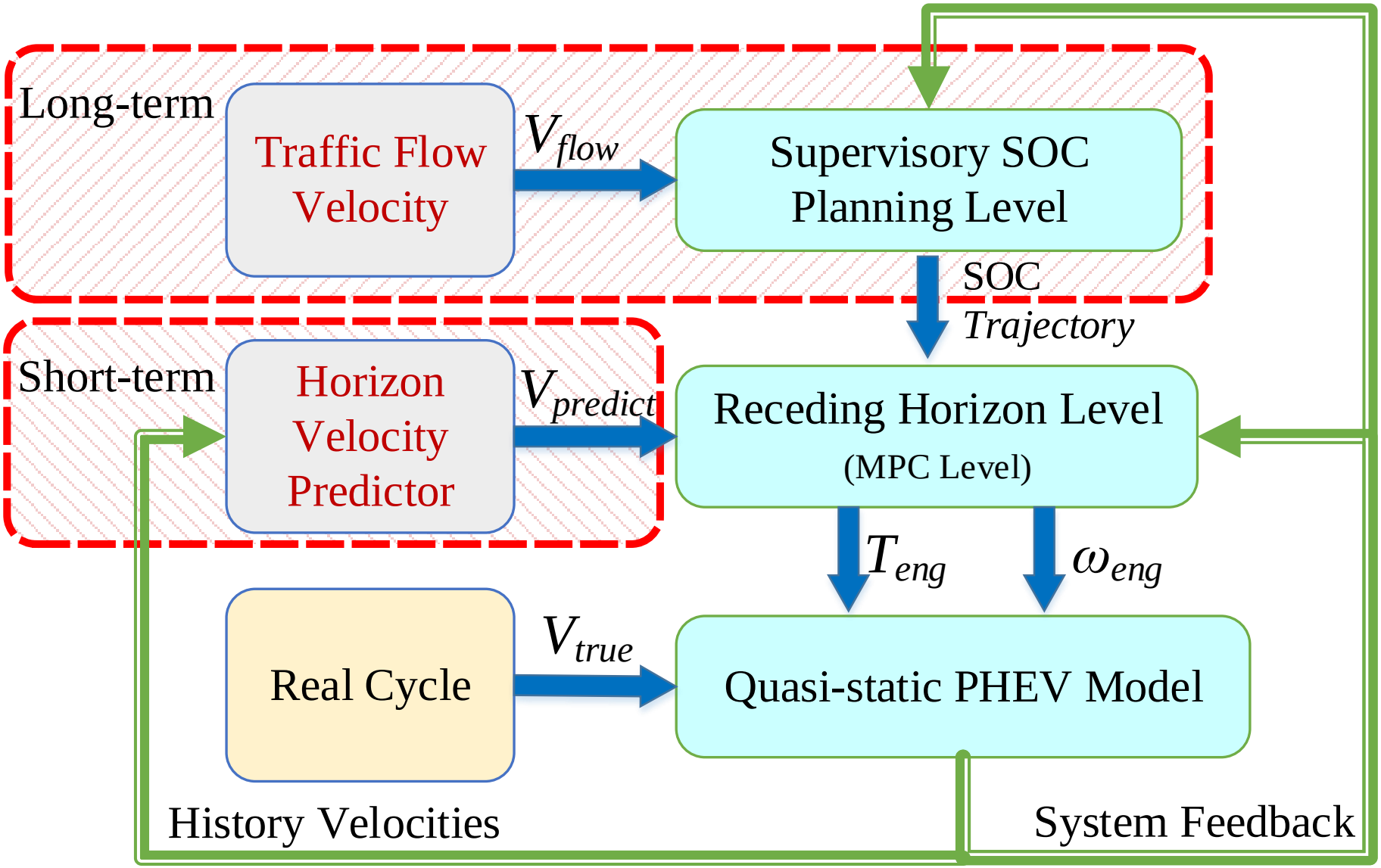
- Real-time traffic data (Google Traffic, PEMS, SigAlert.com) is available
- Cloud computing enables data retrival, optimization, communication
- Adapt PHEV energy management to real-time traffic conditions

