

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

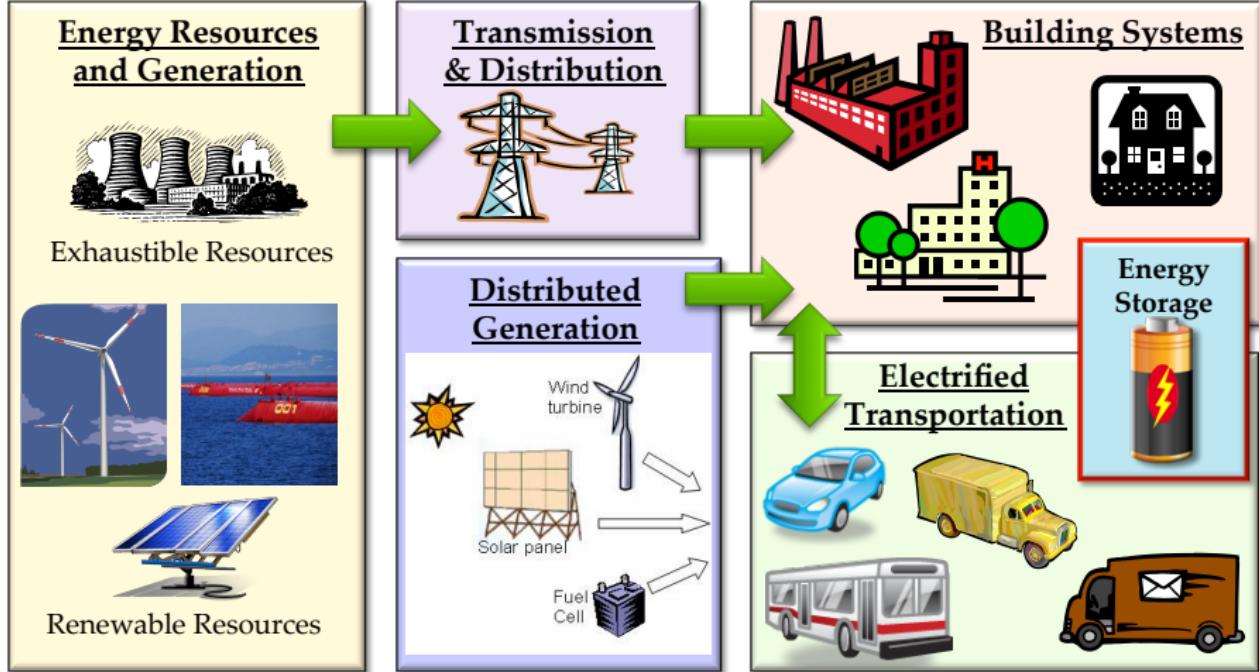
Prof. Scott Moura

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

E93 : Energy Engineering Seminar



Vision for Future Energy Infrastructure



Outline

- 1 STORAGE: Electrochemical-based Battery Controls
- 2 CARS: Traffic Data-Enabled PHEV Energy Management
- 3 BUILDINGS: Smart Home PV-Battery Nanogrid
- 4 CARS+GRID: Vehicle-Grid Integration

The Battery Problem

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

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

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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)

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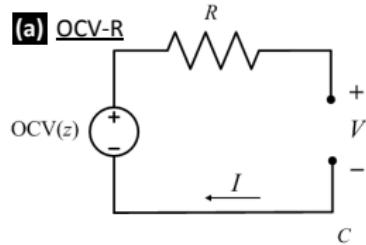
Two Solutions

Design better batteries (materials science & chemistry)	Make current batteries better (estimation and control)
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* Source: MIT Technology Review, "The Electric Car is Here to Stay." (2013)

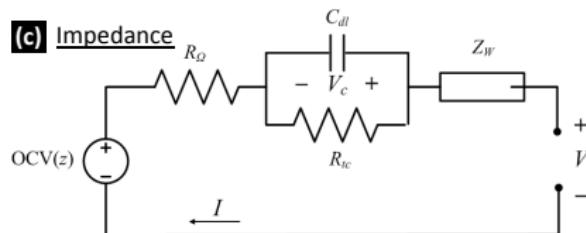
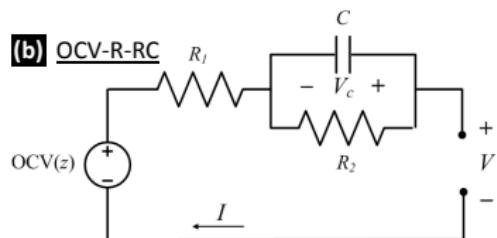
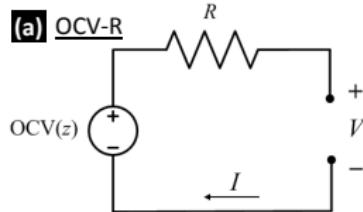
Battery Models

Equivalent Circuit Model



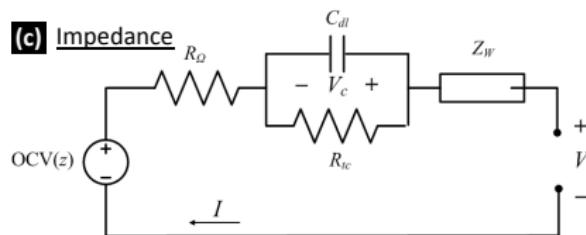
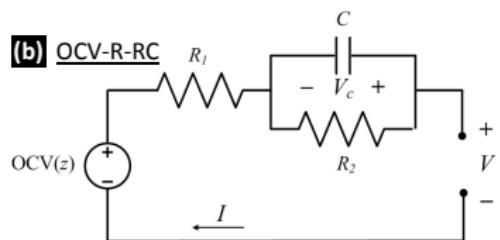
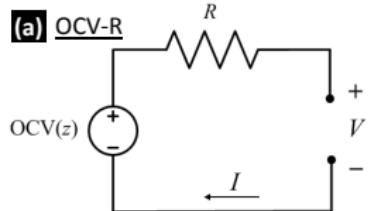
Battery Models

Equivalent Circuit Model

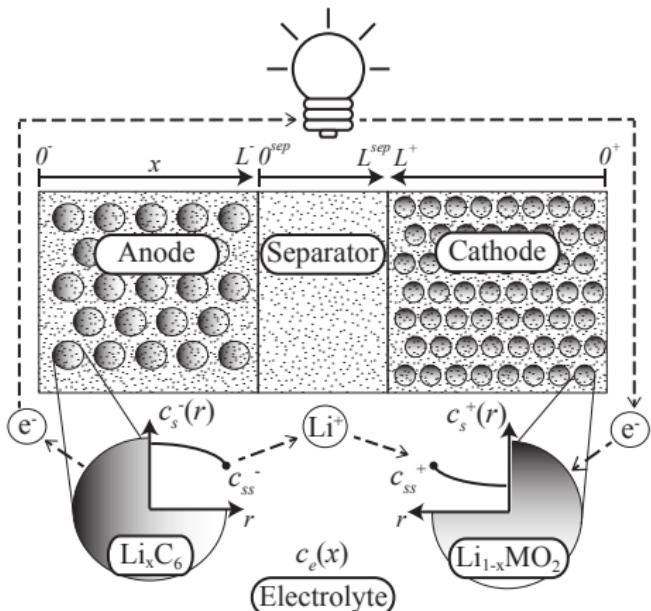


Battery Models

Equivalent Circuit Model

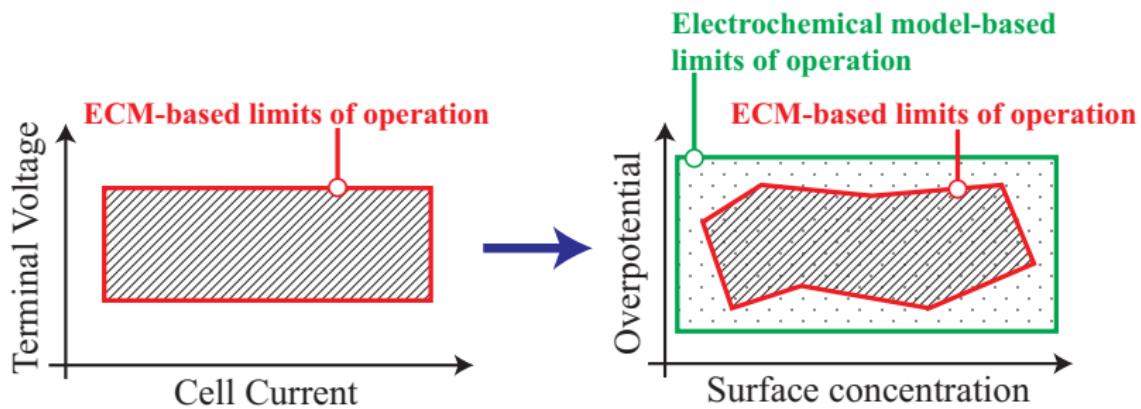


Electrochemical Model





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	$j_n^\pm(x, t) = \frac{1}{F} i_0^\pm(x, t) \left[e^{\frac{\alpha_a F}{RT} \eta^\pm(x, t)} - e^{-\frac{\alpha_e F}{RT} \eta^\pm(x, t)} \right]$
Temperature	$\rho C_P \frac{dT}{dt}(t) = h [T^0(t) - T(t)] + I(t)V(t) - \int_{0^-}^{0^+} a_s F j_n(x, t) \Delta T(x, t) dx$

Animation of Li Ion Evolution

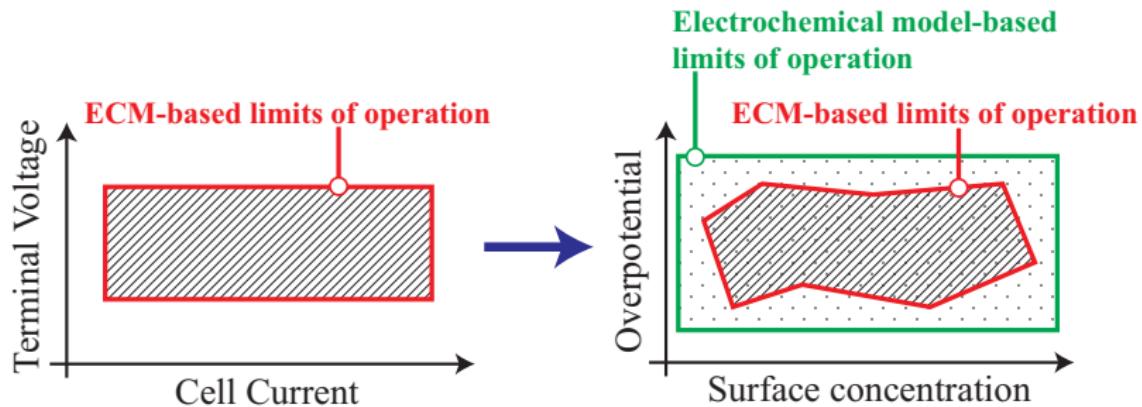
Operate Batteries at their Physical Limits



