Resilient and Sustainable Infrastructures (RESIN)

"A Multi-Scale Design and Control Framework for Dynamically Coupled Sustainable and Resilient Infrastructures, with Application to Vehicle-to-Grid Integration" Team

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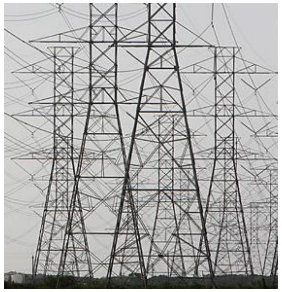
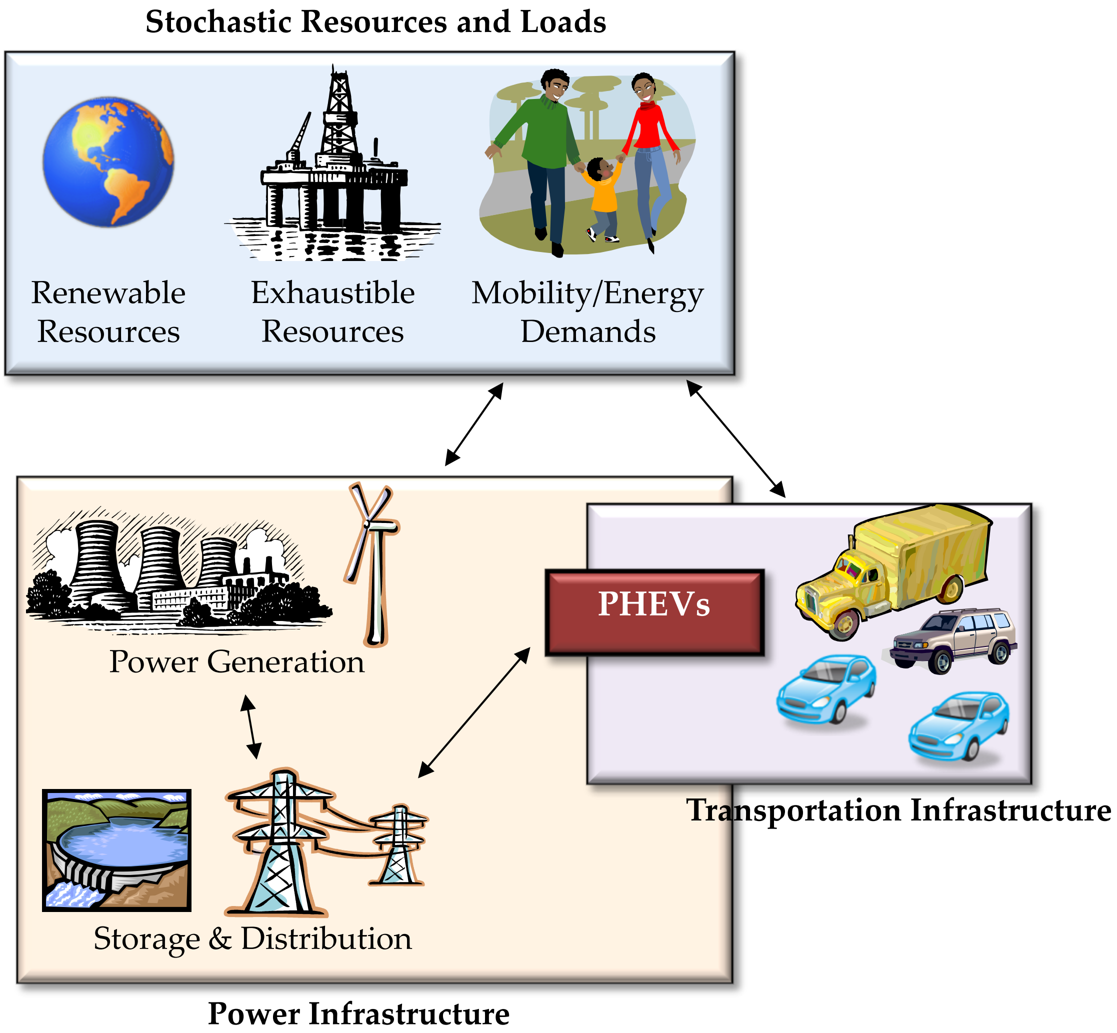
Outline



PHEV/GRID RESIN Project: Overview

- Highlight Two Studies
  - PEV charging, with wind power
  - A Center-wide case study
- Summary

Key Insights: V2G Integration



For the first time in over a century, significant potential to diversify transportation energy away from crude oil (~96%)

Significant interest in natural gas over the last 2 years

Current status: hybrid (~3.4%), plug-in plus pure electric (~0.6%)

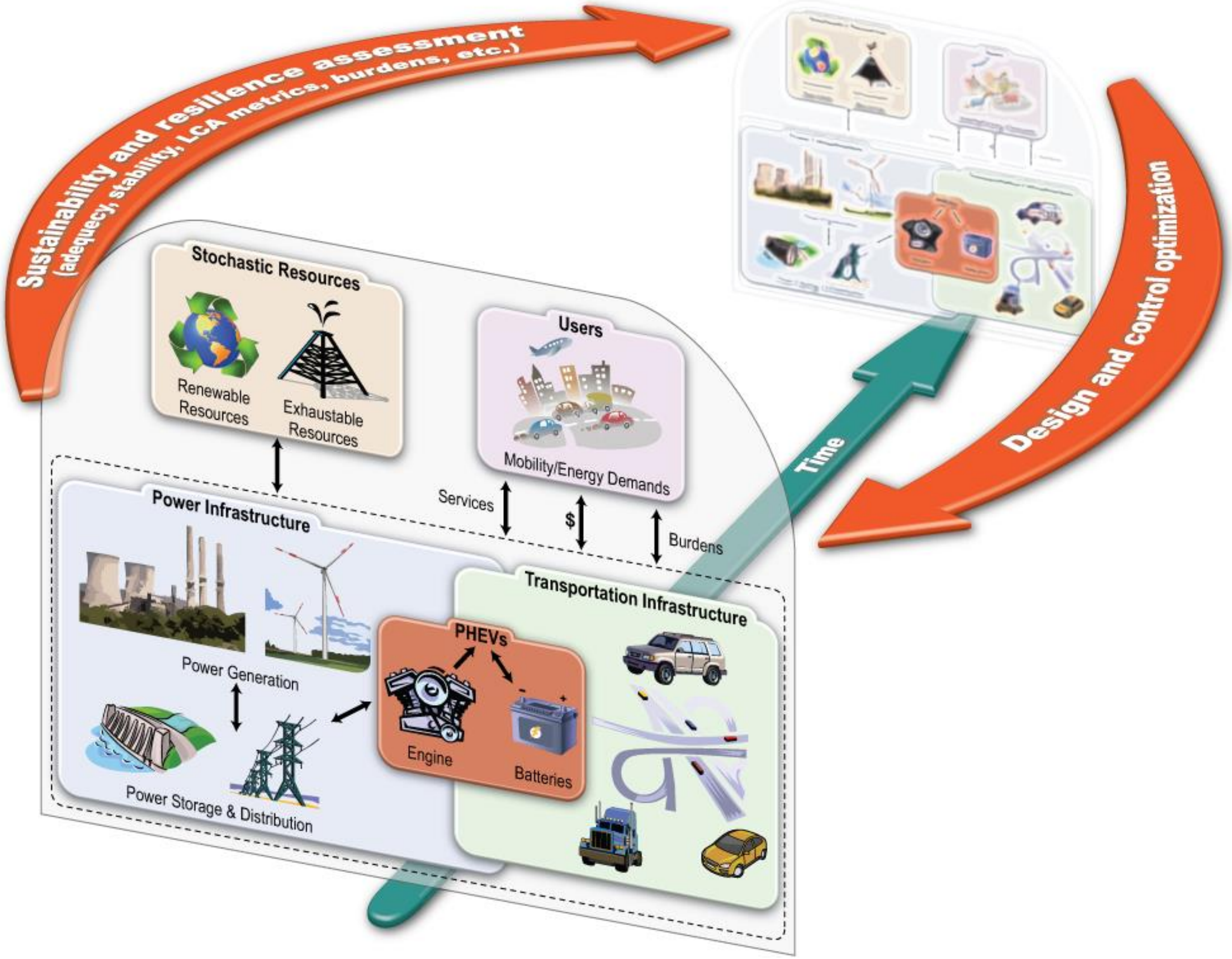
2013 PEV Sales

Mfgr	Model	Jan	Feb	Mar	April	May	**June**
Chevrolet	**Volt**	1,140	1,626	1,478	1,306	1,607	2,698
Tesla	**Model S**	1,000	1,400	1,950	2,100	2,000	1,800
Toyota	Prius Plug In	874	693	786	599	678	584
Nissan	**Leaf**	650	653	2,236	1937	2,138	2,225
Ford	**C-Max Energi**	338	334	494	411	450	455
Mitsubishi	i	257	337	31	127	91	39
Ford	Fusion Energi	0	119	295	364	416	390
Ford	**Focus**	81	158	180	147	157	177
Toyota	RAV4 EV	25	52	133	70	84	44
Honda	Fit EV	8	15	23	22	15	208
Honda	Accord	2	17	26	55	58	42
Smart	forTwo EV	1	1	0	0	60	53
BMW	ActiveE	0	0	0	0	0	
	Total Plug-In	4,376	5,405	7,632	7,138	7,754	8,742
	Total Auto Sales	1,039,926	1,188,060	1,447,674	1,280,776	1,436,748	1,397,279
	Plug-in Take Rate	**0.42%**	**0.45%**	**0.53%**	**0.56%**	**0.54%**	**0.63%**

Units sold in the first 6 months of 2013: 41,000

Units sold in all of 2012: 53,000

Project Description: Vision & Themes



Sustainability and resilience assessment
(adequecy, stability, LCA metrics, burdens, etc.)