Optimize PHEV Energy Management w/ Real-time Traffic Data

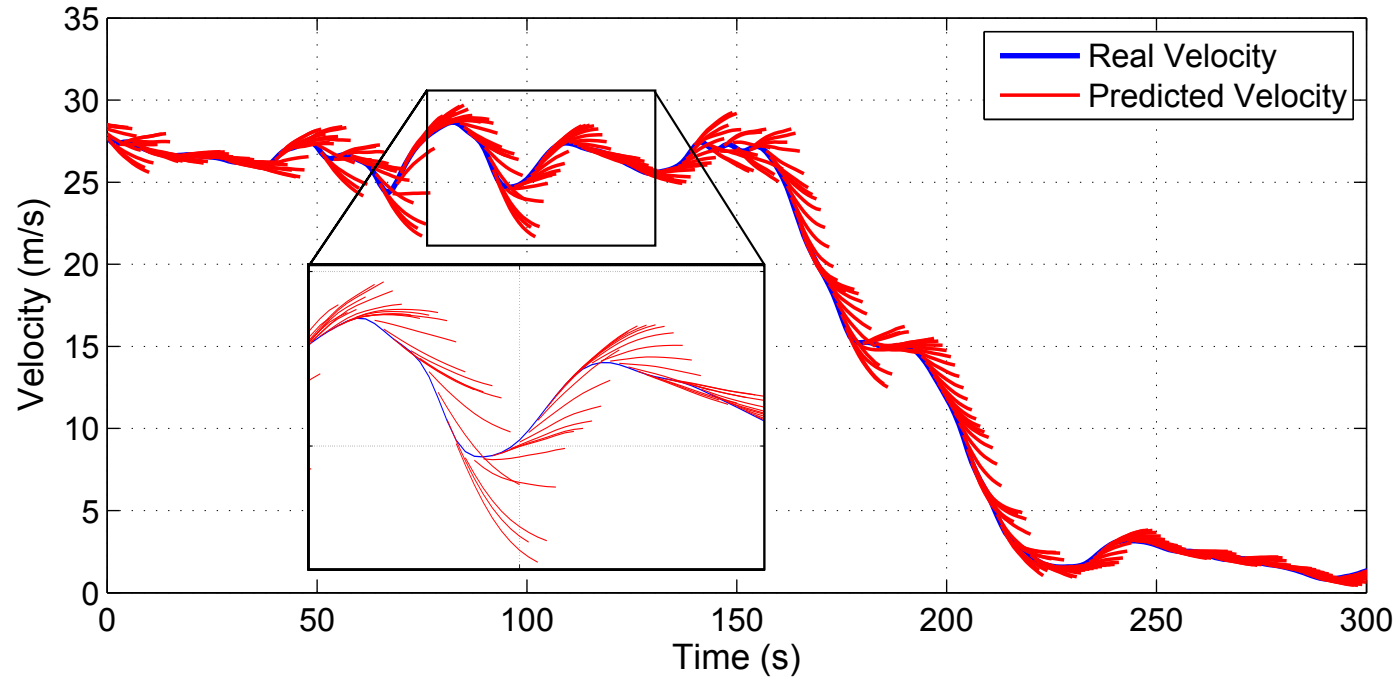


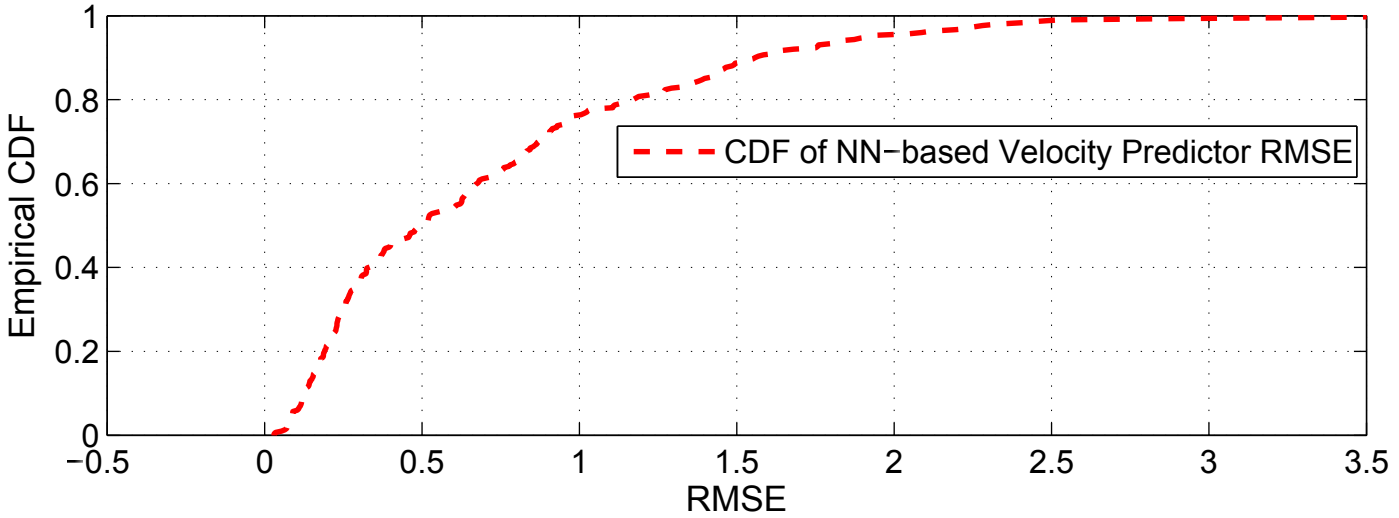


Algorithm Flow Chart

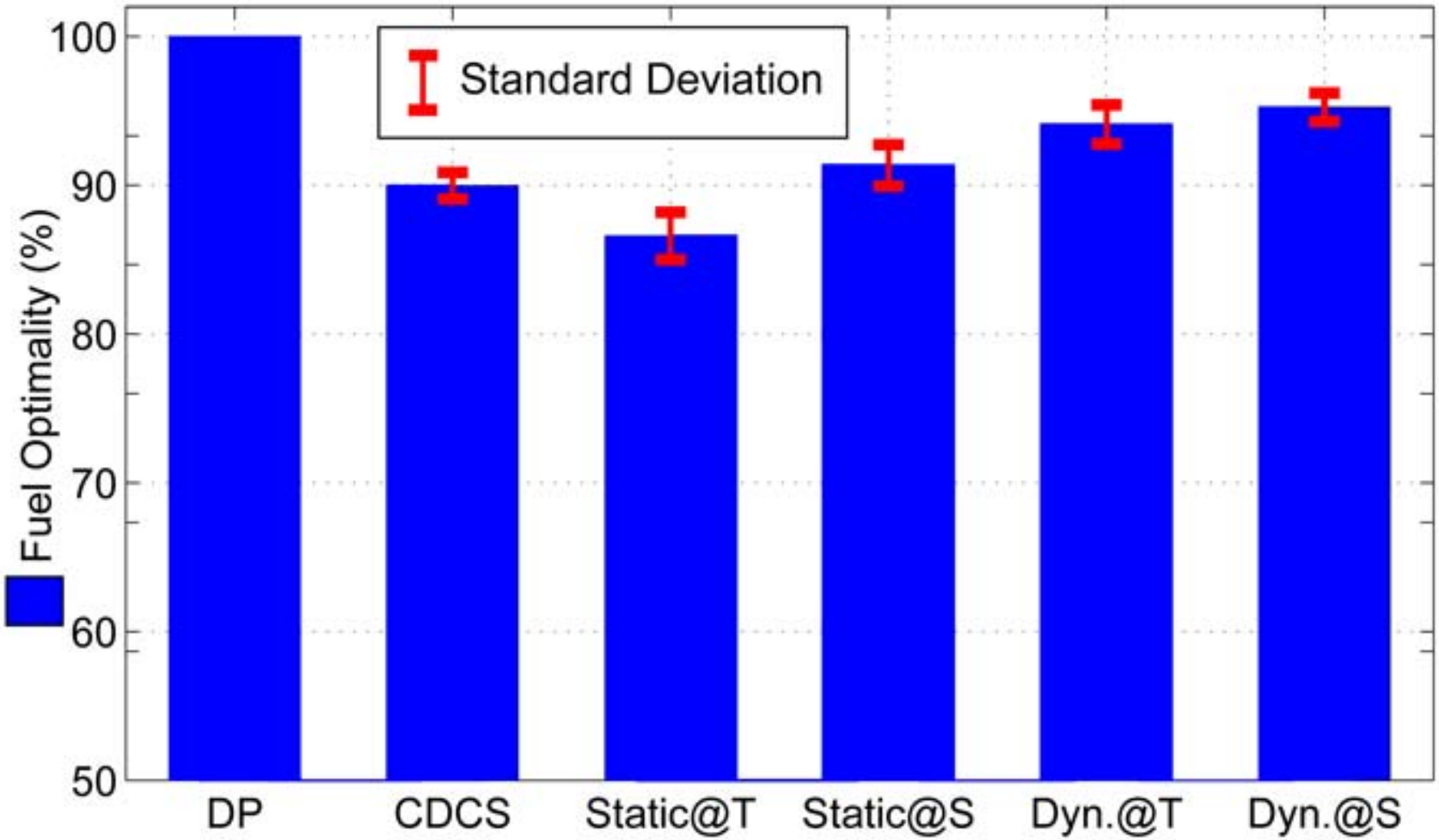