Operate Batteries at their Physical Limits

Problem Statement

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

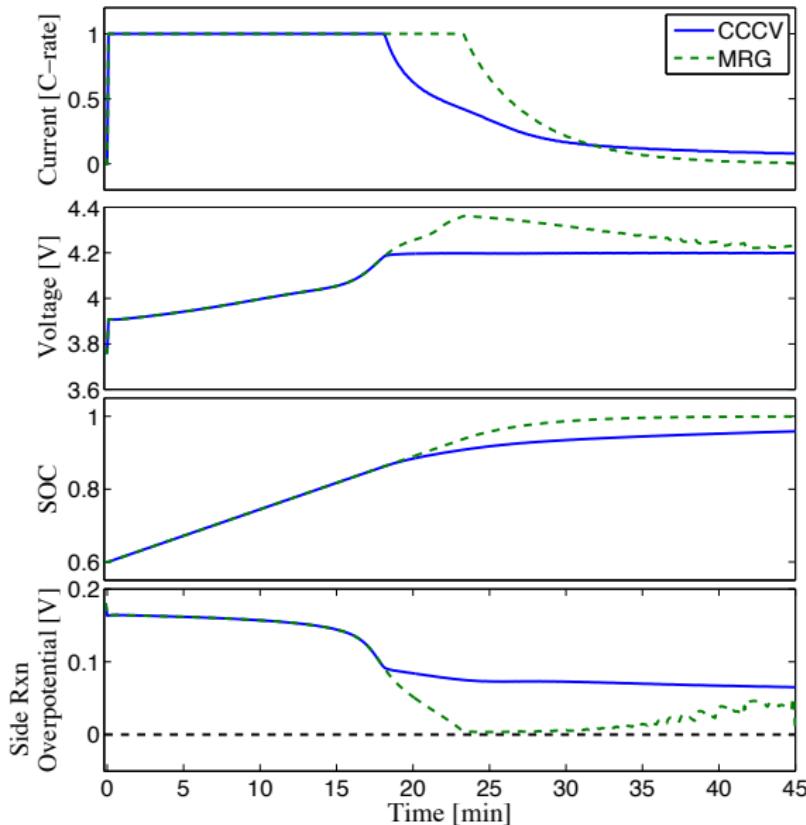


Constraints

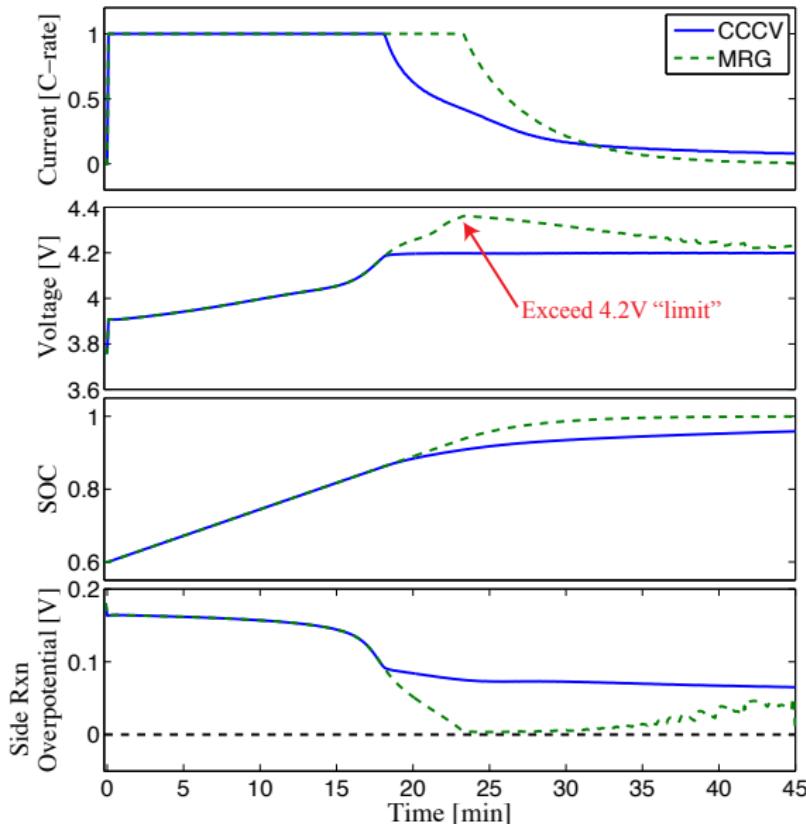
Variable	Definition	Constraint
$I(t)$	Current	Power electronics limits
$c_s^\pm(x, r, t)$	Li concentration in solid	Saturation/depletion
$\frac{\partial c_s^\pm}{\partial r}(x, r, t)$	Li concentration gradient	Diffusion-induced stress
$c_e(x, t)$	Li concentration in electrolyte	Saturation/depletion
$T(t)$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

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

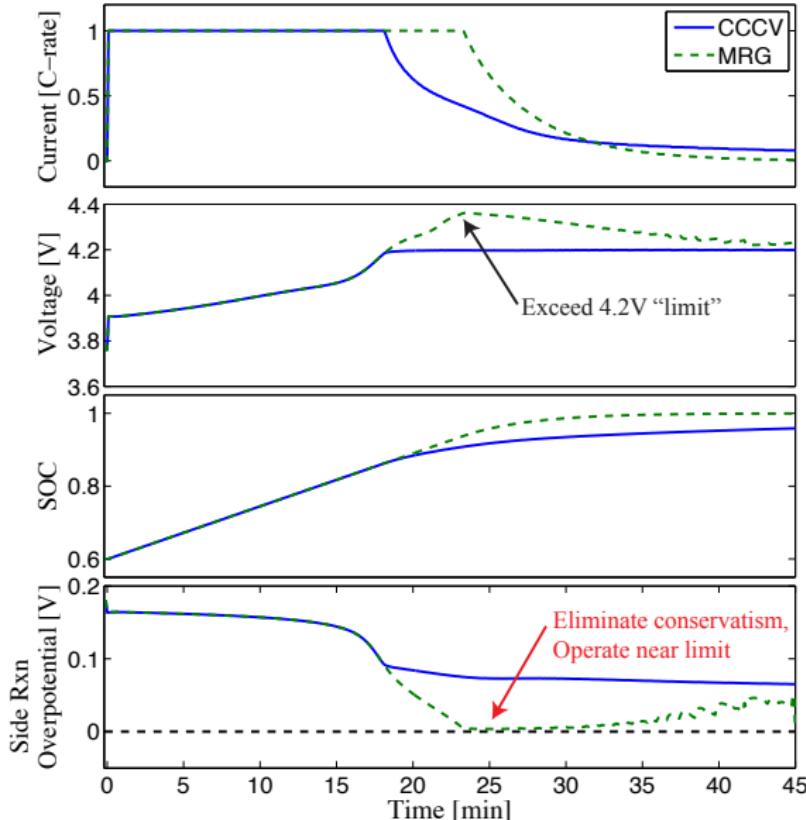
Application to Charging



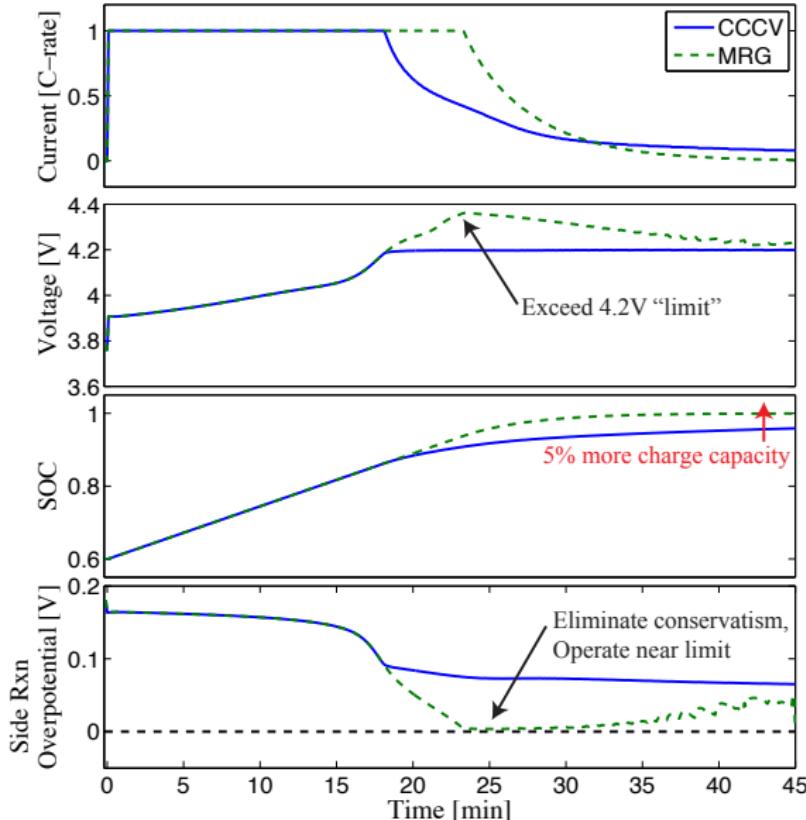
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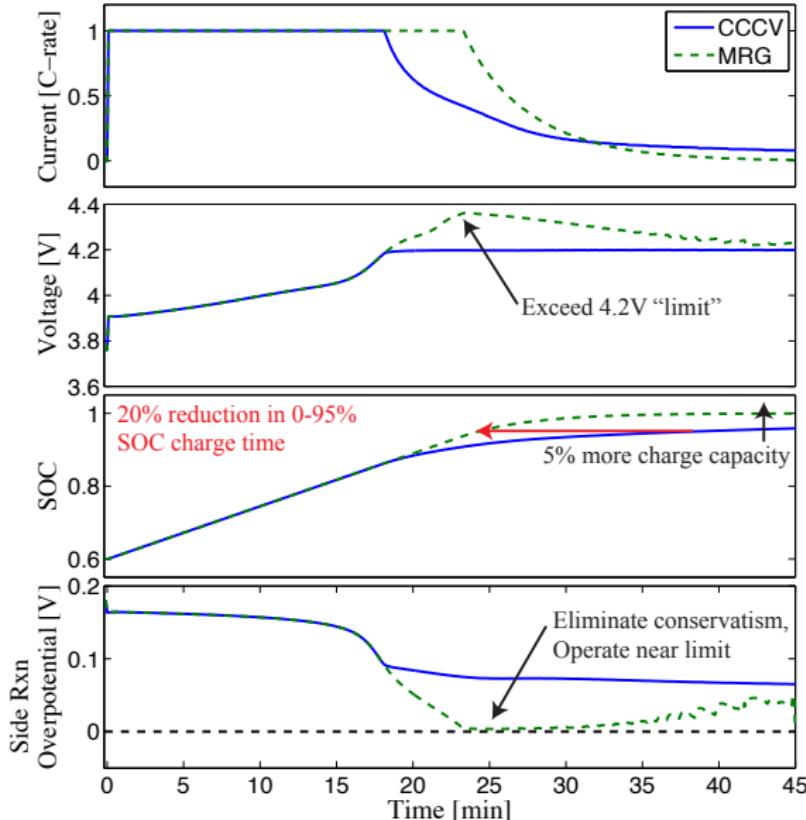
Application to Charging