Design and control optimization

Time

Stochastic Resources

Renewable Resources

Exhaustable Resources

Users

Mobility/Energy Demands

Services

$

Burdens

Power Infrastructure

Power Generation

Power Storage & Distribution

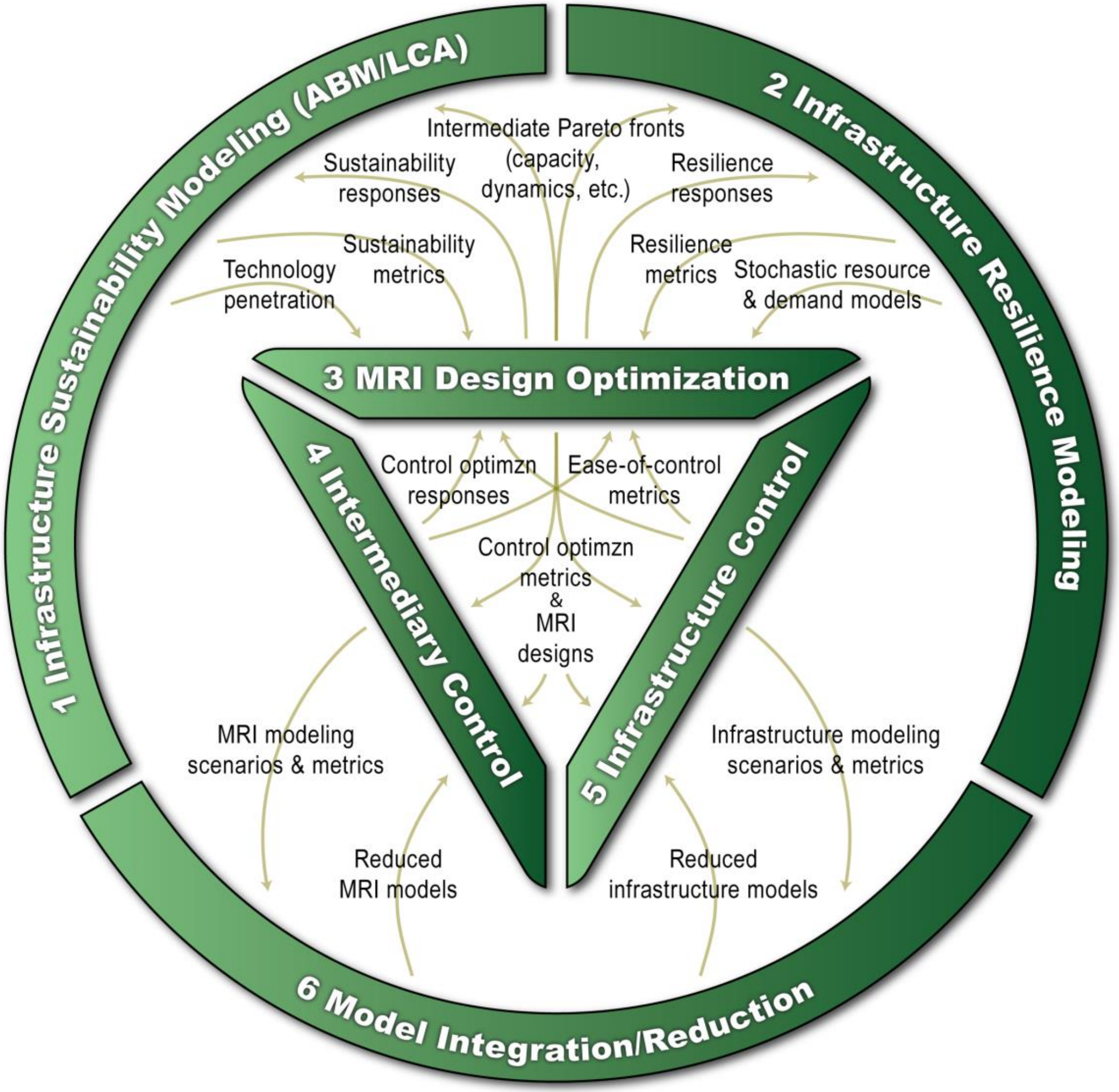
Transportation Infrastructure

PHEVs

Engine

Batteries

The Big Picture

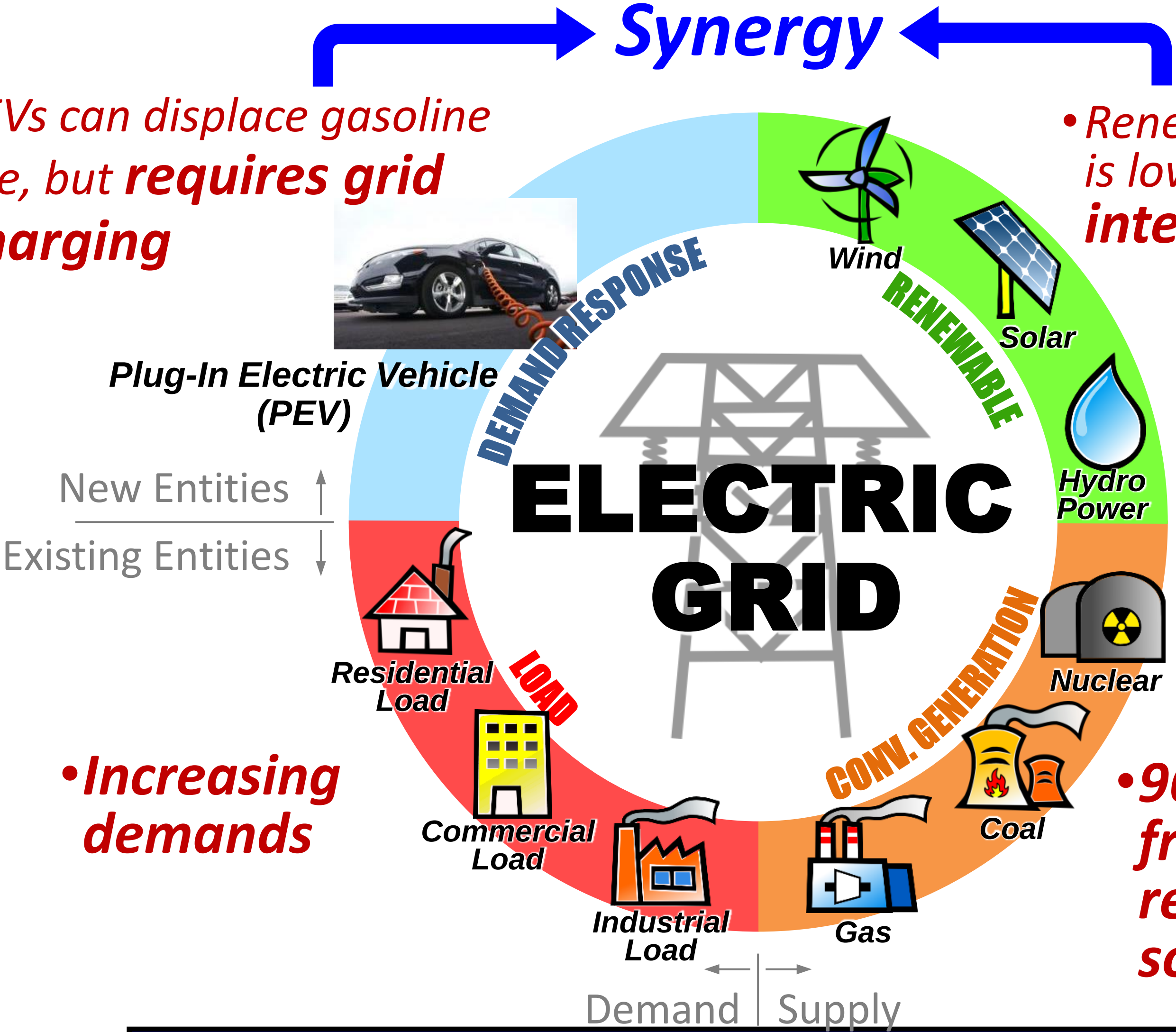


“Project 4” The Big Picture

- *PEVs can displace gasoline use, but **requires grid charging***

- *Renewable generation is low-carbon, but **intermittent***

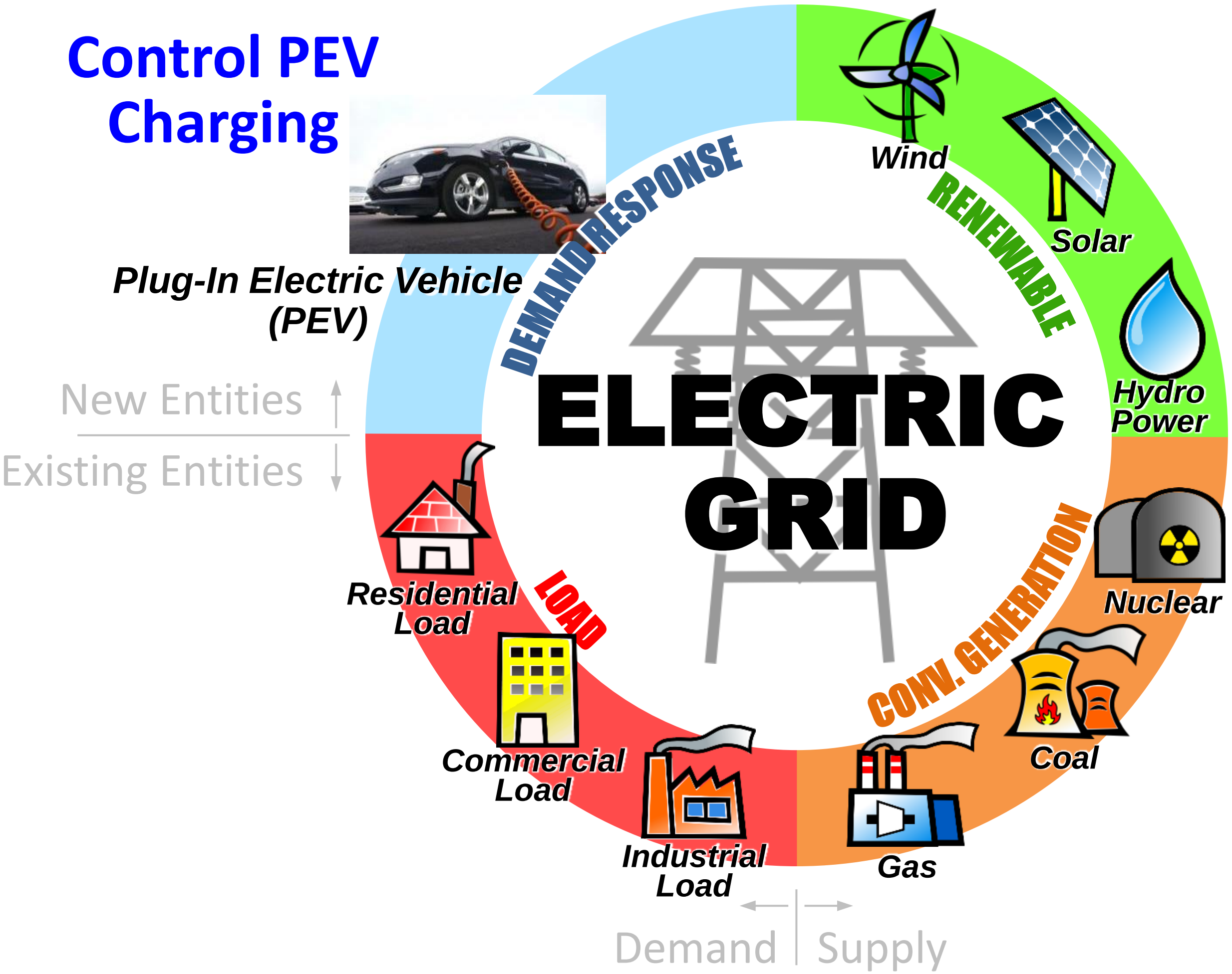
800MW wind (10%)
2 million PEVs (25%)



- ***Increasing demands***

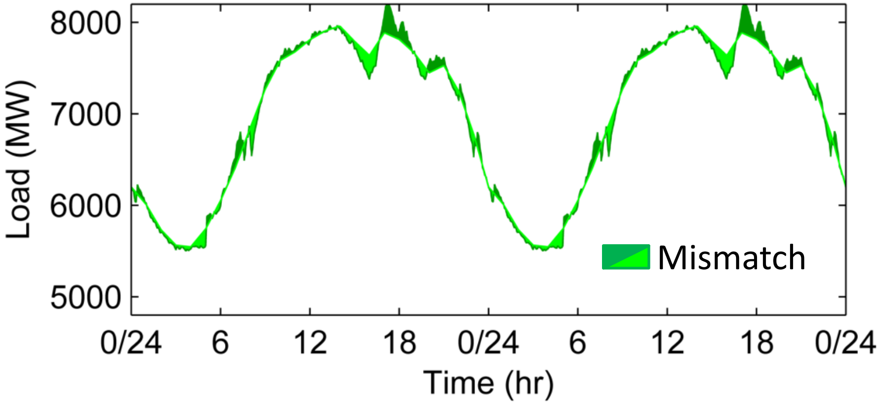
- ***96% electricity from non-renewable sources***