Forecast Vehicle Velocity



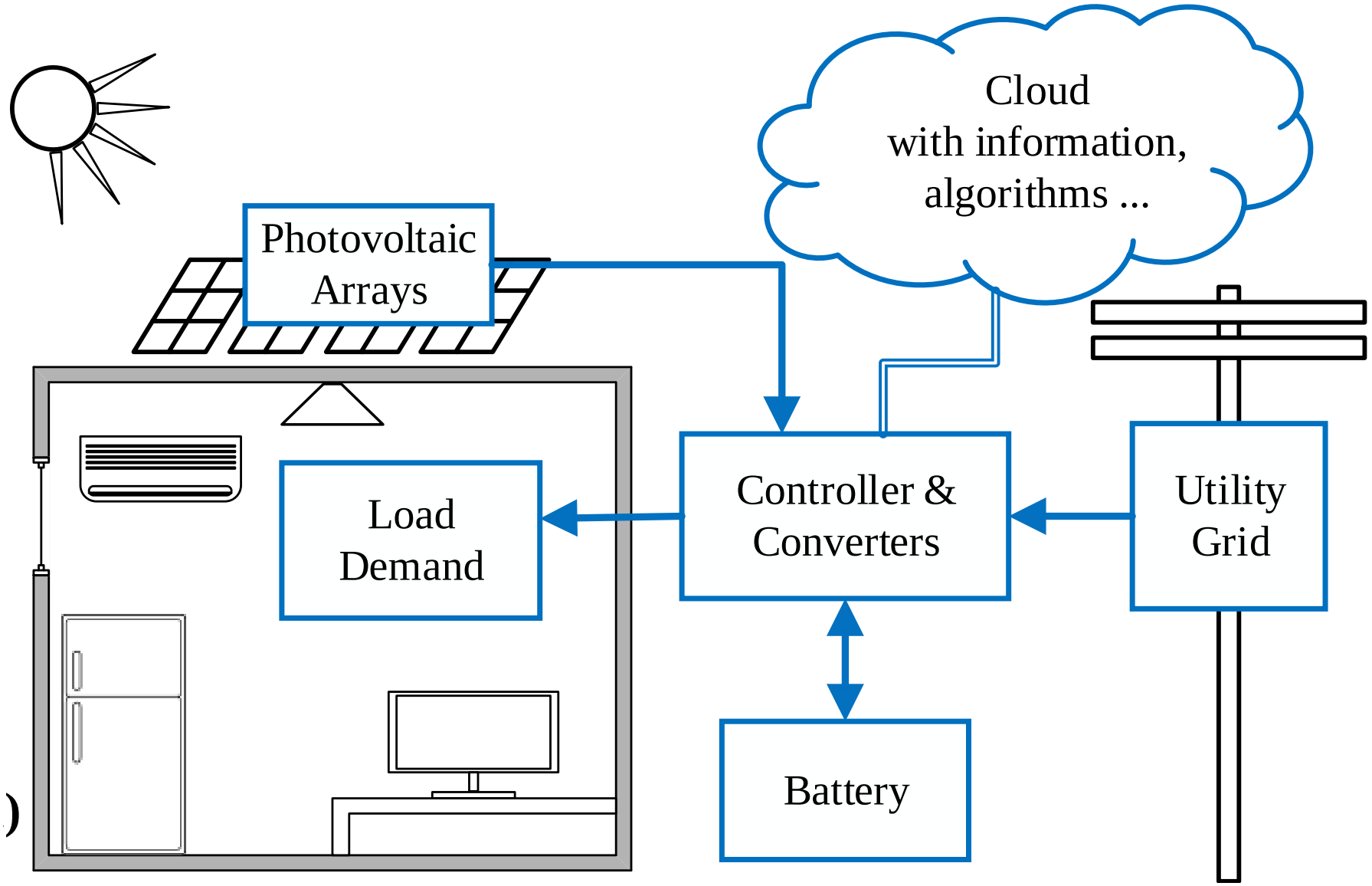


Closing the Optimality Gap

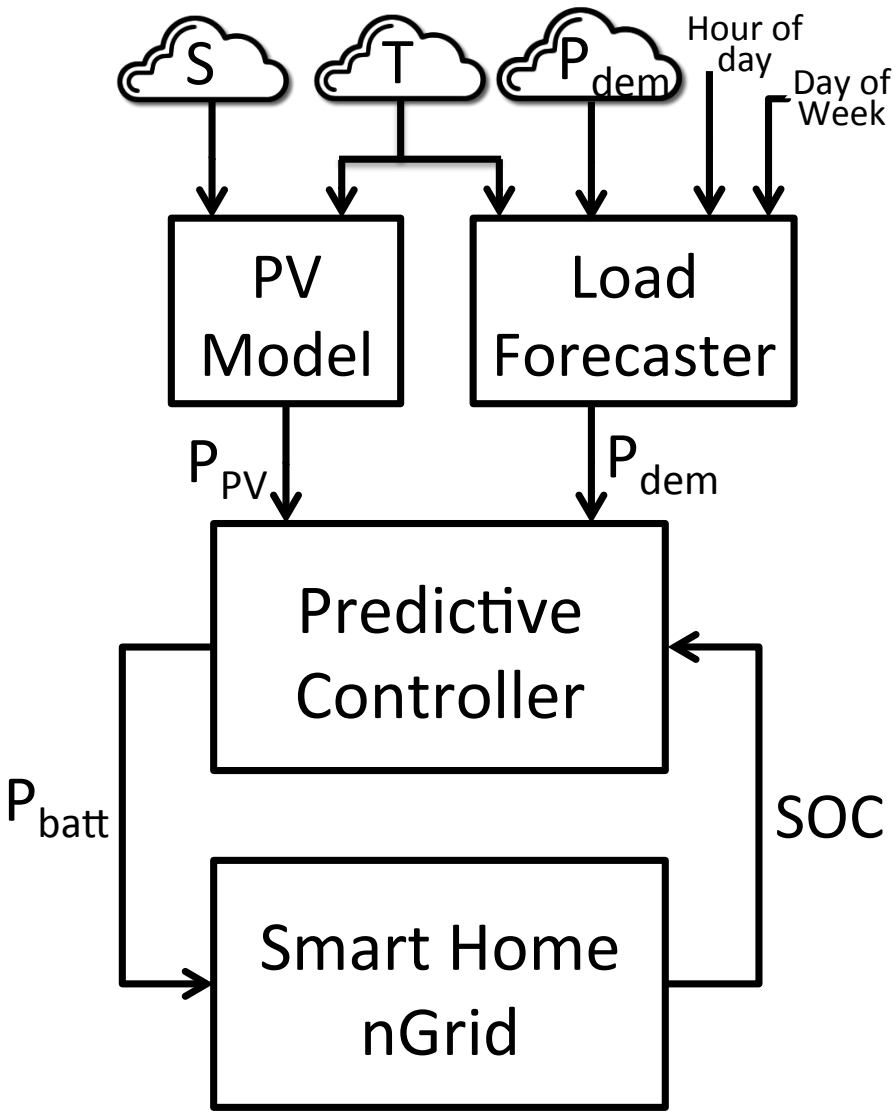


Outline

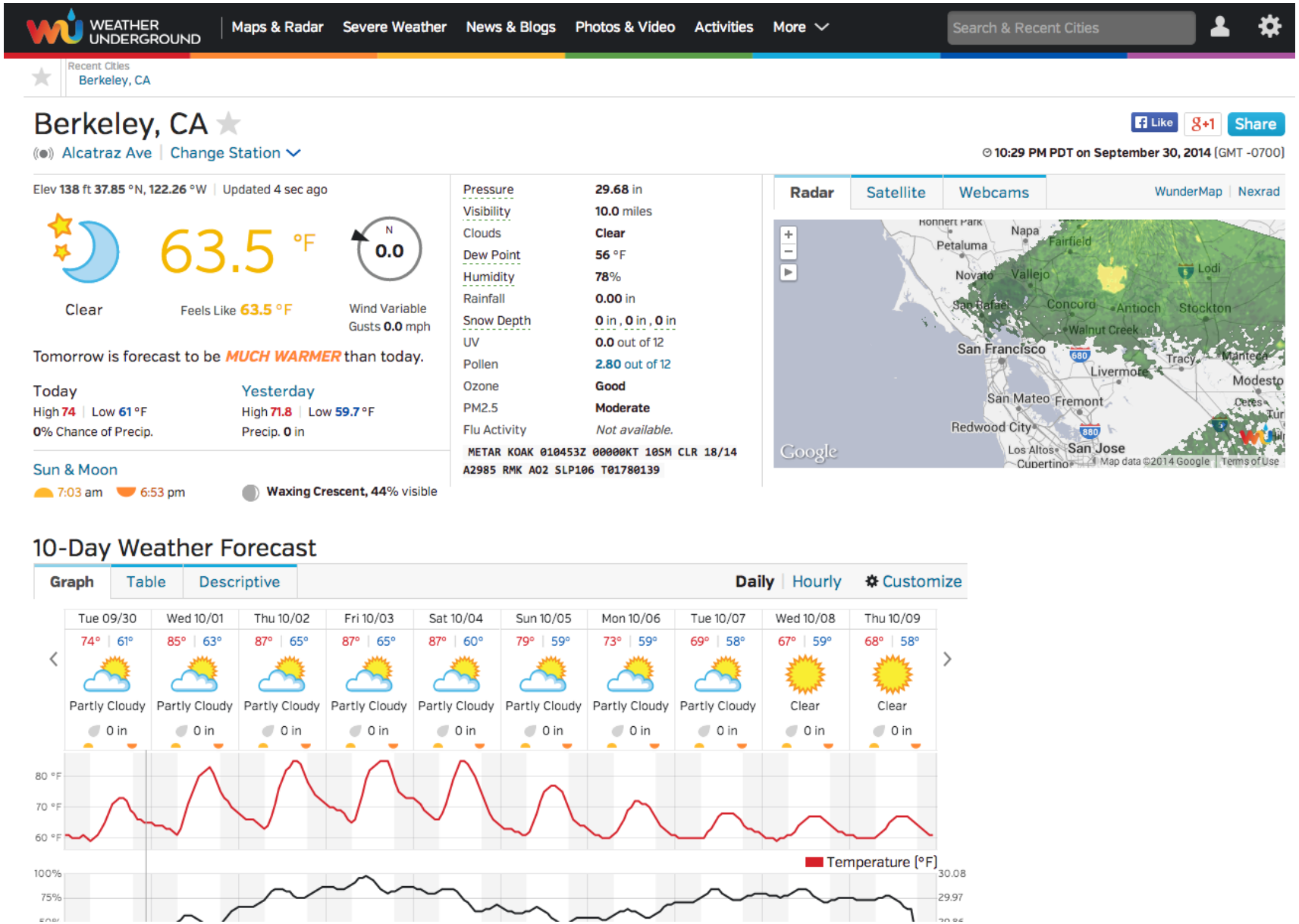