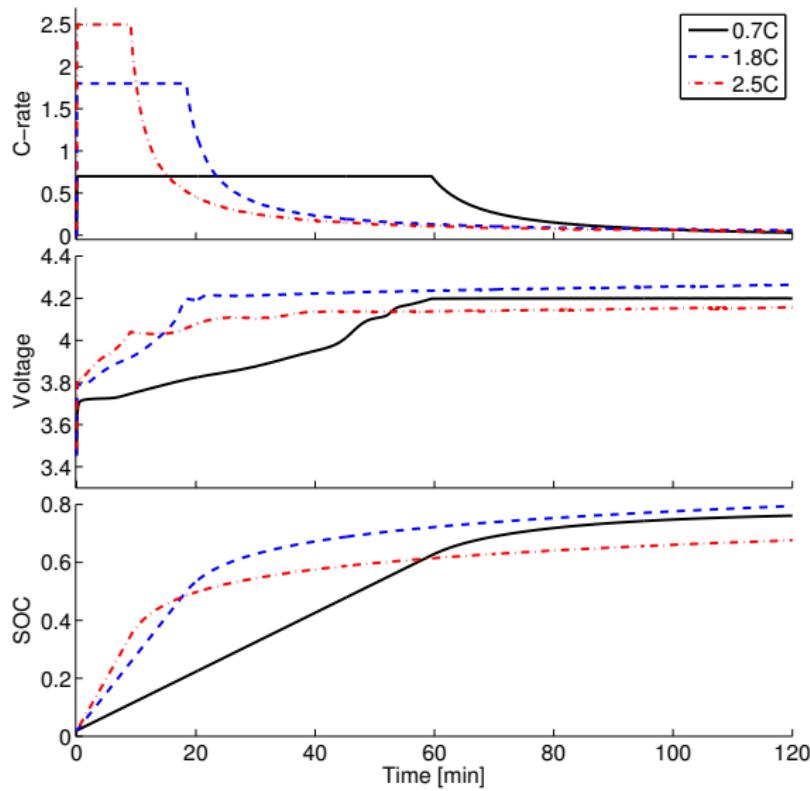
Application to Charging



Application to Charging



Fast Charging



Fast charge your smartphone/EV while getting coffee

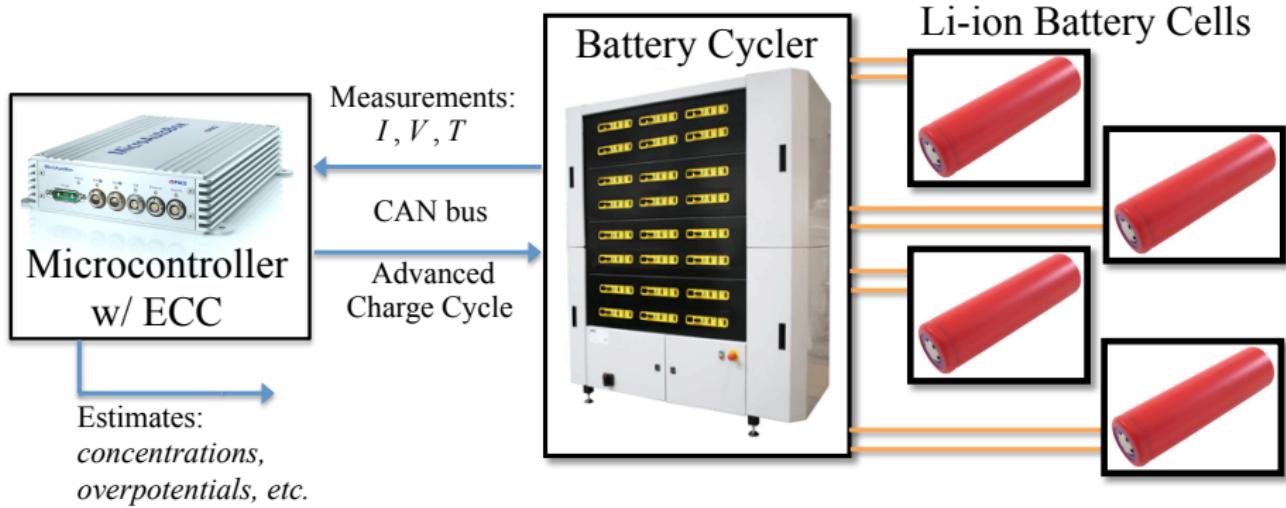
Table: Simulated fast charge times for various C-rates

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:

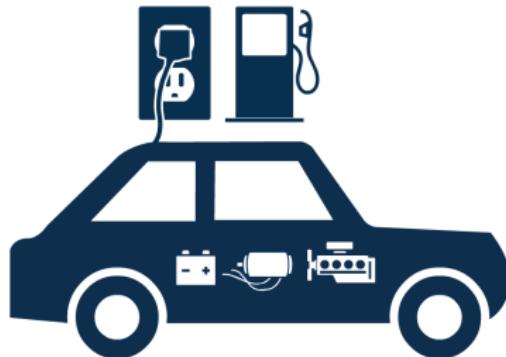
6.7B subscription accounts, 5.2B handsets in use,
1.7B sold worldwide in 2012

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PHEV Energy Management Background

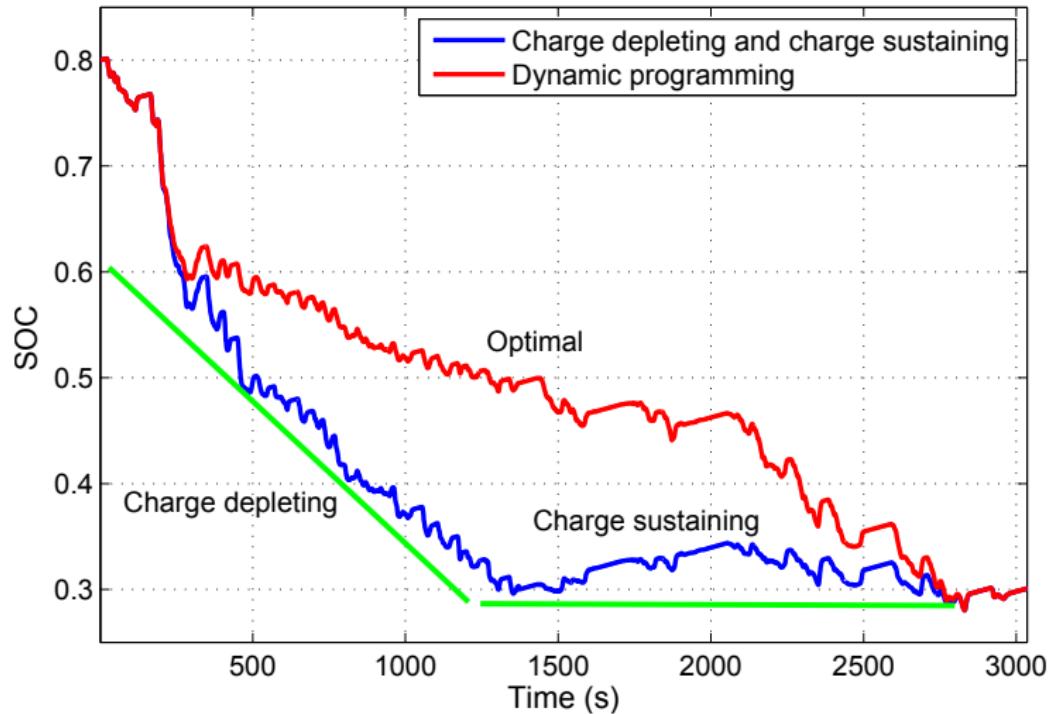
Plug-in Hybrid Electric Vehicles (PHEV)



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

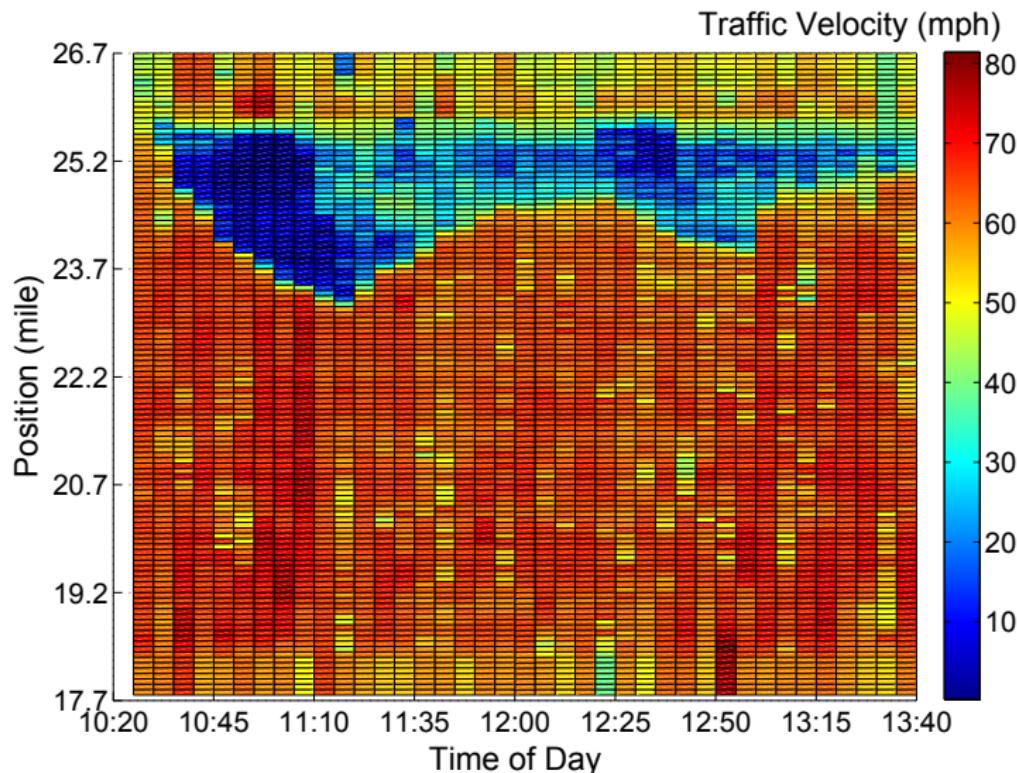
Ex: Chevy Volt, Prius PHEV, Fusion Energi, C-MAX Energi

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?