Control PEV Charging



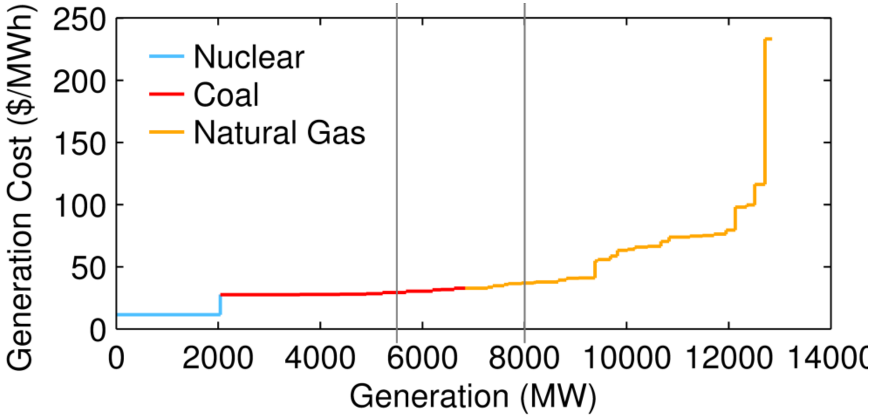
Modeling – Supply & Demand on the Grid

- **Demand**: non-PEV grid load in Michigan



The Michigan grid load varies between 5,500-8,000MW throughout the day

- **Supply**: electricity generation follows the **merit order dispatch**

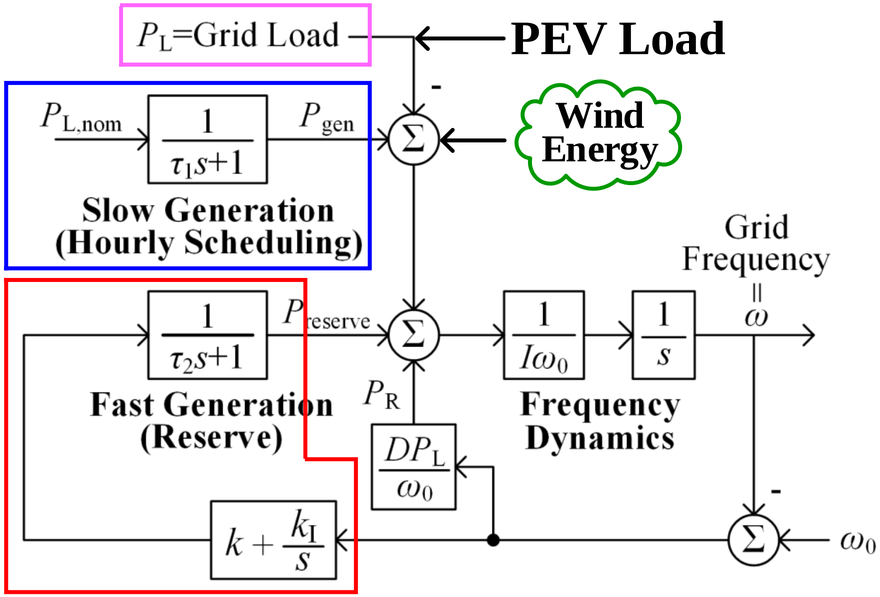


Cheaper power plants will be dispatched before expensive ones

Data source:
Federal Energy Regulatory Commission (FERC), Form 714-Annual Electric Control and Planning Area Report, 2009, [Online]. Available: http://www.ferc.gov/docs-filing/ferconline.asp
S. Hadley, "The Oak Ridge Competitive Electricity Dispatch (ORCED) Model," Oak Ridge National Laboratory, Report #ORNL/TM-2007/230, 2008.