Smart Home PV-Battery Nanogrid



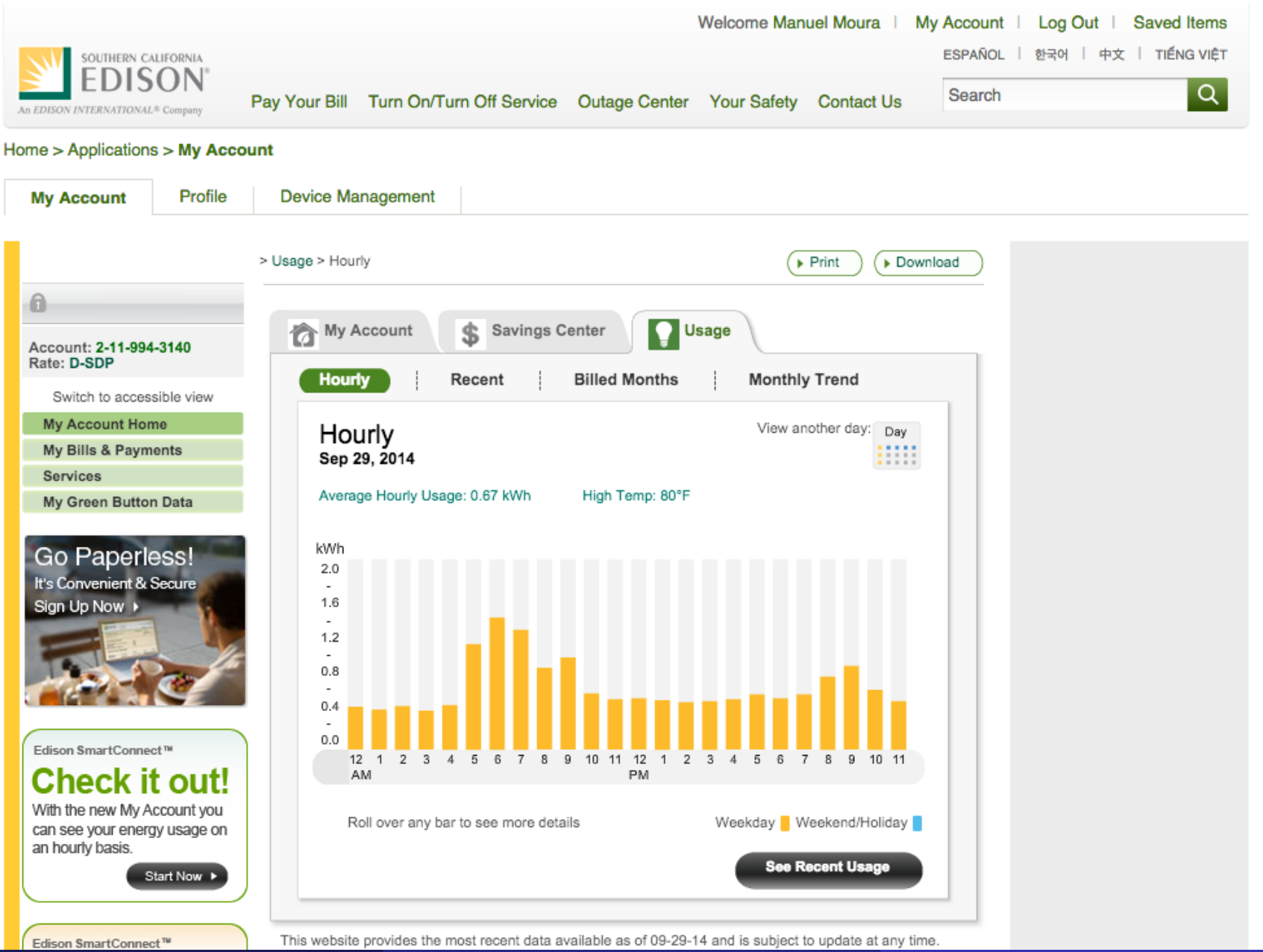
Cloud-Enabled Control



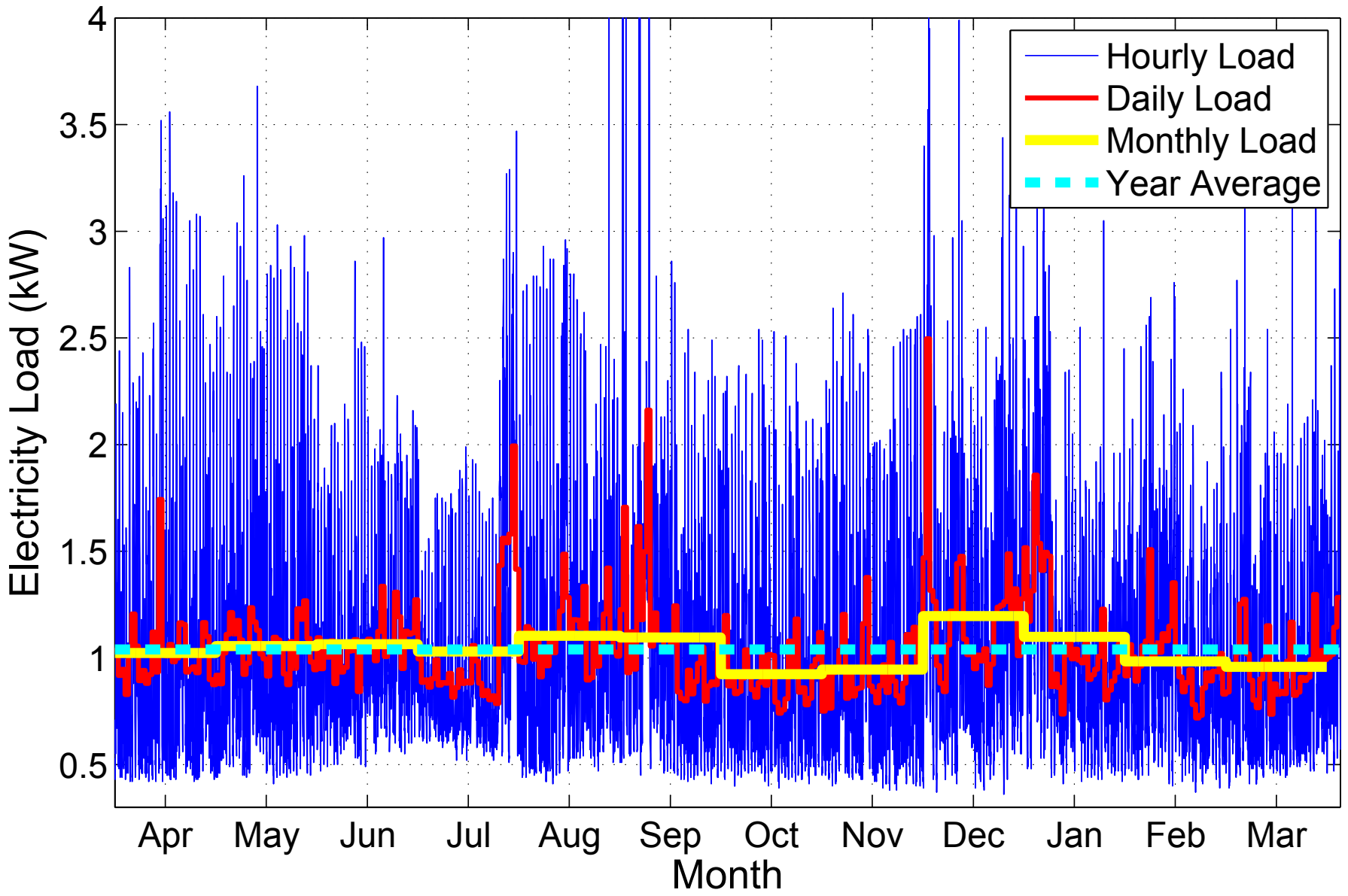
Cloud-Enabled Control



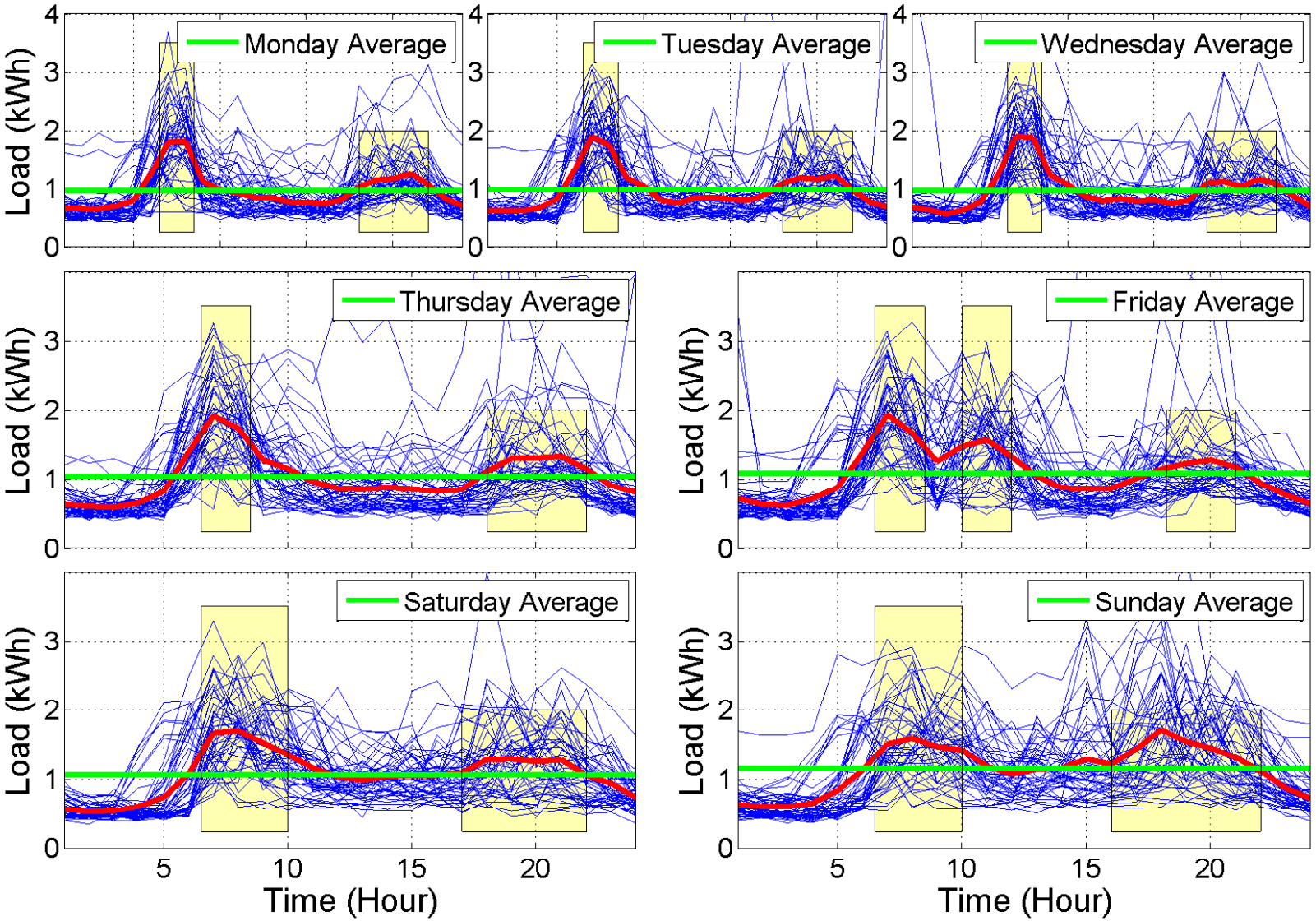