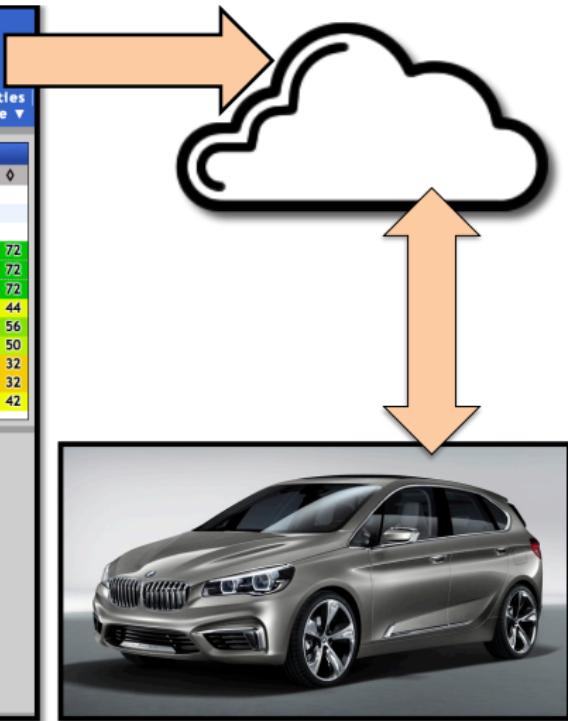
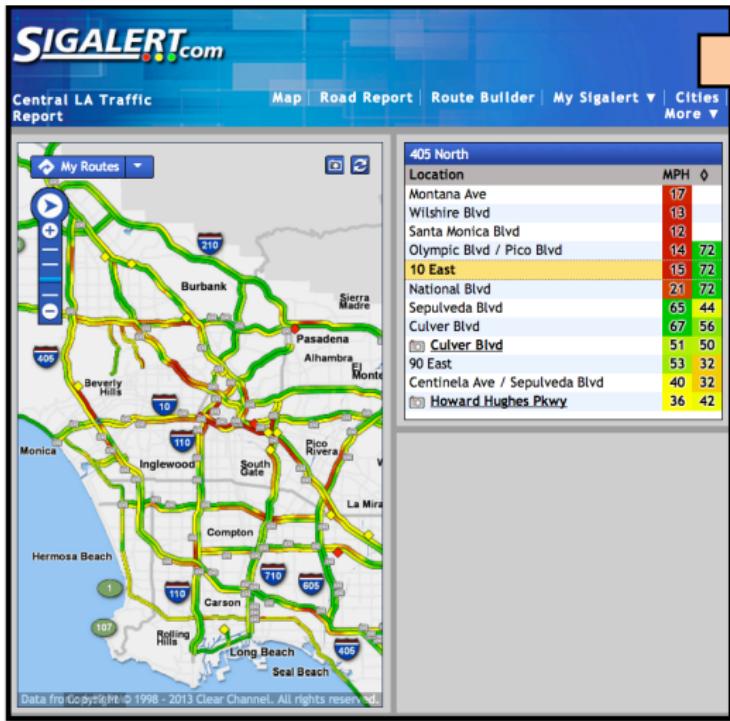
The Problem

- 54.5 MPG CAFE by 2025
- Increased CAFE → Increased powertrain tech costs
- Urbanization → traffic → lower MPG

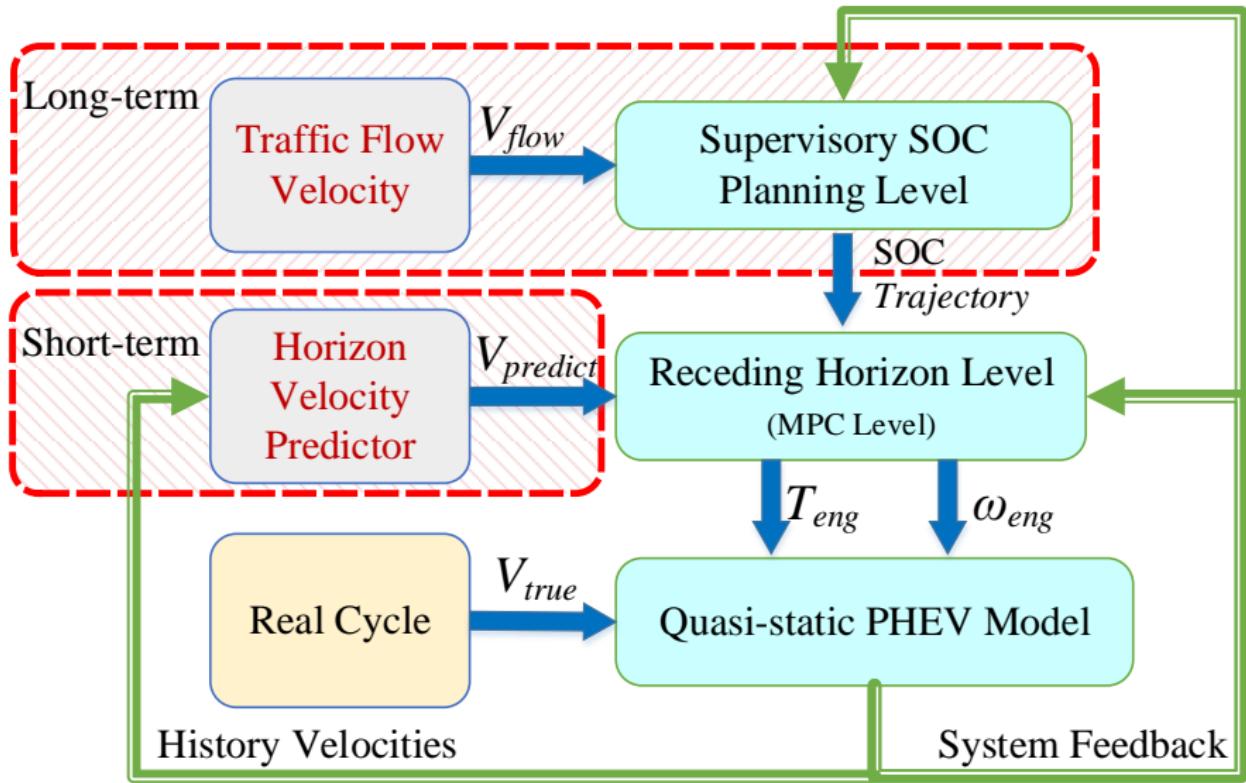
An Interesting Solution

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

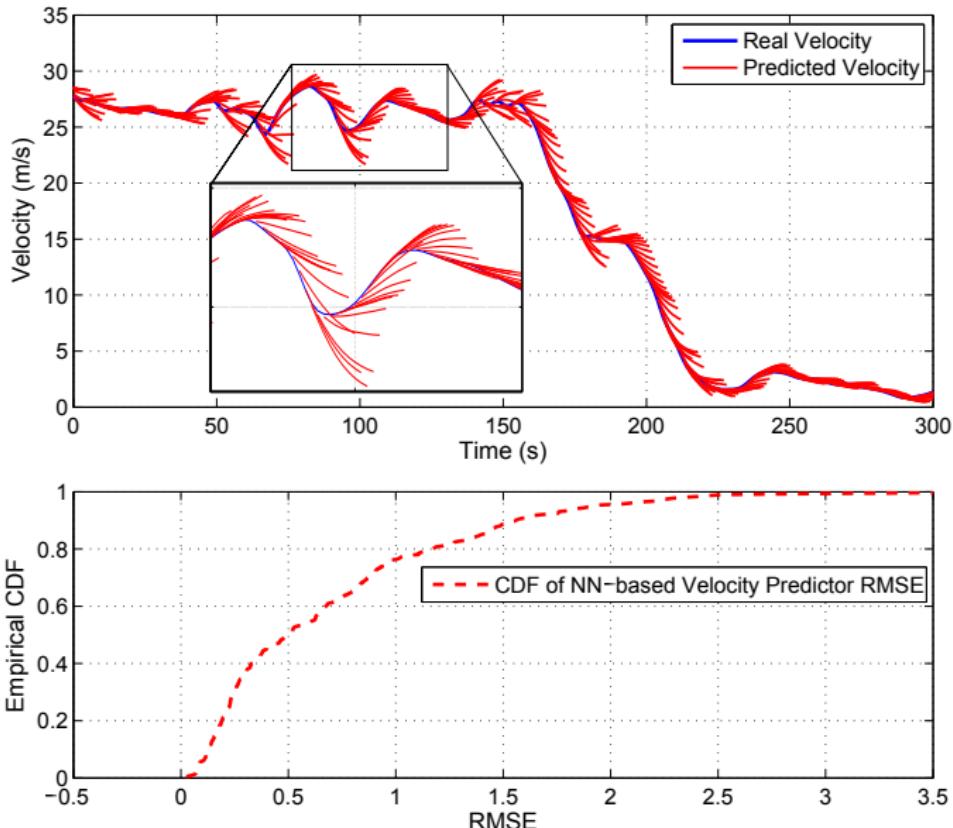
Optimize PHEV Energy Management w/ Real-time Traffic Data