Modeling – Grid Reserves

- Grid power supply and demand must match, otherwise, the grid frequency deviates from the nominal 60 Hz.
- The grid operator schedules and dispatched **reserves** to regulate grid frequency

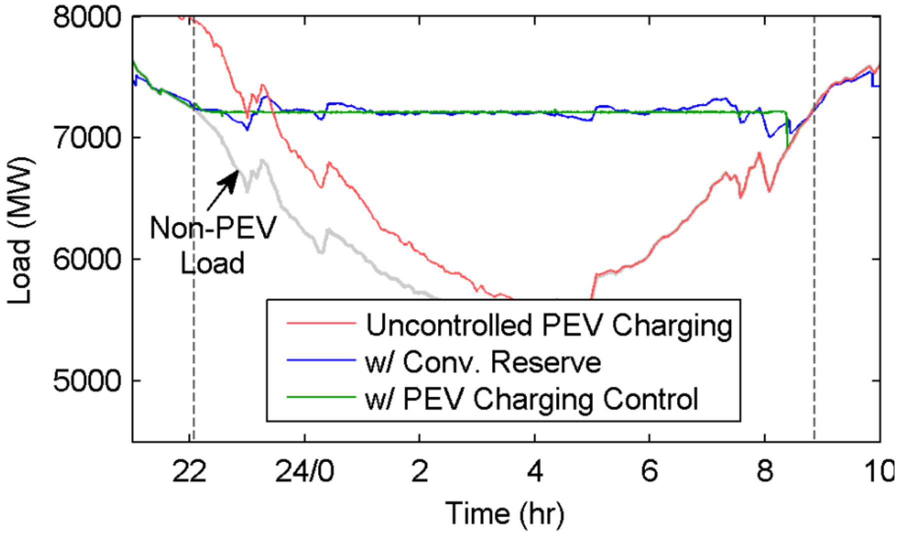


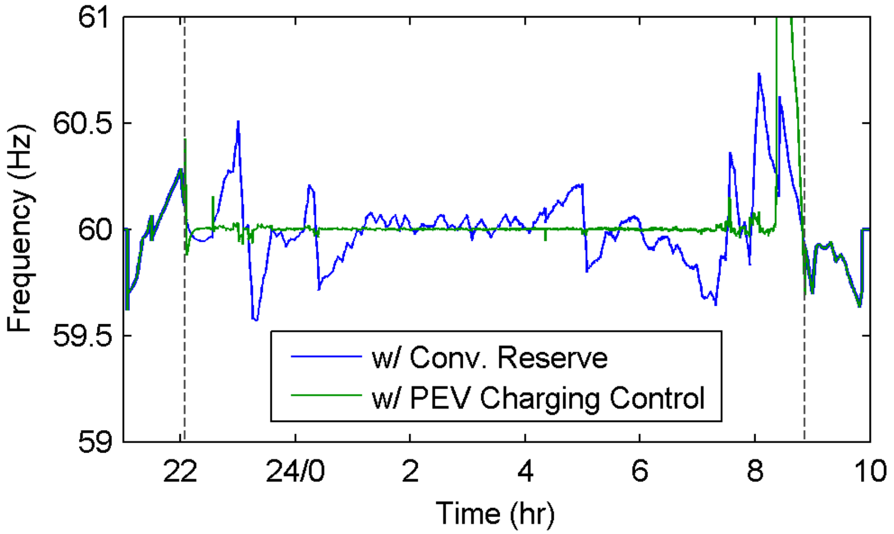
- Fast-responding reserves are **more expensive** than the hourly scheduling
- PEVs can be "Demand Response" to achieve FASTER and BETTER performance than fast ancillary reserves (more or less charging, but no V2G)

PEV Charging Control

details

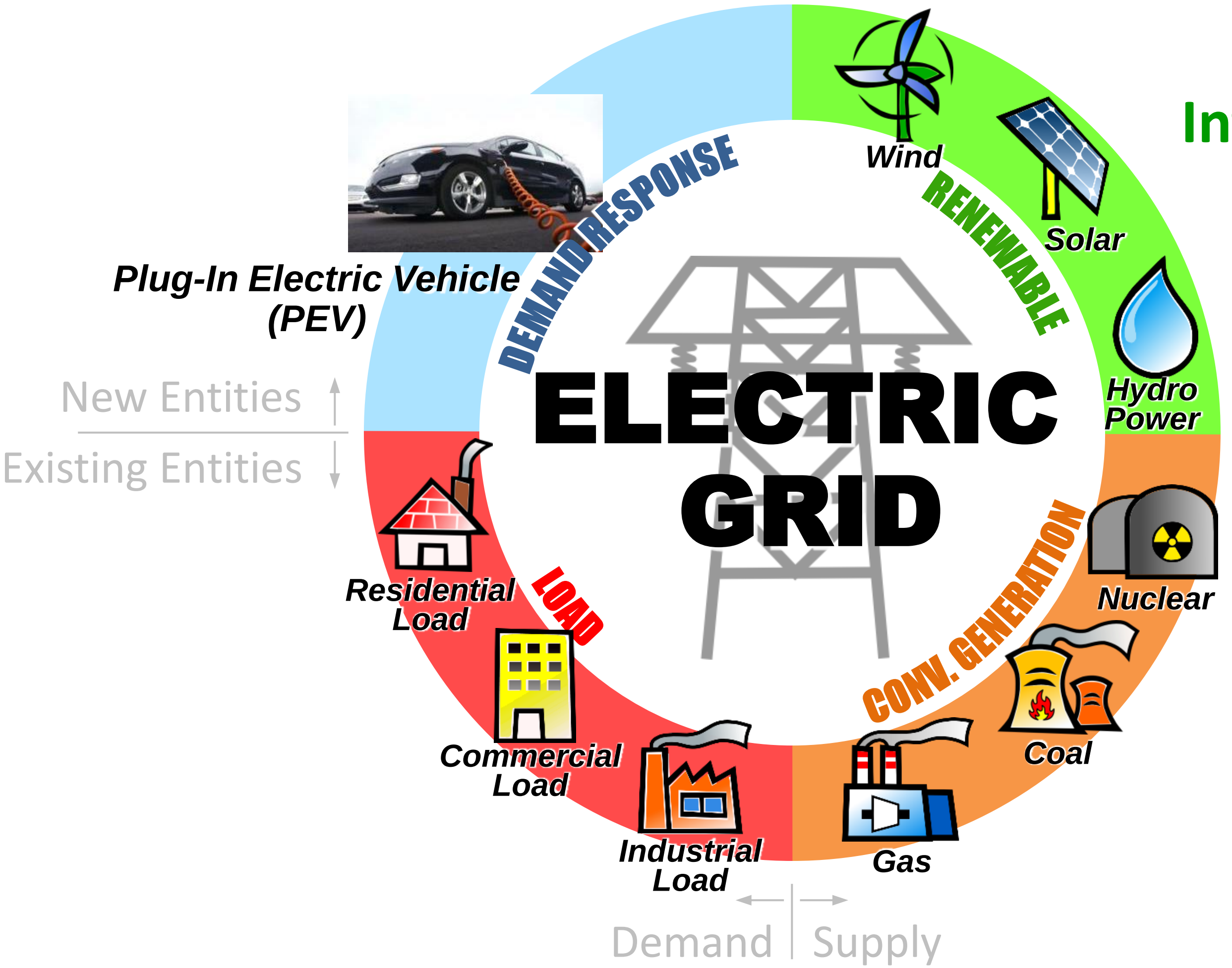
- We devised a distributed control algorithm, assuming 2 million PEVs on the Michigan grid:
  - The local controller → 98.45% of PEVs are fully charged
  - Feed forward control → valley filling
  - Feedback control → grid frequency regulation





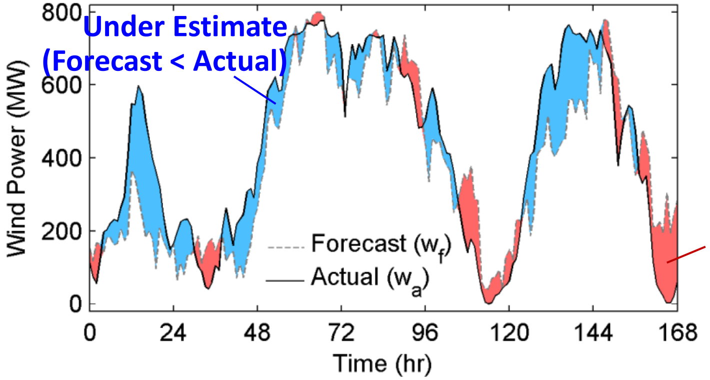
Major Finding: There is no trade-off between the goals of individual drivers and grid service quality. This is because of the separation of time scale and the nature of the horizon optimization problems

Mitigate Wind Intermittency



Mitigate Wind Intermittency with Battery Energy Storage

Current Practice



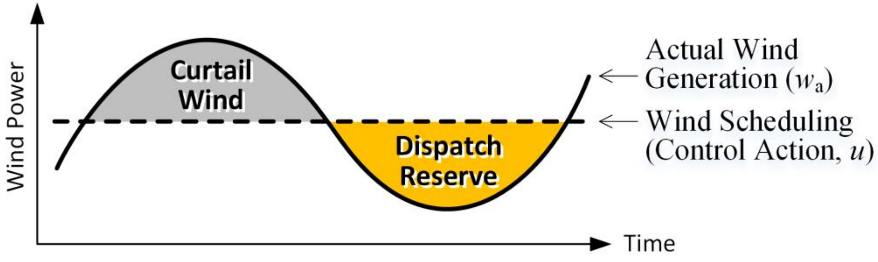
Under Estimate (Forecast < Actual)