Cloud-Enabled Control



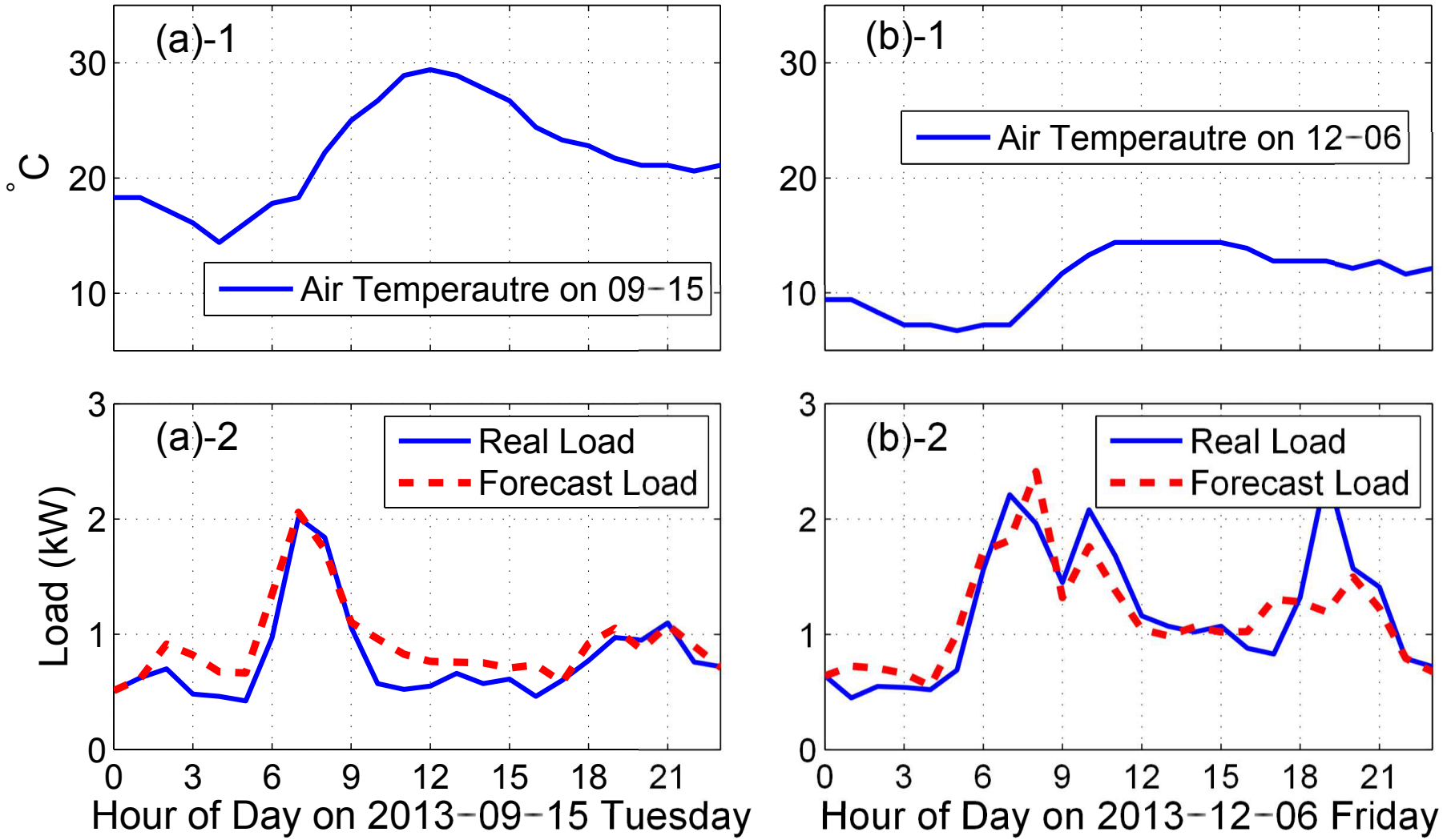
Single-Family Home Energy Patterns in LA



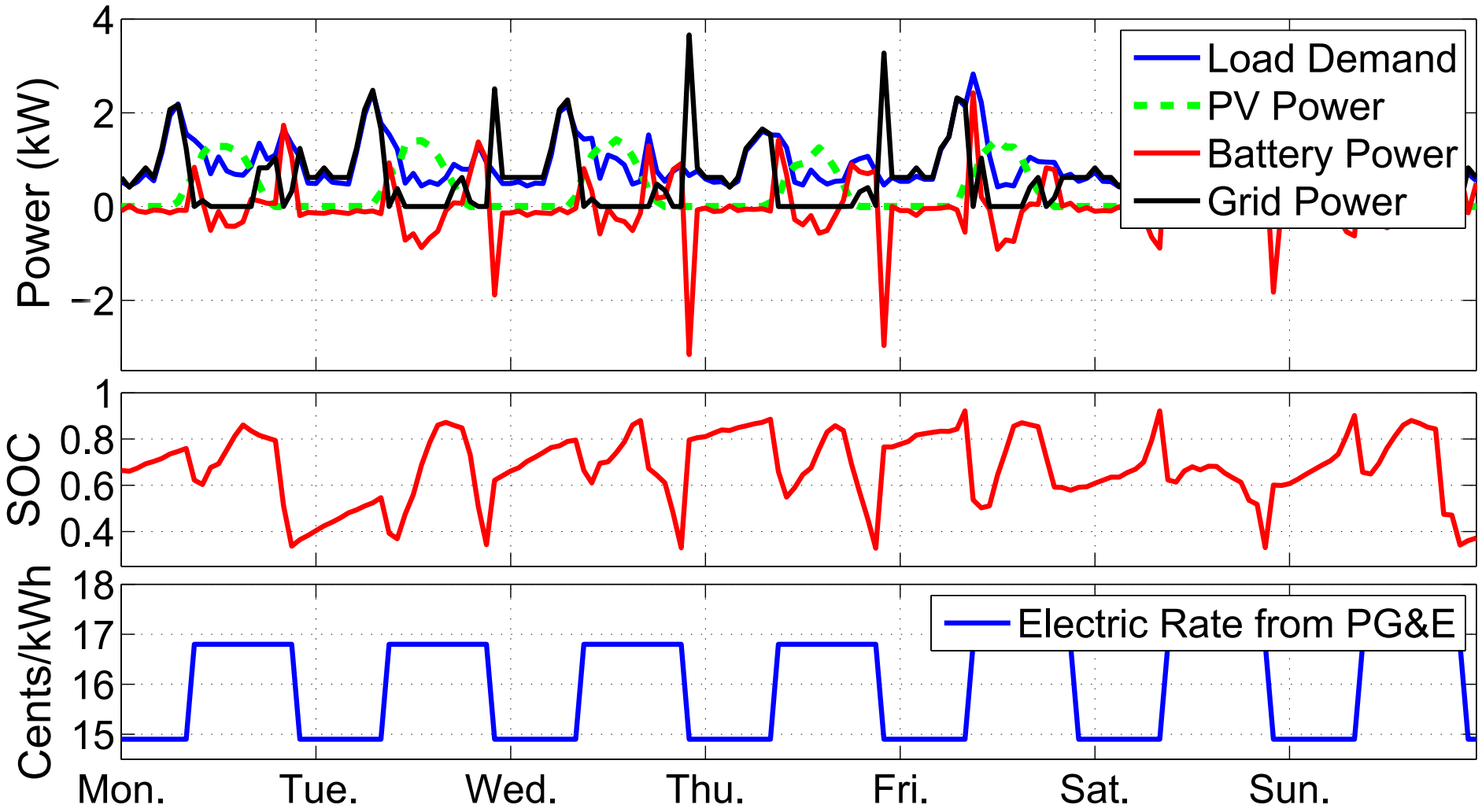
Single-Family Home Energy Patterns in LA