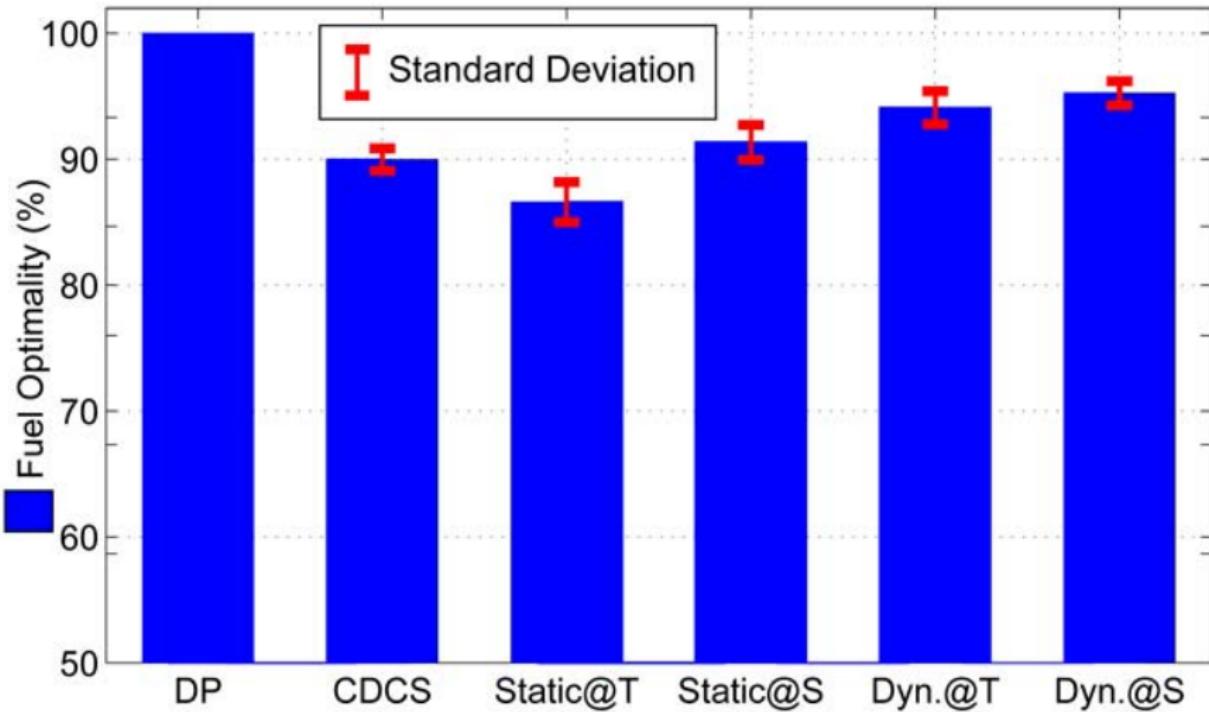
Algorithm Flow Chart



Forecast Vehicle Velocity



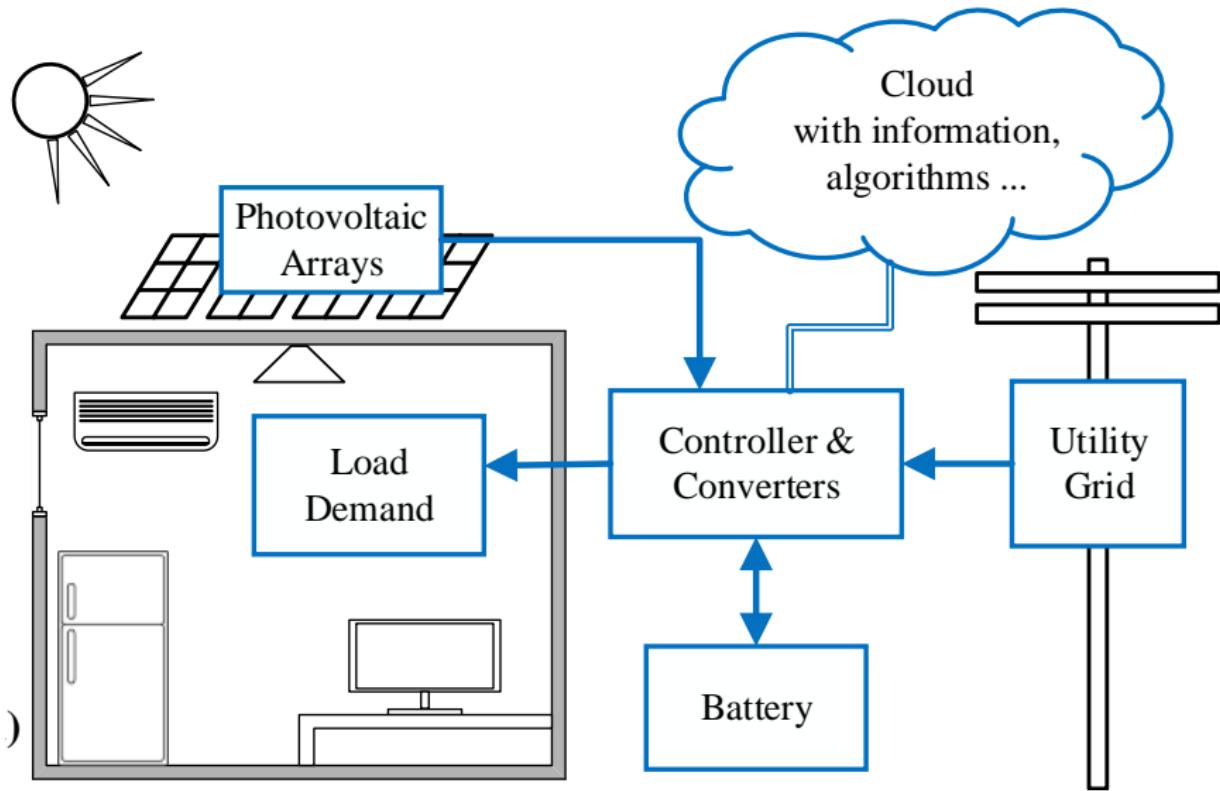
Closing the Optimality Gap



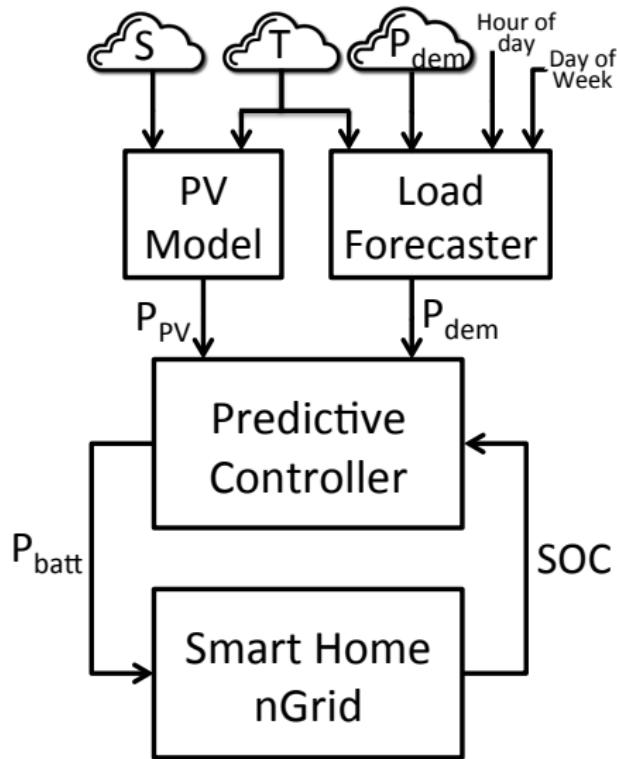
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Smart Home PV-Battery Nanogrid



Cloud-Enabled Control



Cloud-Enabled Control

WEATHER UNDERGROUND | Maps & Radar | Severe Weather | News & Blogs | Photos & Video | Activities | More ▾

Search & Recent Cities | [Profile](#) | [Settings](#)

Recent Cities: Berkeley, CA

Berkeley, CA

([Alcatraz Ave](#)) | Change Station ▾

Elev 138 ft 37.85 °N, 122.26 °W | Updated 4 sec ago

 **63.5 °F** 

Clear Feels Like **63.5 °F** Wind Variable Gusts 0.0 mph

Tomorrow is forecast to be **MUCH WARMER** than today.

Today	Yesterday
High 74 Low 61°F 0% Chance of Precip.	High 71.8 Low 59.7°F Precip. 0 in

Sun & Moon
7:03 am | 6:53 pm  Waxing Crescent, 44% visible

Pressure **29.68 in**
Visibility **10.0 miles**
Clouds **Clear**
Dew Point **56 °F**
Humidity **78%**
Rainfall **0.00 in**
Snow Depth **0 in** in **0 in** in
UV **0.0 out of 12**
Pollen **2.80 out of 12**
Ozone **Good**
PM2.5 **Moderate**
Flu Activity **Not available.**

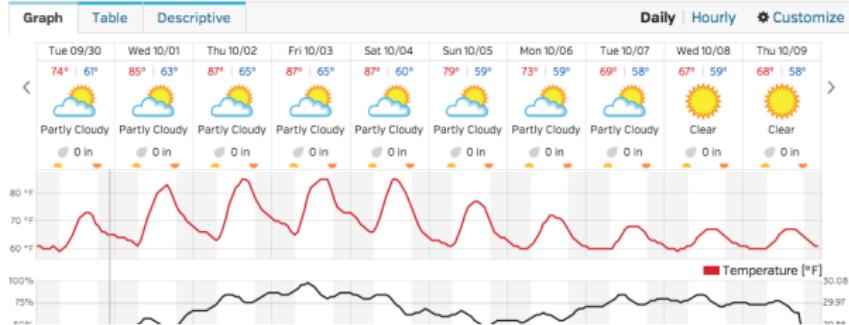
METAR KOAK 010453Z 00000KT 10SM CLR 18/14
A2985 RMX A02 SLP106 T0127B0139

Radar | Satellite | Webcams | WunderMap | Nexrad



© 10:29 PM PDT on September 30, 2014 [GMT -0700]

10-Day Weather Forecast



Cloud-Enabled Control

SOUTHERN CALIFORNIA EDISON An EDISON INTERNATIONAL® Company

Welcome Manuel Moura | My Account | Log Out | Saved Items
ESPAÑOL | 한국어 | 中文 | TIẾNG VIỆT

Pay Your Bill Turn On/Turn Off Service Outage Center Your Safety Contact Us

Search 

Home > Applications > My Account

My Account Profile Device Management

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 Account: 211-994-3140 Rate: D-SDP

Switch to accessible view

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Go Paperless!
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Sign Up Now! 