Over Estimate (Forecast >Actual)

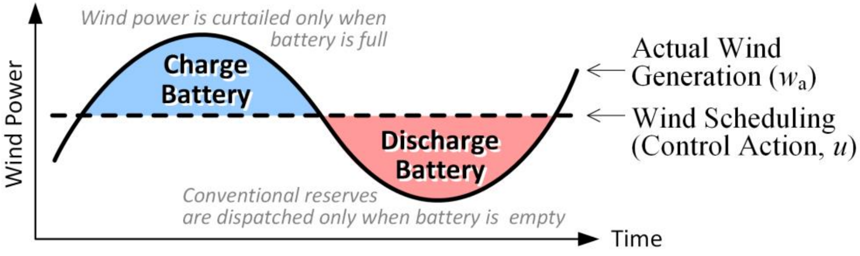
Problem: Wind forecast is intermittent and the prediction is never perfect

- Solution—other than relying on large-scale averaging

(a) Dispatch Conventional Reserves



(b) Add ESS (Battery)



Wind power is curtailed only when battery is full

Conventional reserves are dispatched only when battery is empty

- Energy storage system (ESS, typically battery) can absorb wind surplus or deficit
- But, how large should the battery capacity be (they are expensive)?

Mitigate Wind Intermittency

- Performance comparison: conventional reserves vs. BESS:

Conventional reserves

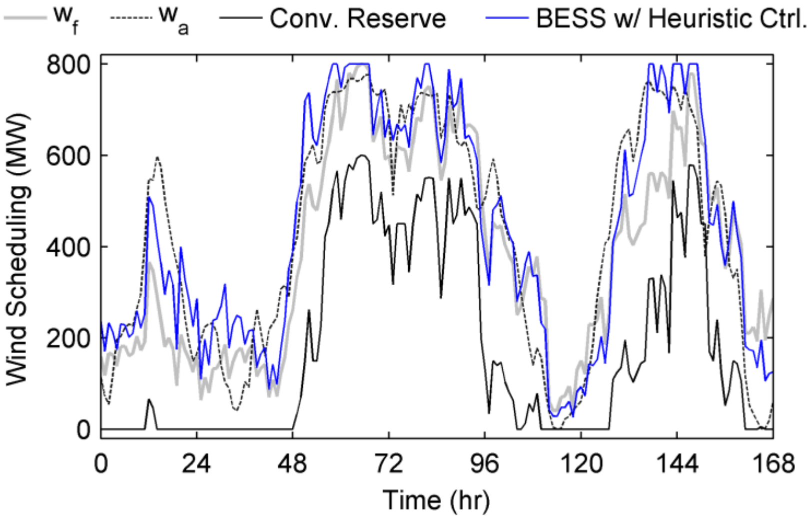
$$\min_{u} : J = -C_1 \cdot u + C_2 \cdot R_{\mathrm{w,rqd}} + C_3 \cdot w_{\mathrm{d}}$$

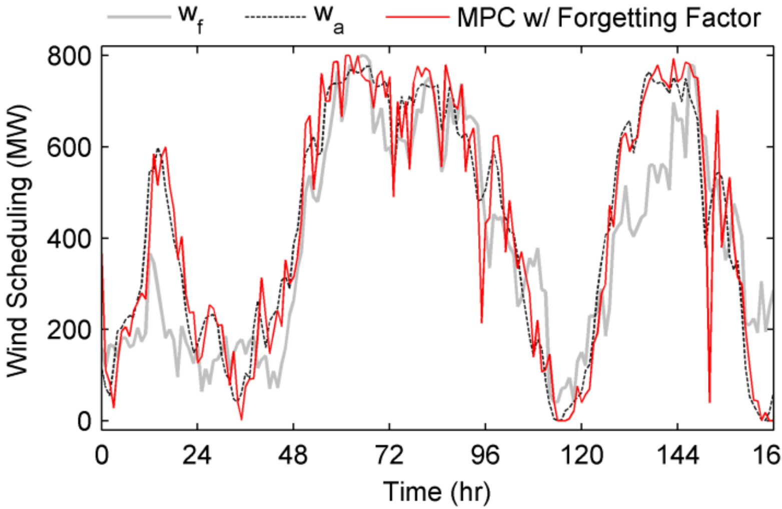
Instantaneous heuristics for BESS

$$u = w_{\mathrm{s}} = w_{\mathrm{f}} \cdot \underbrace{g(SOC)}_{\text{Scaling factor}}$$

Model Predictive Control for BESS

$$\min_{\boldsymbol{u}} : J_k = \sum_{t=k}^{k+N-1} \left[-C_1 \cdot u(t) + C_2 \cdot R_{\mathrm{s}}(t) + C_3 \cdot R_{\mathrm{d}}(t) \right] \cdot \gamma^{t-k}$$





Mitigate Wind Intermittency

Conventional reserves

$$\min_{u} : J = -C_1 \cdot u + C_2 \cdot R_{\mathrm{w,rqd}} + C_3 \cdot w_{\mathrm{d}}$$

Instantaneous heuristics for BESS

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Model Predictive Control for BESS

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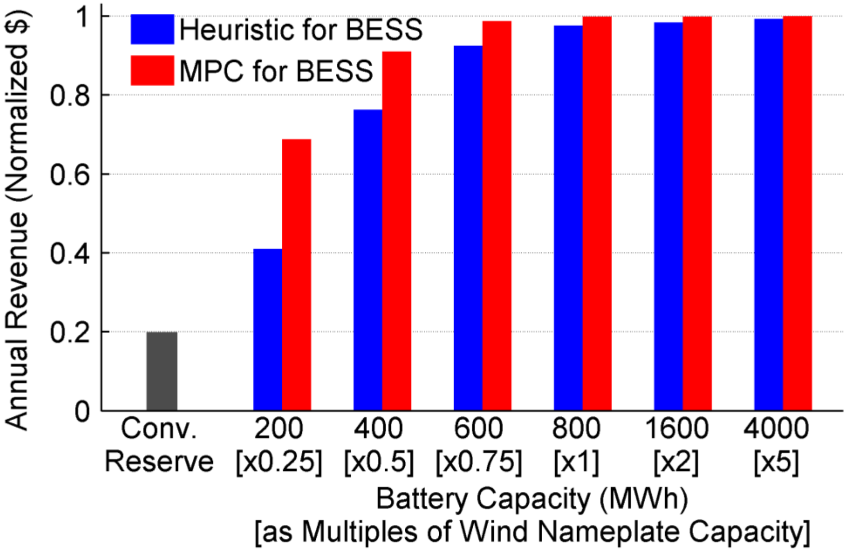
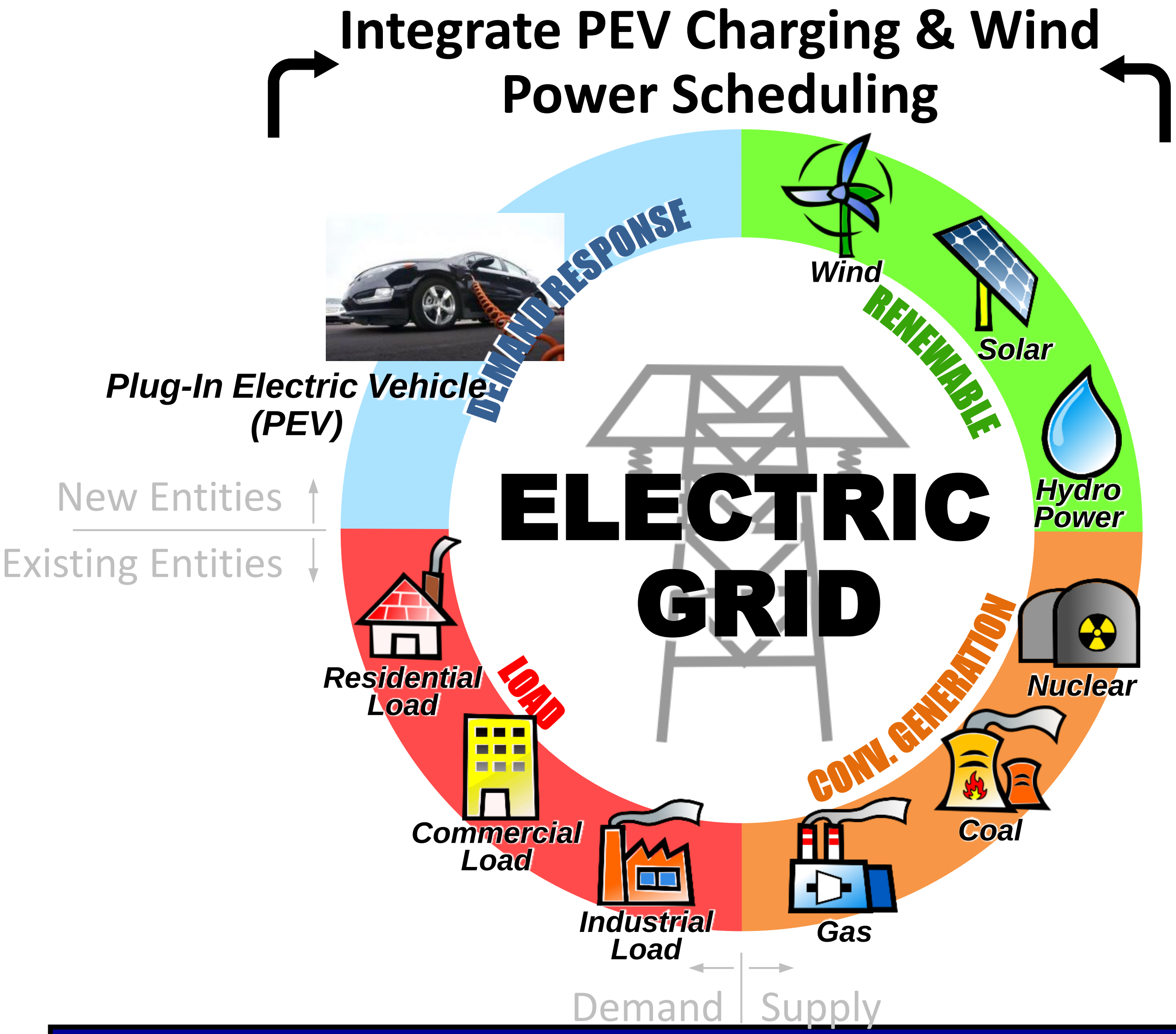