Short-term Forecast of Home Load

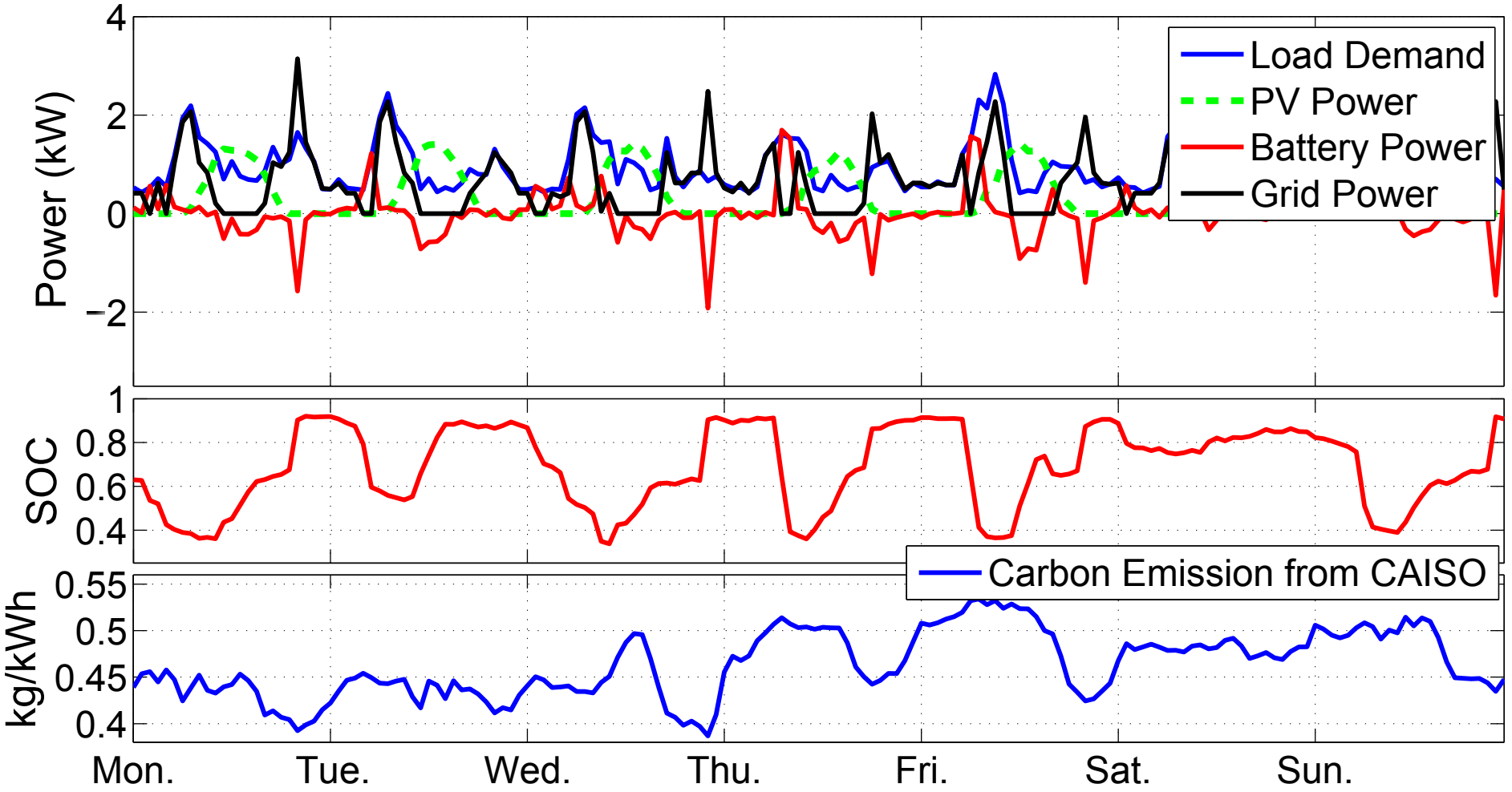


Model Predictive Control w/ Cloud-enabled Forecasts



Optimize for Grid Electricity Cost

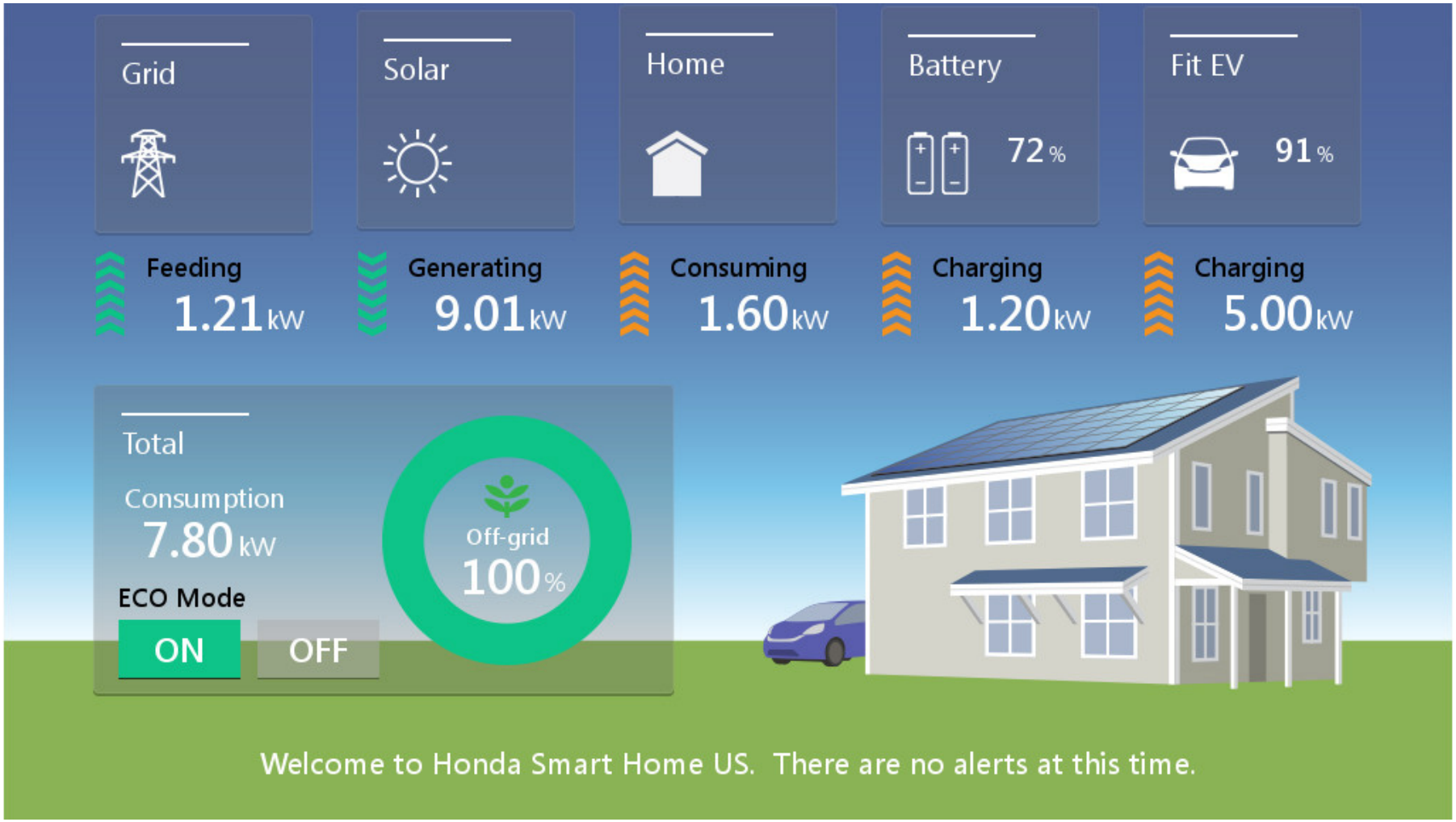
Model Predictive Control w/ Cloud-enabled Forecasts