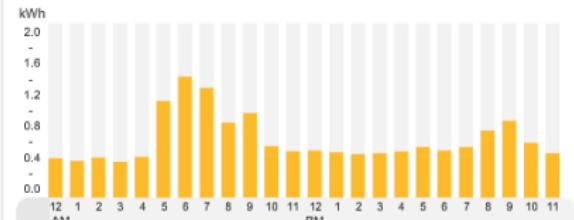
Edison SmartConnect™ **Check it out!**
With the new My Account you can see your energy usage on an hourly basis.
Start Now >

Hourly Recent Billed Months Monthly Trend

Hourly Sep 29, 2014 View another day: Day 

Average Hourly Usage: 0.67 kWh High Temp: 80°F

kWh



Hour	Usage (kWh)
12 AM	0.35
1 AM	0.35
2 AM	0.35
3 AM	0.35
4 AM	0.35
5 AM	1.10
6 AM	1.40
7 AM	1.30
8 AM	0.80
9 AM	0.80
10 AM	0.45
11 AM	0.45
12 PM	0.45
1 PM	0.45
2 PM	0.45
3 PM	0.45
4 PM	0.45
5 PM	0.45
6 PM	0.45
7 PM	0.60
8 PM	0.70
9 PM	0.70
10 PM	0.45
11 PM	0.45

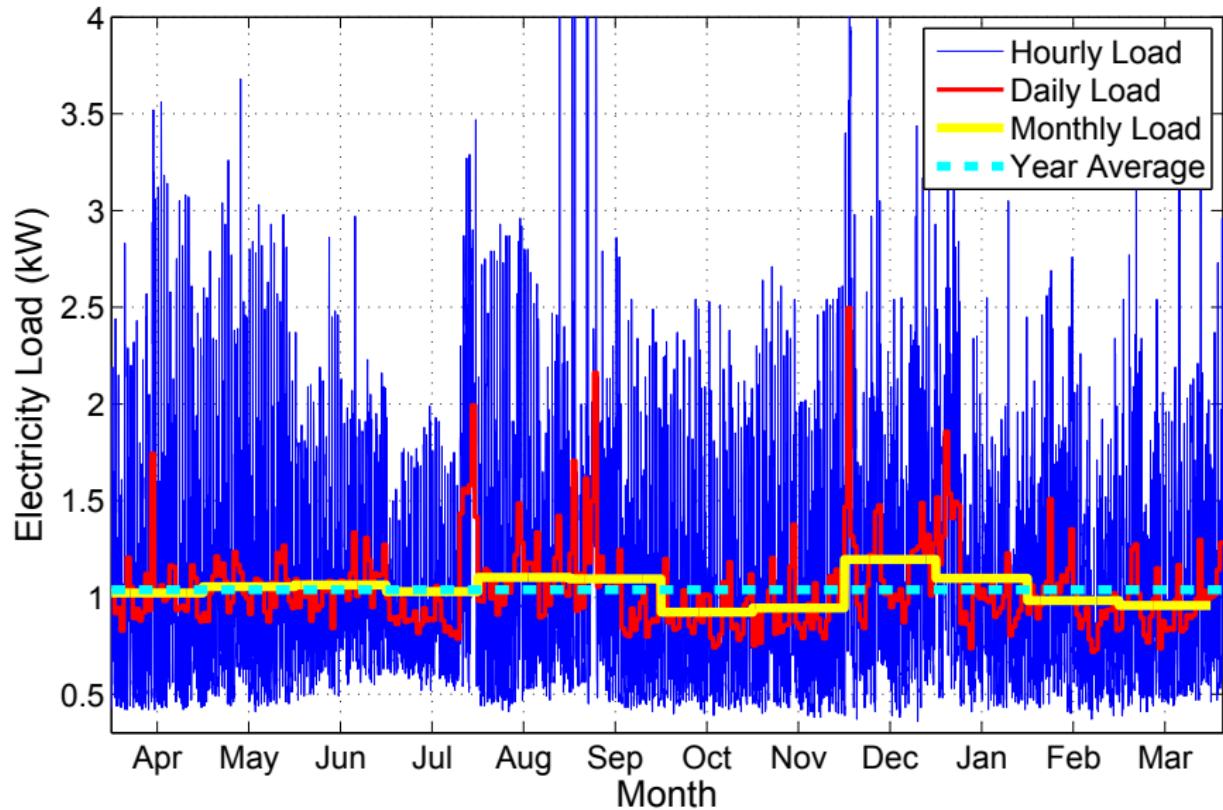
Roll over any bar to see more details Weekday  Weekend/Holiday 

See Recent Usage

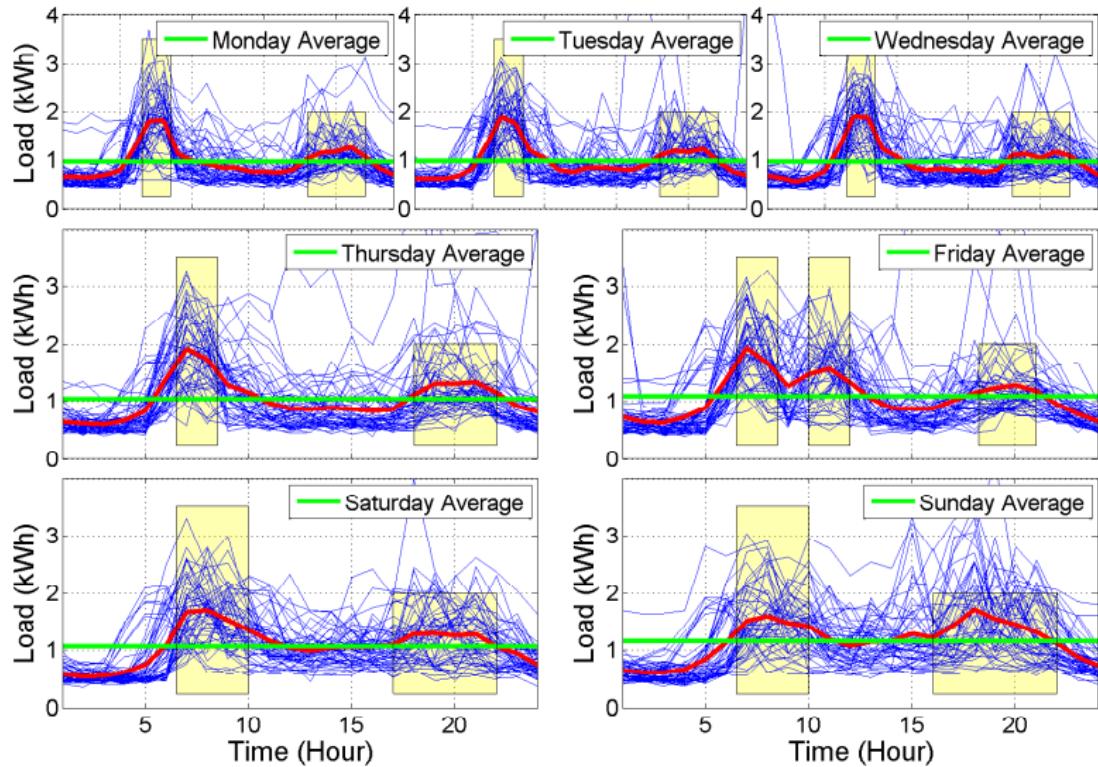
This website provides the most recent data available as of 09-29-14 and is subject to update at any time.

Smarter Cars, Homes, and Grids

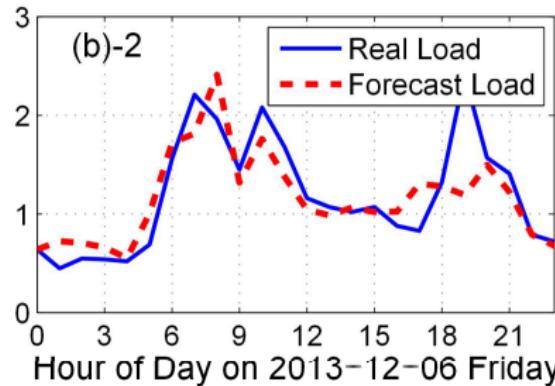
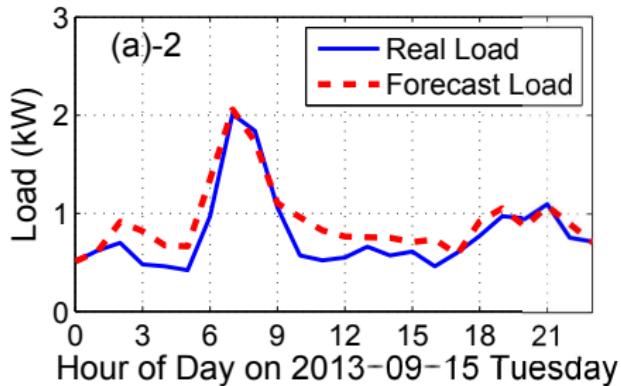
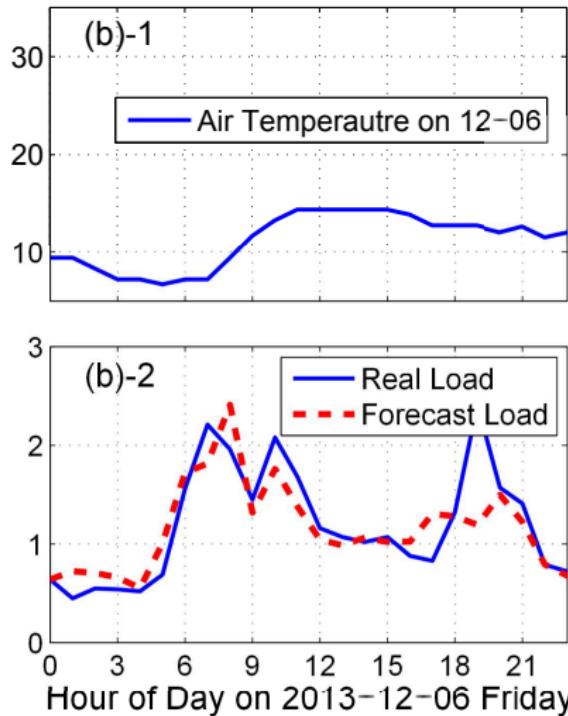
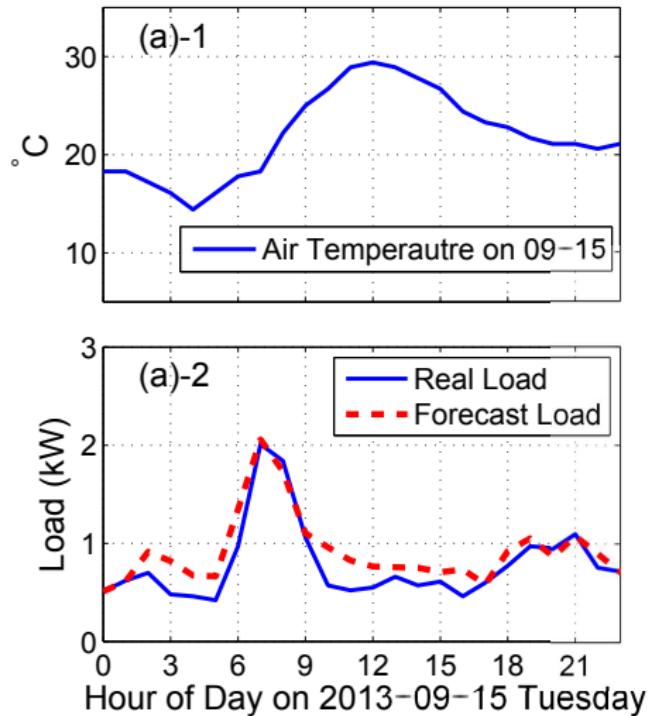
Single-Family Home Energy Patterns in LA