- **Major finding:** To reduce curtailment and maximize wind farm revenue, the battery only needs to be 50%-75% of the nameplate capacity, if its charging is properly controlled

Integrate PEV Charging & Wind Power Scheduling



Integrate PEV Charging & Wind Scheduling

- Scheduling to minimize the **grid-wide** cost of electricity generation, and in the meantime control the PEV charging
  - u_1: Scheduling of non-renewable generation
  - u_2: Scheduling of wind energy

details

$$\min_{u_1,u_2} : J = \sum_{t=1}^{T} \Big[\underbrace{C_{\mathrm{g}}(u_1(t))}_{\text{Electricity generation from non-renewables}} + \underbrace{C_{\mathrm{Rs}}(R_{\mathrm{s}}(t)) + C_{\mathrm{Rd}}(R_{\mathrm{d}}(t))}_{\text{Reserves}} \Big]$$

subject to

$$u_1(t) + u_2(t) - P_{\mathrm{L,nom}}(t) = P_{\mathrm{PEV}}(t) \ , \ \forall t$$

$$\sum_t P_{\mathrm{PEV}}(t) \cdot \Delta t = K$$

No V2G $$\boxed{0 \le P_{\mathrm{PEV}}(t) \le \min\{x(t),\ U_{\mathrm{PEV}}\} \ , \ \forall t}$$

$$x(t+1) = x(t) - P_{\mathrm{PEV}}(t) \cdot \Delta t \ , \ \forall t$$

$$x(0) = K$$

Electricity generation-related constraints

$$R_{\mathrm{L,rqd}}(t) = 0.05 \cdot P_{\mathrm{L,nom}}(t) \ , \ \forall t$$

Reserves for wind

$$\boxed{R_{\mathrm{w,rqd}}(t) = [u_2 - \mathbf{F}^{-1}(0.05)]^+ \ , \ \forall t}$$

$$\boxed{R_{\mathrm{s}}(t) + P_{\mathrm{PEV}}(t) \ge R_{\mathrm{L,rqd}}(t) + R_{\mathrm{w,rqd}}(t) \ , \ \forall t}$$

$$\boxed{w_{\mathrm{d}}(t) = \mathbf{E}\{[u_2 - w_{\mathrm{a}}]^+\} \ , \ \forall t}$$

PEVs as reserves

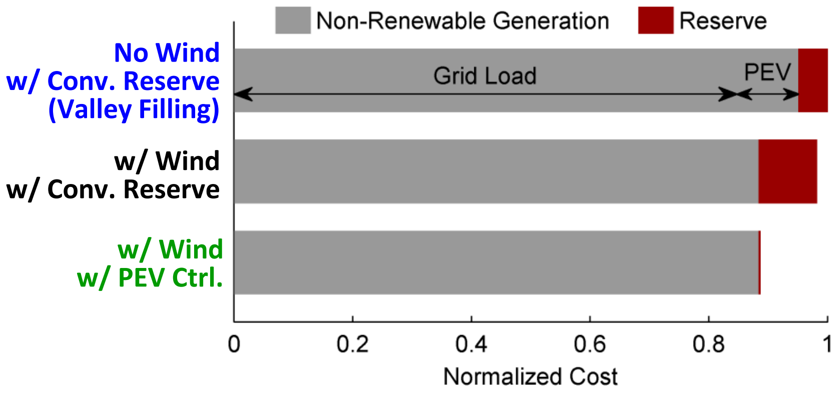
$$\boxed{R_{\mathrm{d}}(t) = [w_{\mathrm{s}}(t) - P_{\mathrm{PEV}}(t)]^+ \ , \ \forall t}$$

Reserve-related constraints

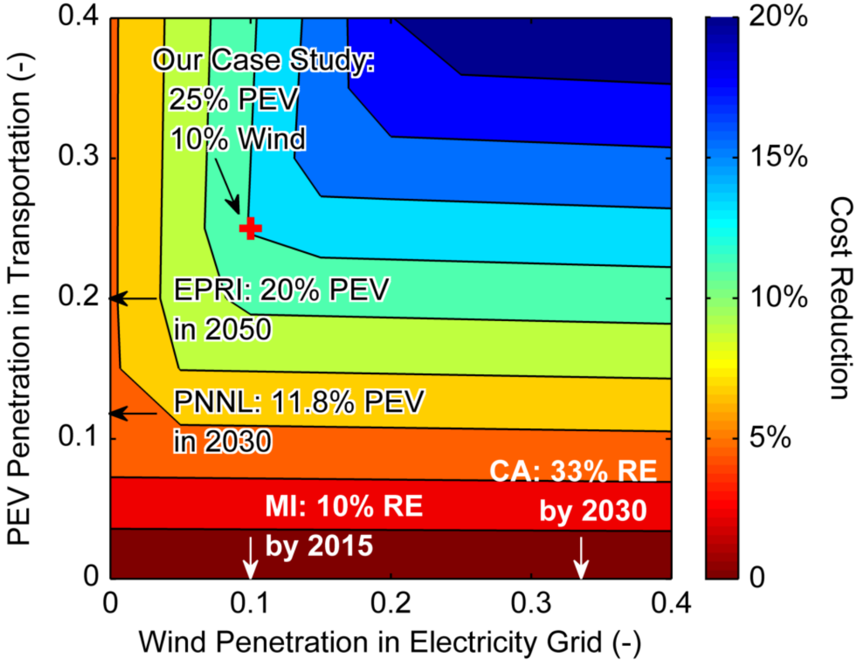
Integrate PEV Charging & Wind Scheduling

- Total cost of electricity generation:

25% PEV (2M), 10% Wind (800MW)