Optimize for Marginal CO_2 Produced from Power Plants

Smart Home Demonstration Project @ UC Davis

Smart Home Demonstration Project @ UC Davis



Outline

The Vehicle-Grid Integration (VGI) Problem

Needs: Resilient and sustainable energy/transportation infrastructure

Obstacle: Unprecedented constraints and demands on grid

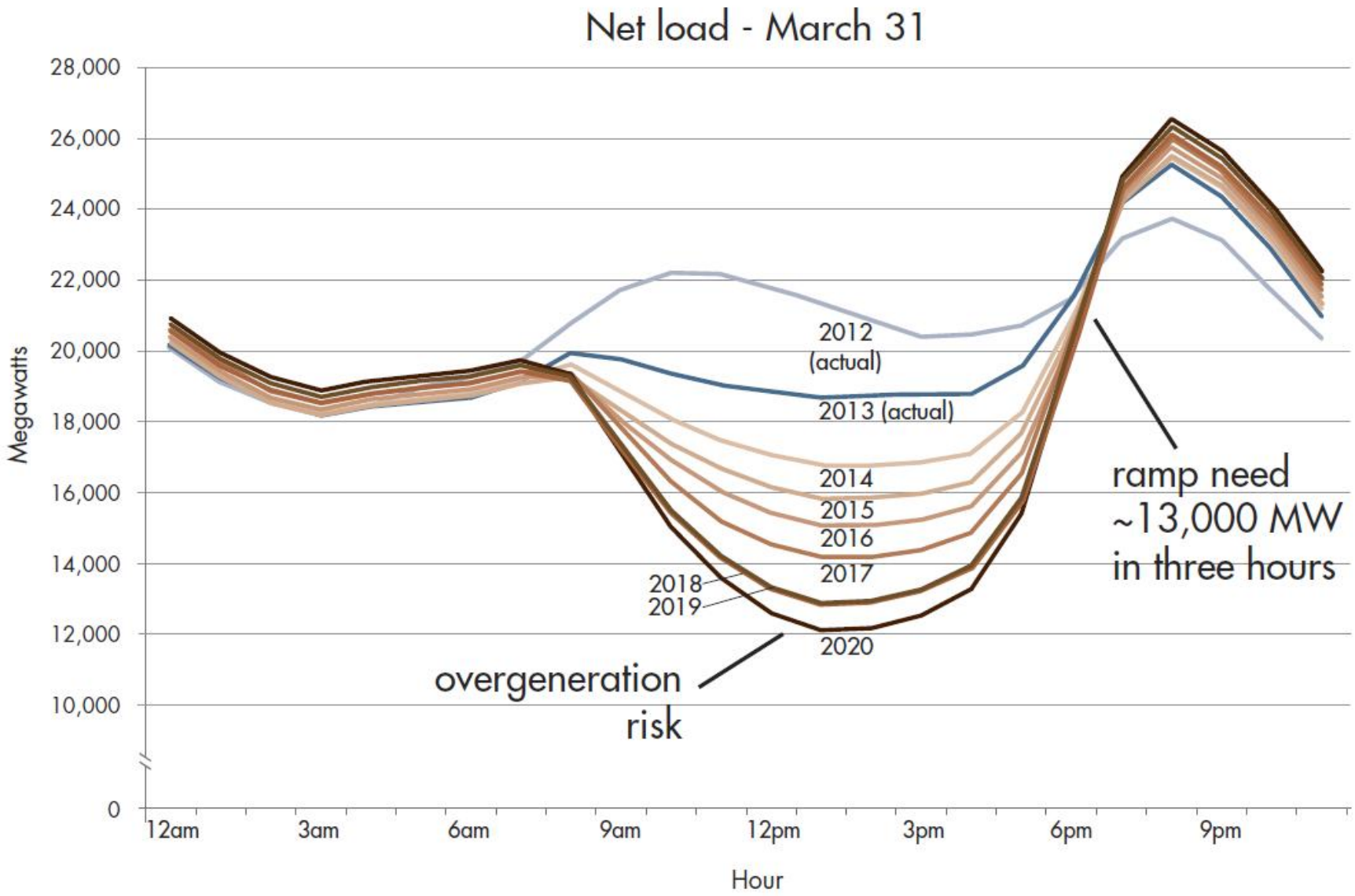
Some Interesting Facts

Plug-in Electric Vehicles (PEVs)	Potentially dispatchable loads
	"carbitrage" opportunity
	Firm variable renewables

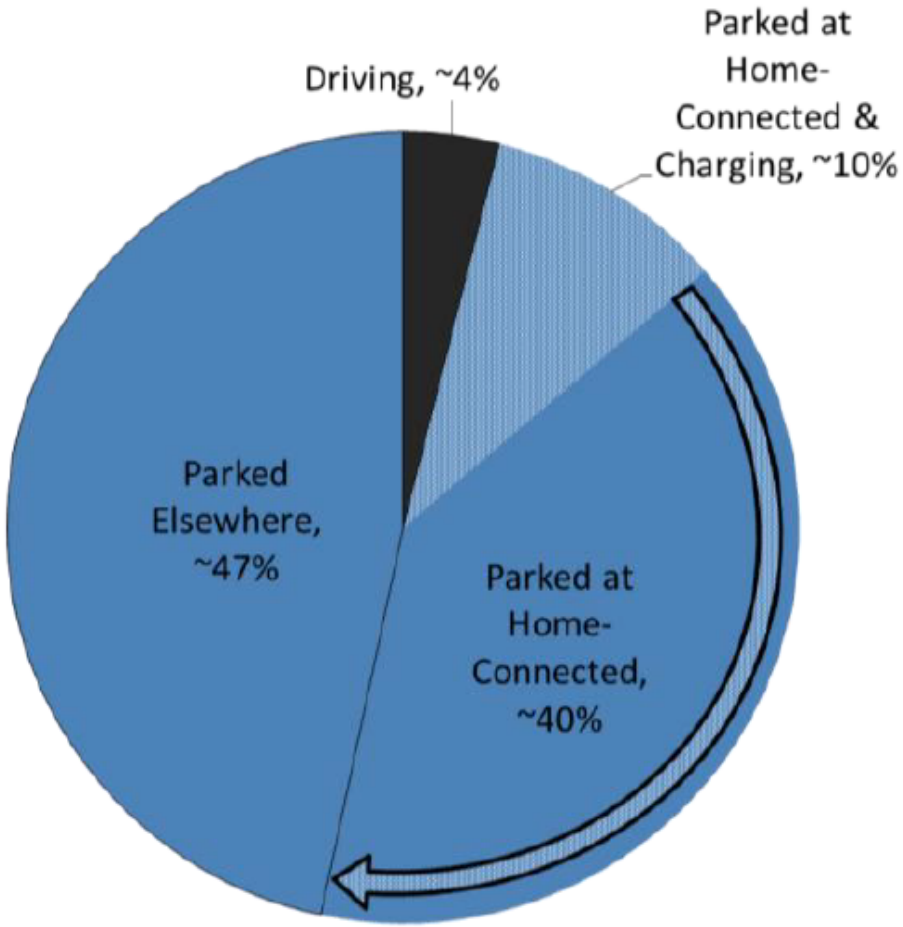
The Punchline

Exploit flexibility of PEV charging to enhance efficiency across infrastructures

The duck curve shows steep ramping needs and overgeneration risk



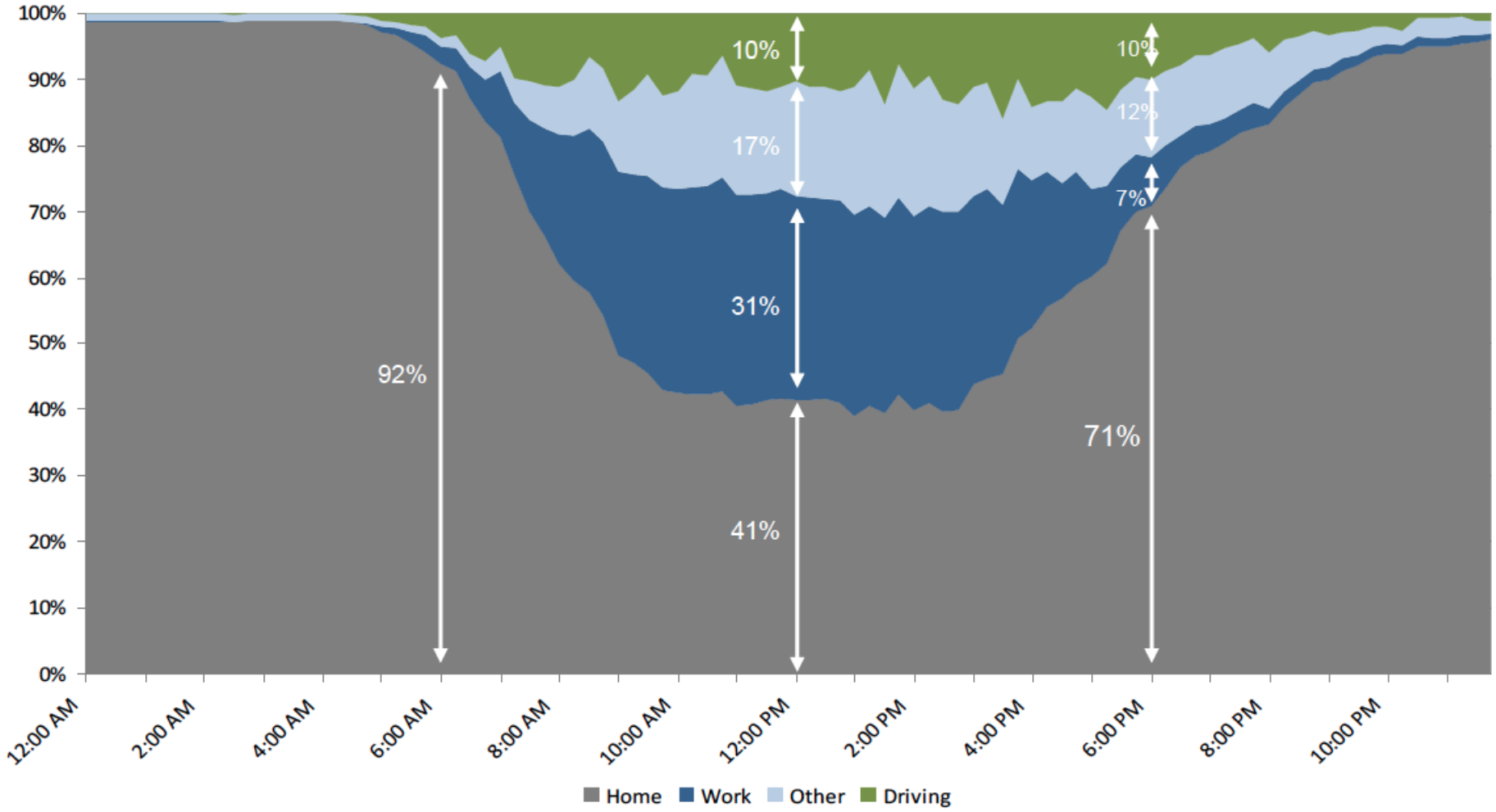
PEV Energy Storage: How much, when, and where?