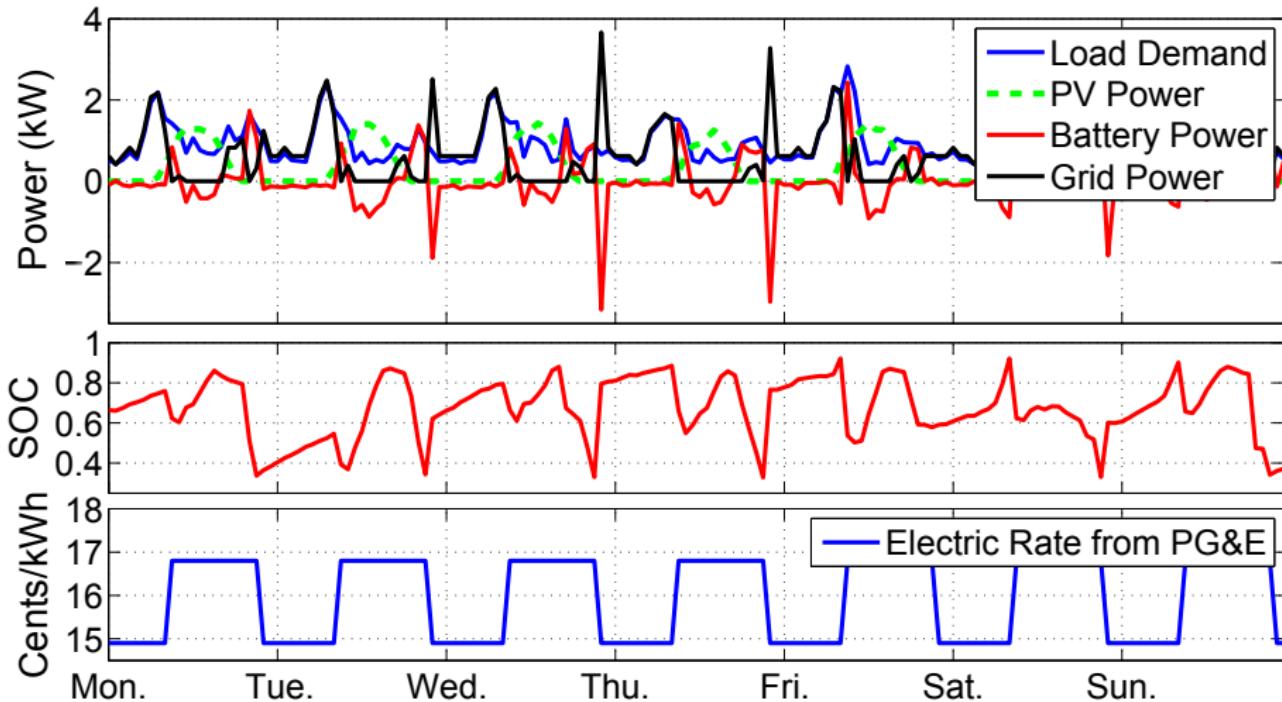
Single-Family Home Energy Patterns in LA



Short-term Forecast of Home Load

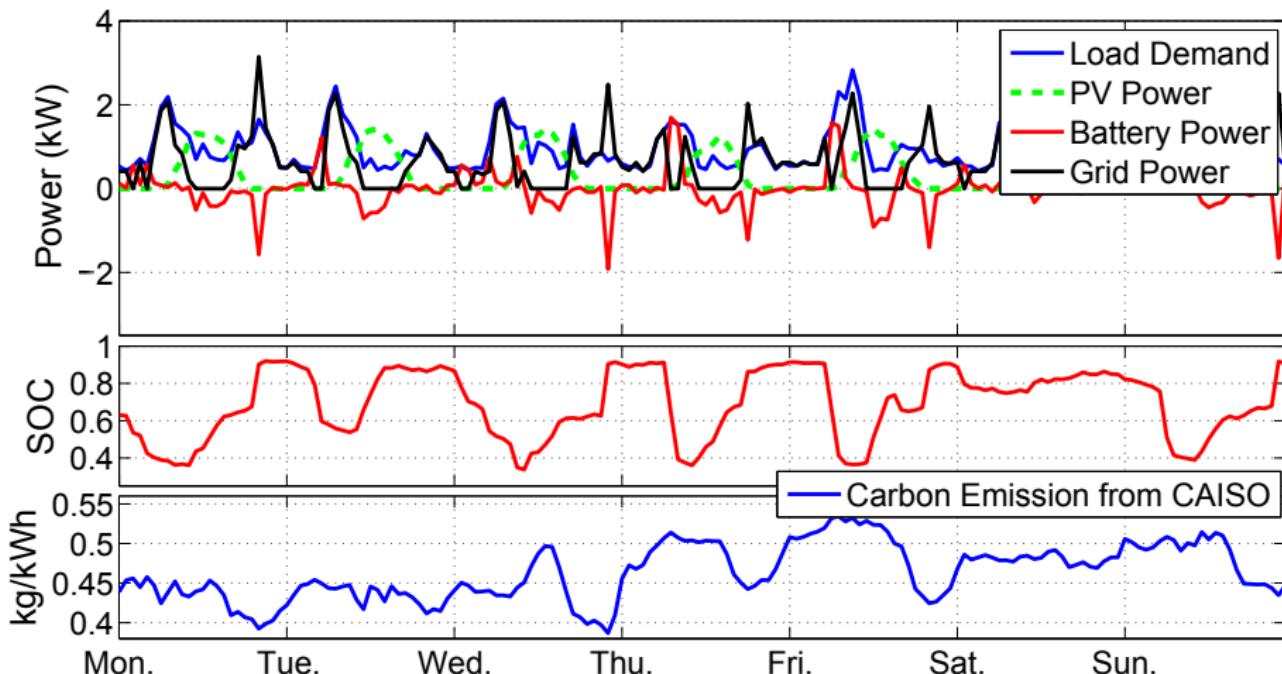


Model Predictive Control w/ Cloud-enabled Forecasts



Optimize for Grid Electricity Cost

Model Predictive Control w/ Cloud-enabled Forecasts

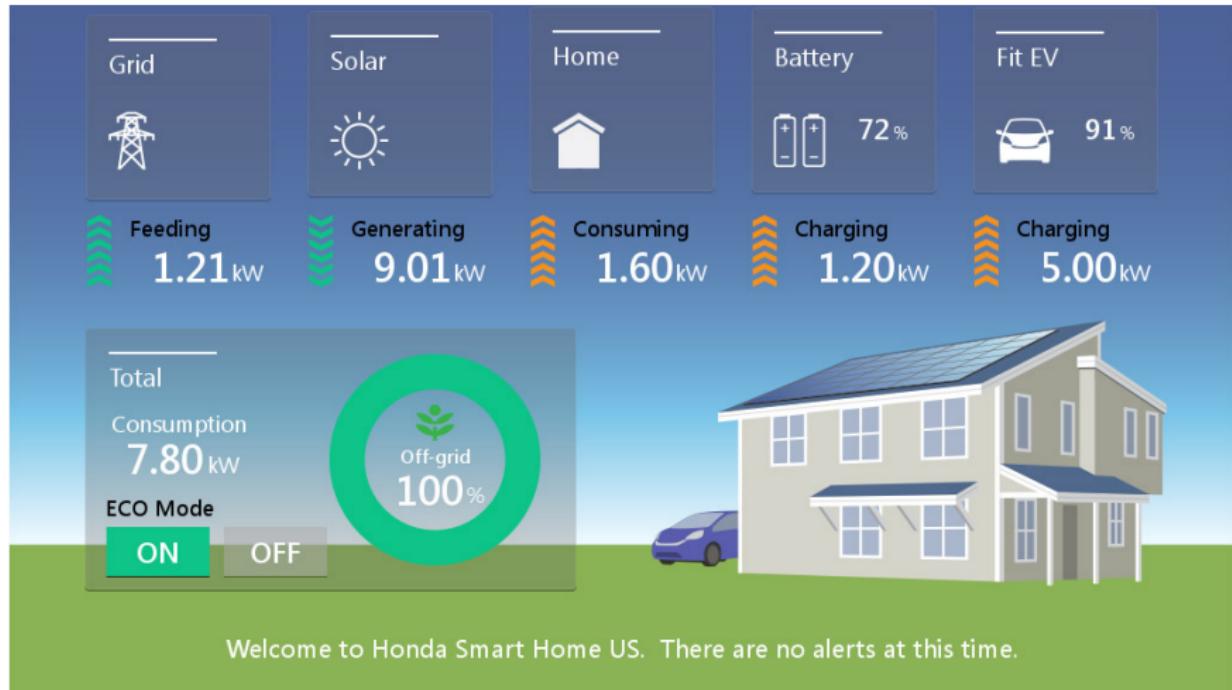


Optimize for Marginal CO₂ Produced from Power Plants

Smart Home Demonstration Project @ UC Davis



Smart Home Demonstration Project @ UC Davis



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The Vehicle-Grid Integration (VGI) Problem

Needs: Resilient and sustainable energy/transportation infrastructure

Obstacle: Unprecedented constraints and demands on grid

Some Interesting Facts

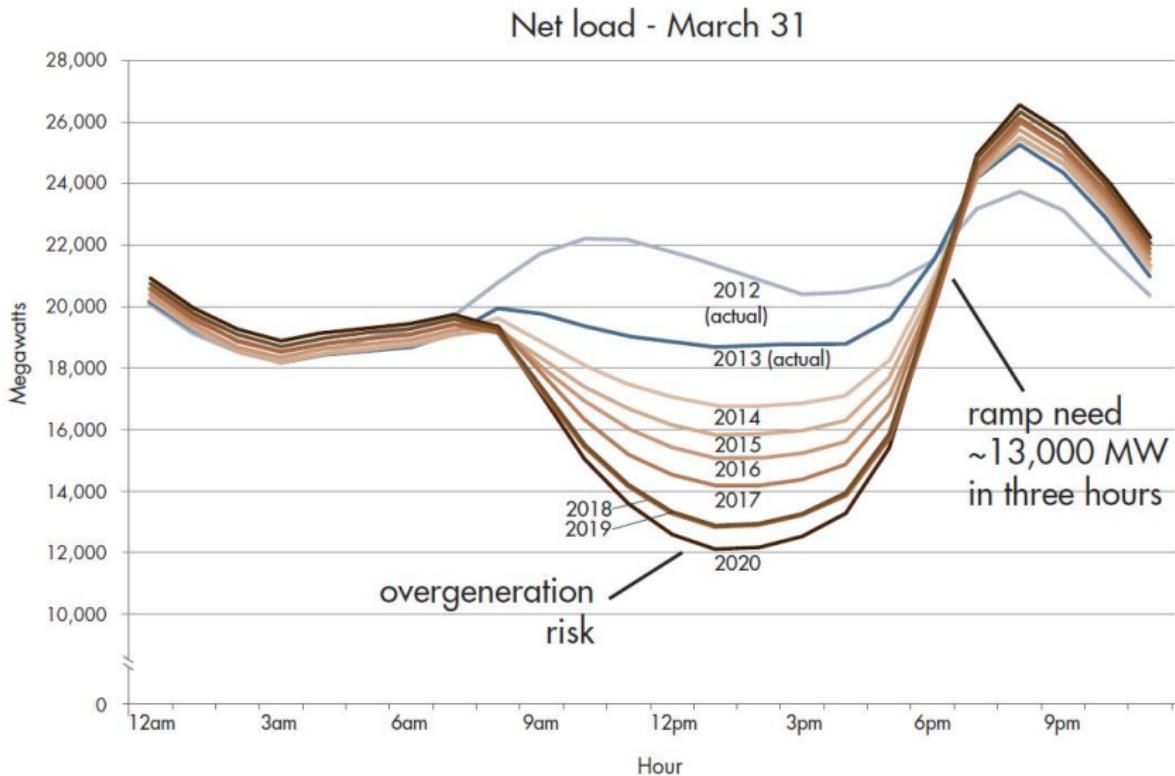
Plug-in Electric
Vehicles
(PEVs)