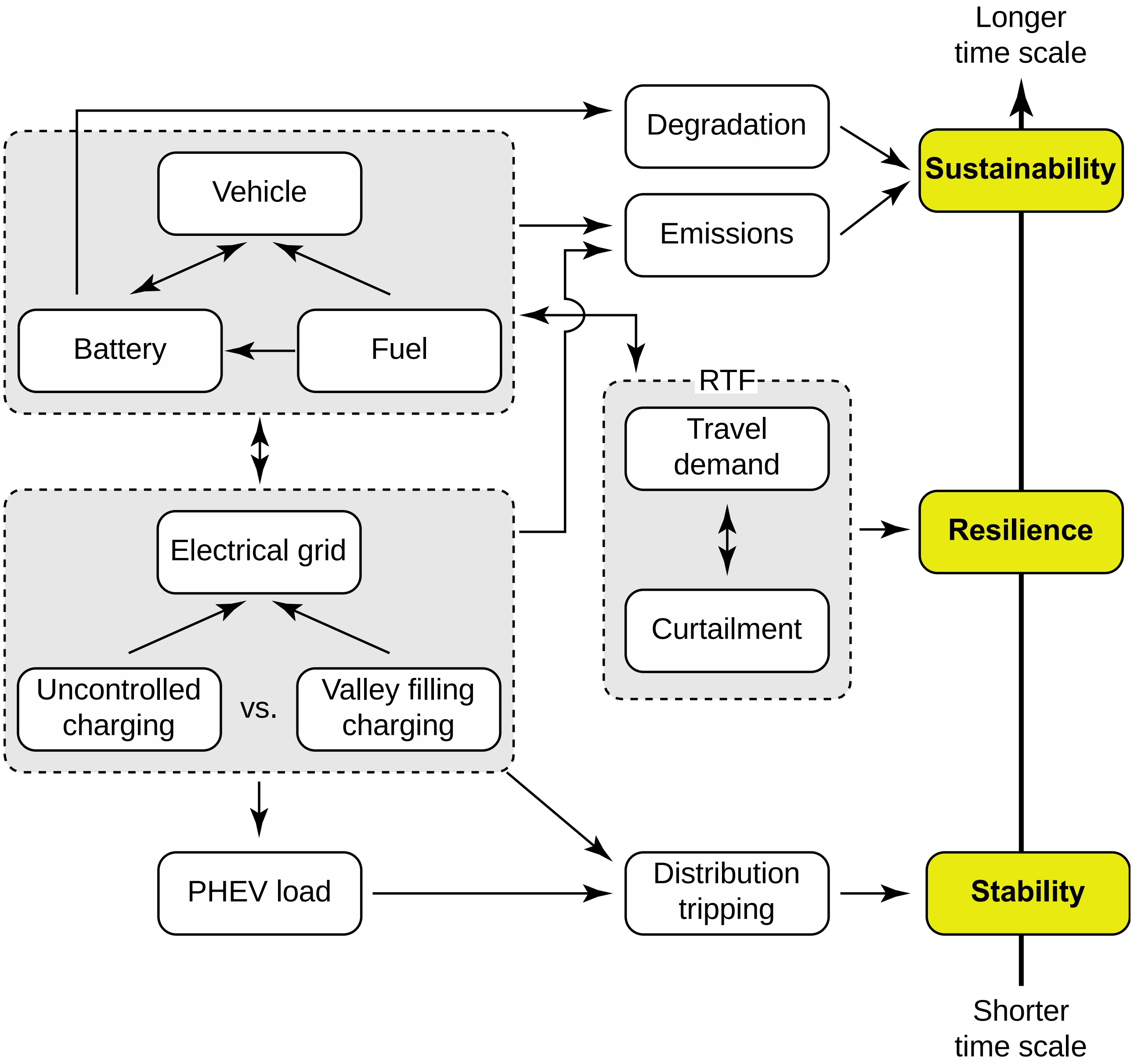
Various Penetration Levels



- **Major finding:** Wind and PEVs should be deployed simultaneously. Their operations must be coordinated for synergy (control both supply and demand)

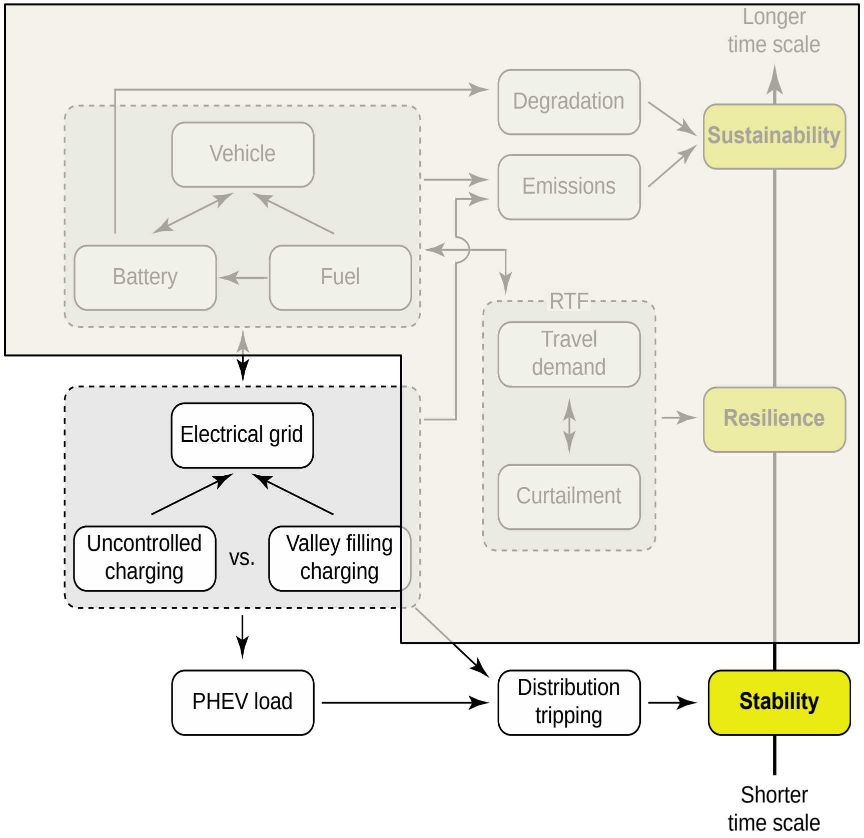
EFRI Case Study

- Goal: Determine the interaction effects of PHEV and the electrical grid in terms of sustainability and resiliency metrics
  - Sustainability metrics: GHG and criteria pollutant emissions (decade timeframe)
  - Resiliency metrics: Realized Travel Factor (daily time frame), and electrical grid stability (millisecond time frame)

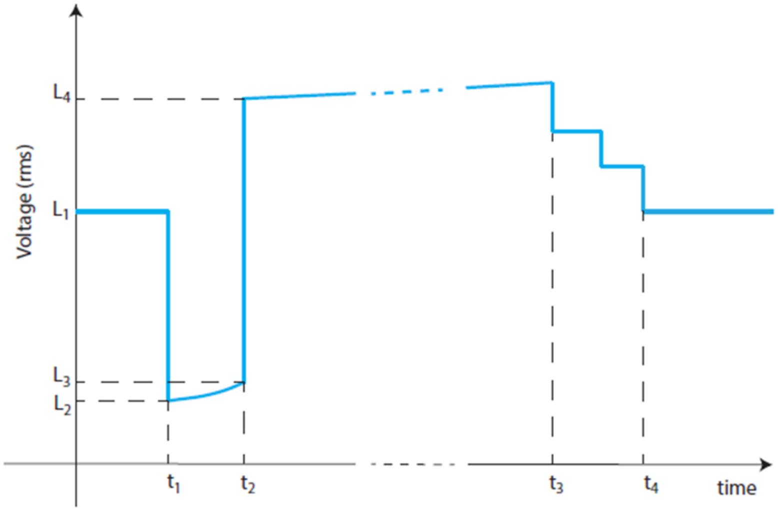

Longer
time scale
Degradation
Emissions
Sustainability
Vehicle
Battery
Fuel
RTF
Travel
demand
Curtailment
Resilience
Electrical grid
Uncontrolled
charging
vs.
Valley filling
charging
PHEV load
Distribution
tripping
Stability
Shorter
time scale

Case Study: Grid stability

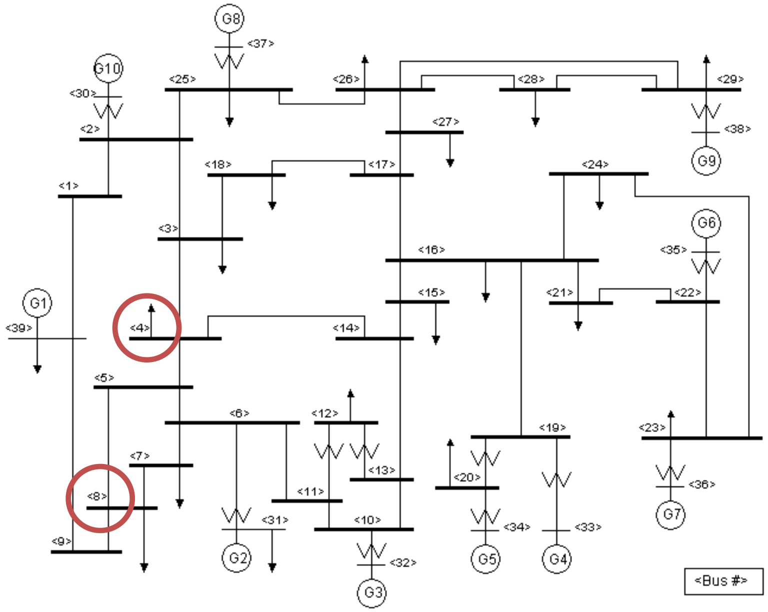
- Effects very short timescale (milliseconds)
- Examine effect of PHEV *charging algorithms* along with *penetration*
- Voltage sag in transmission cascades to residential disruption



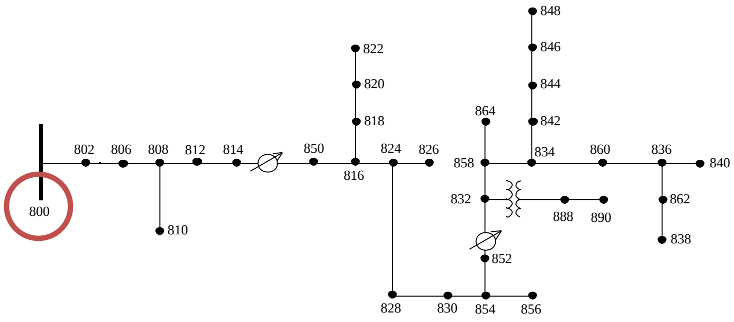
Case Study: Grid stability



- Voltage sag at some nodes of the transmission grid causes PHEVs on distribution feeder (connected to node 4) to drop
- Dropped PHEV load then causes overvoltage scenario within distribution feeder