Estimated percent of time PEVs spend by location and activity.

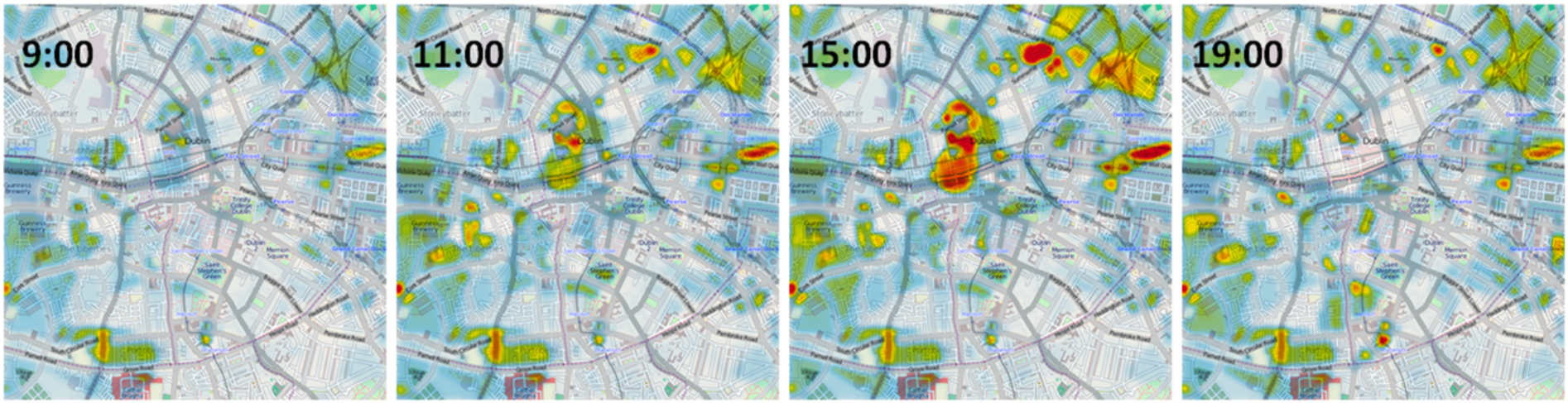
A. Langton and N. Crisostomo, “Vehicle-grid integration: A vision for zero-emission transportation interconnected throughout Californias electricity system,” California Public Utilities Commission, Tech. Rep. R. 13-11-XXX, 2013.

PEV Energy Storage: How much, when, and where?



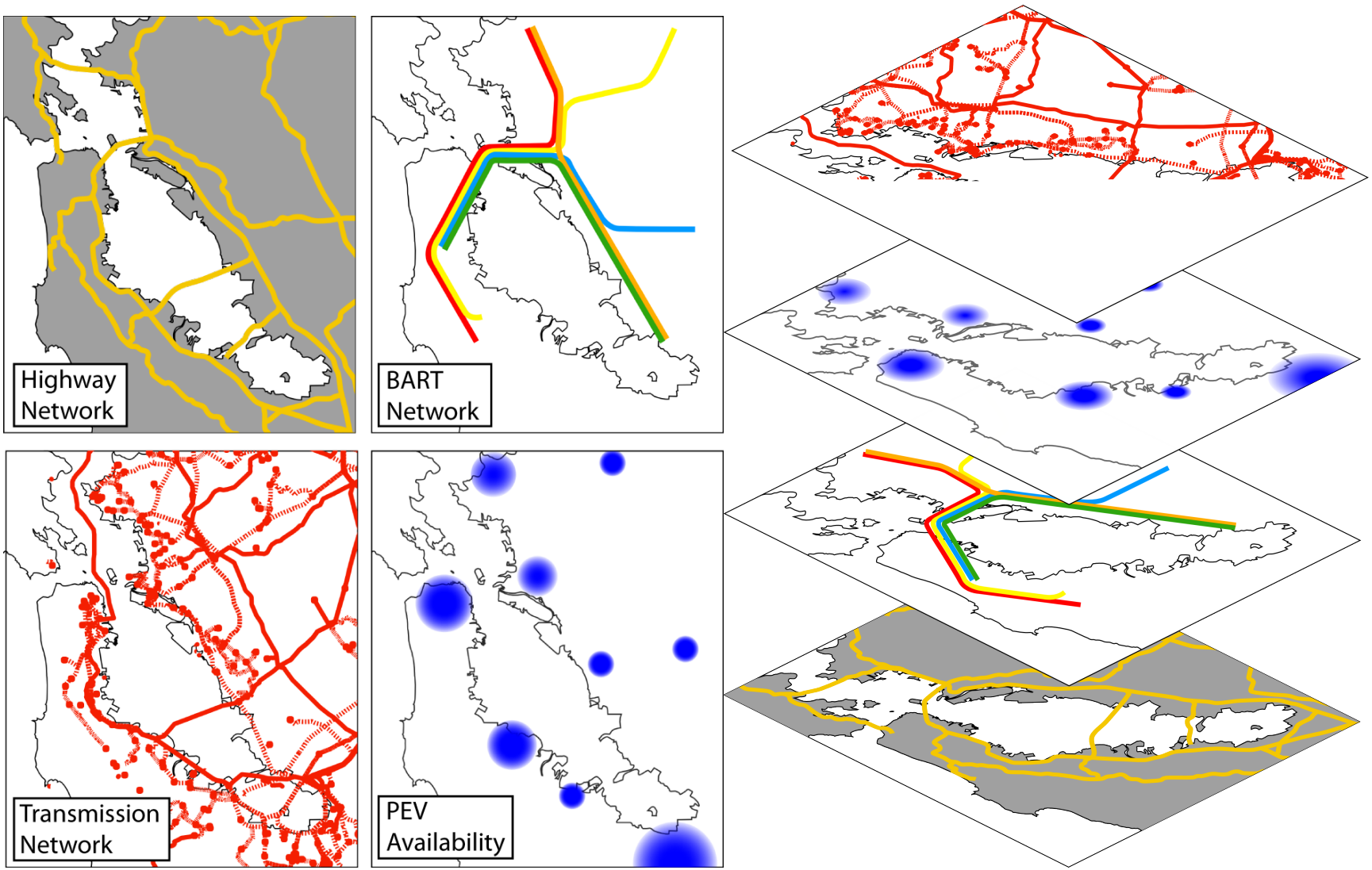
A. Langton and N. Crisostomo, “Vehicle-grid integration: A vision for zero-emission transportation interconnected throughout Californias electricity system,” California Public Utilities Commission, Tech. Rep. R. 13-11-XXX, 2013.

Spatio-Temporal Evolution



Population densities estimated from cell phone usage at different time of the day: morning (left), shopping time (both images in the centre), evening (right) (Source: Kaiser and Pozdnoukhov 2013)

Coupled Transportation-Energy Networks



CE 186

DESIGN OF CYBER-PHYSICAL SYSTEMS

Fall 2015 in Jacobs Hall (NEW!)

Topics Include:

- Energy Management and Power Systems
- Vehicle-to-Grid and Battery Models
- Internet-based Systems
- Data Collection and Analysis

Project-based Course on Vehicle-Grid Integration

- Fleet of eScooters
- Collect shared mobility data, design VGI system
- Learn hardware, software, algorithms, big data, cloud-based computing
- Berkeley Energy and Climate Lectures Curriculum Innovation Award

Where can I get a job?

TESLA

ohmconnect

C3 Energy

Google

PG&E

NEC Laboratories America

Relentless passion for innovation

SUNPOWER

ZERO MOTORCYCLES

OPOWER

SolarCity

stem

SAMSUNG

BOSCH

chargepoint

Ford

BERKELEY LAB
Lawrence Berkeley National Laboratory

STATE OF CALIFORNIA ENERGY COMMISSION

BMW

Statoil

MITSUBISHI ELECTRIC
RESEARCH LABORATORIES

Mercedes-Benz

RECARGO
Renewable Energies • Electric Car • Grid Optimization

VISIT US!

Energy, Controls, and Applications Lab (eCAL)

ecal.berkeley.edu

smoura@berkeley.edu