Potentially dispatchable loads
“carriage” opportunity
Firm variable renewables

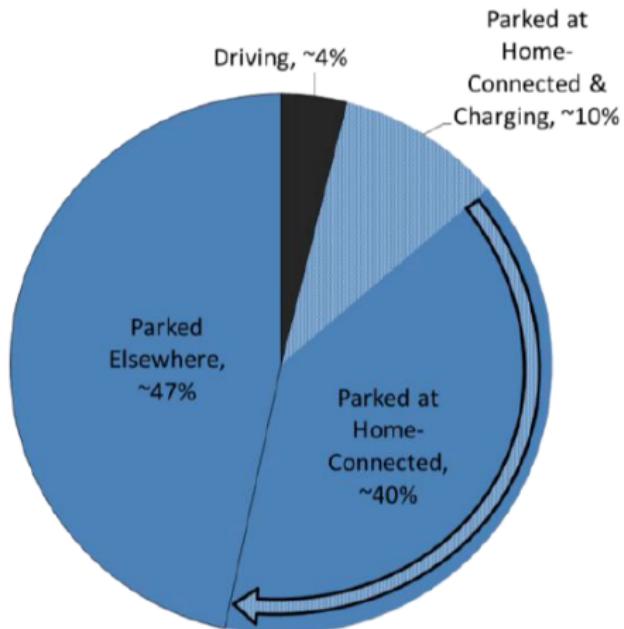
The Punchline

Exploit flexibility of PEV charging to enhance efficiency across
infrastructures

The duck curve shows steep ramping needs and overgeneration risk



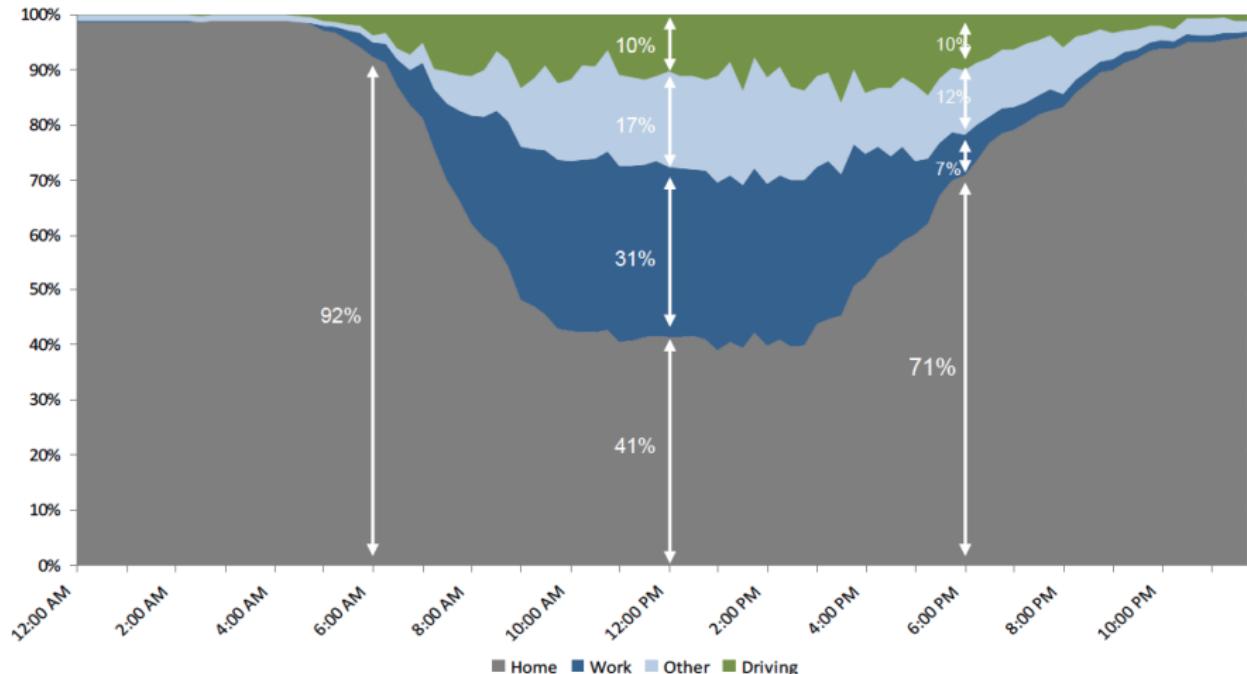
PEV Energy Storage: How much, when, and where?



Estimated percent of time PEVs spend by location and activity.

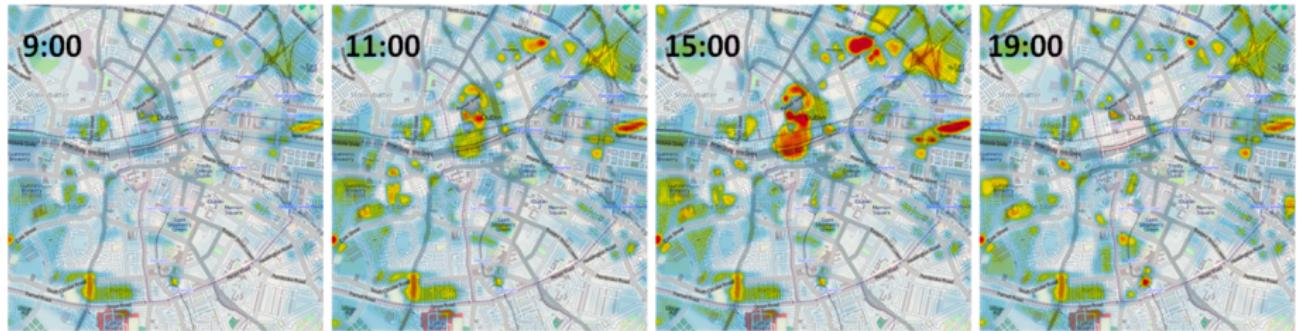
A. Langton and N. Crisostomo, "Vehicle-grid integration: A vision for zero-emission transportation interconnected throughout California's electricity system," California Public Utilities Commission, Tech. Rep. R. 13-11-XXX, 2013.

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



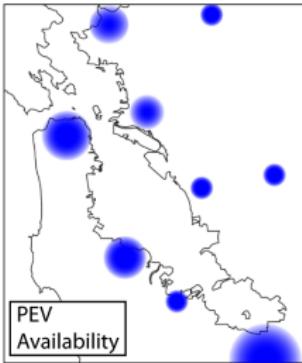
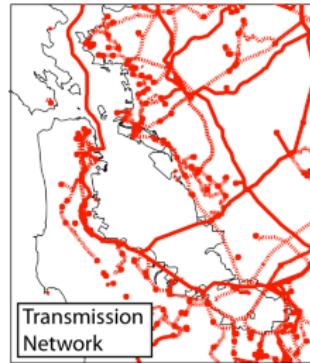
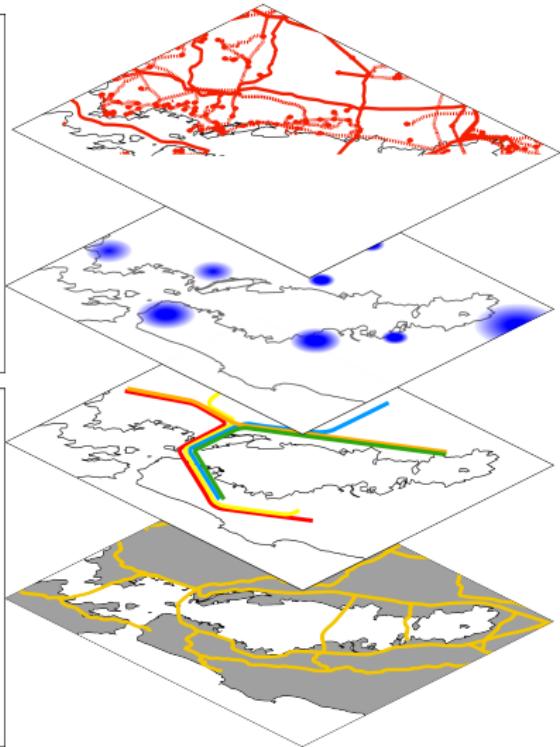
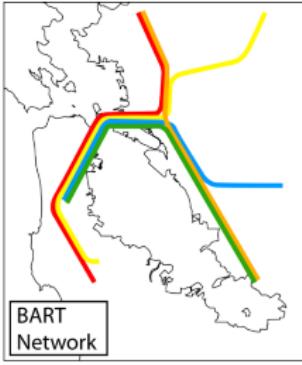
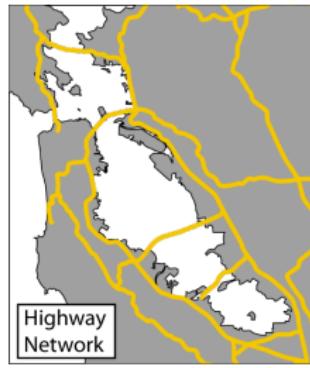
A. Langton and N. Crisostomo, "Vehicle-grid integration: A vision for zero-emission transportation interconnected throughout California's electricity system," California Public Utilities Commission, Tech. Rep. R. 13-11-XXX, 2013.

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?



Google



NEC Laboratories America
Relentless passion for innovation



ZERO
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stem



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VISIT US!

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