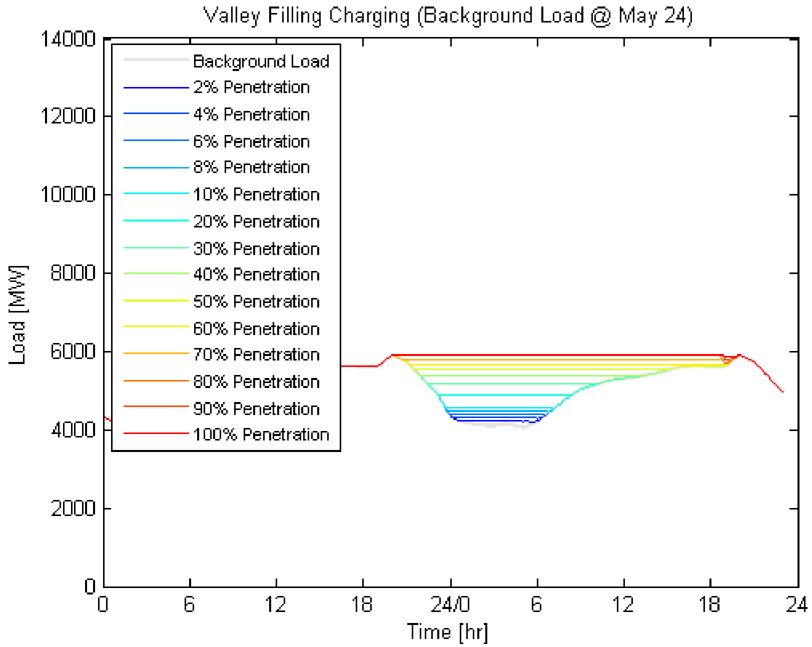


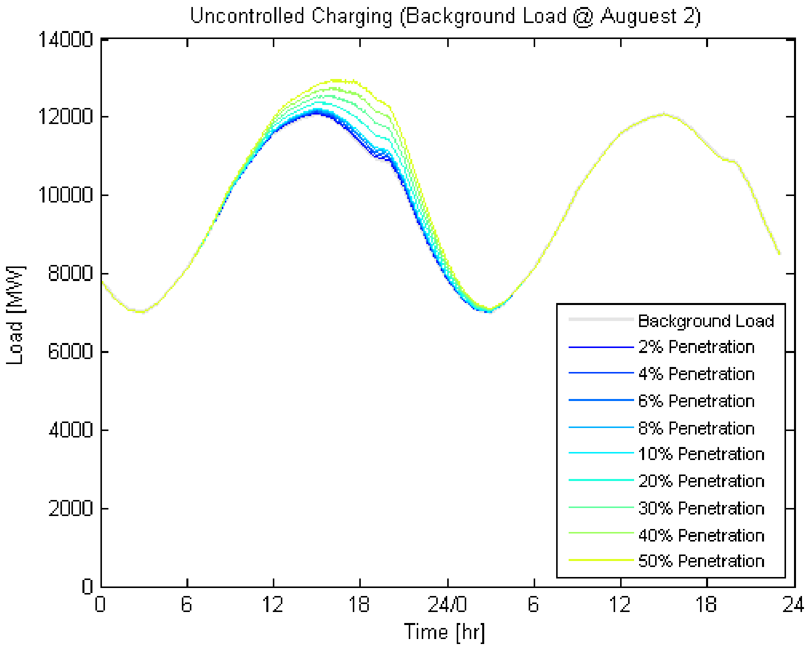
IEEE 39-bus transmission grid model



IEEE 34-node test distribution feeder

Case Study: Grid capacity

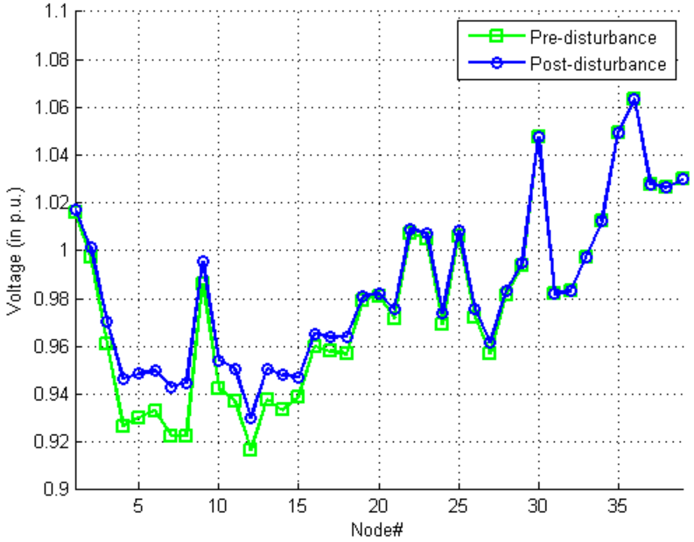




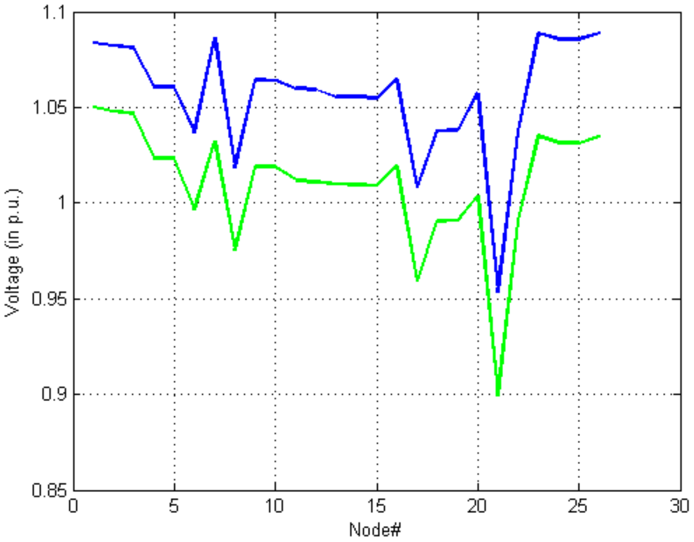
- Valley filling mode can safely fill great percentage of vehicles
- Uncontrolled charging can cause demand to exceed capacity at penetrations above 50%

Case Study: Grid stability

- Voltage rise at transmission level is within limits
- But, that same rise at distribution level can be unsafe for grid

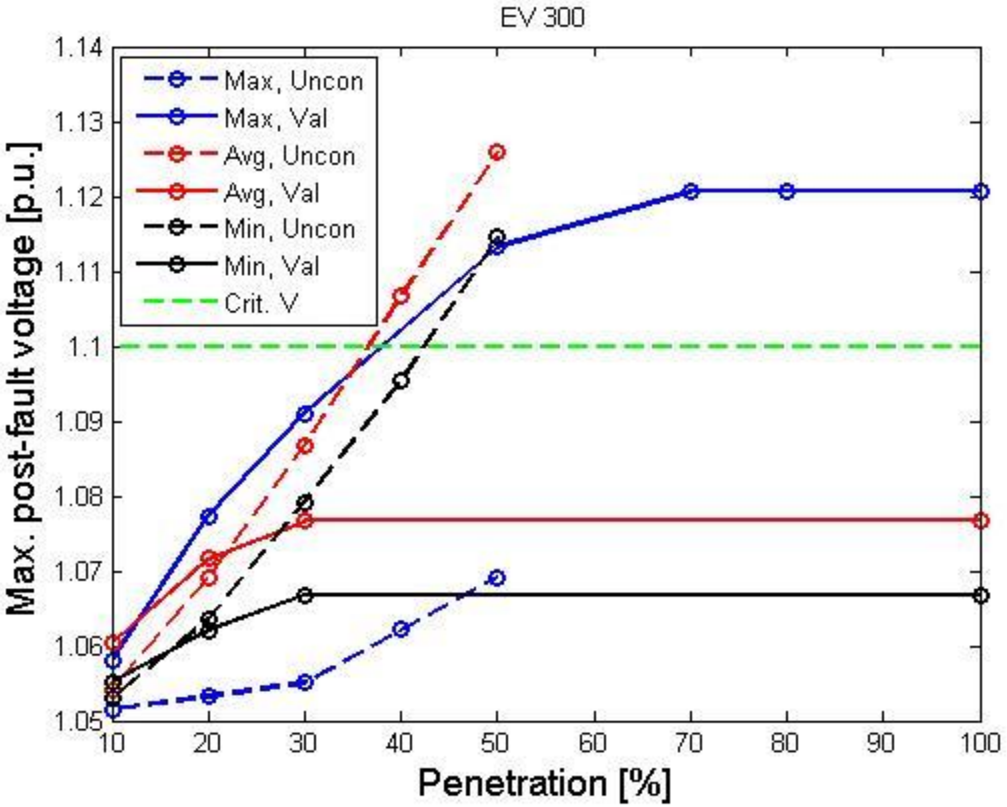


Voltage rise on IEEE-39 grid



Voltage rise on IEEE-34 feeder

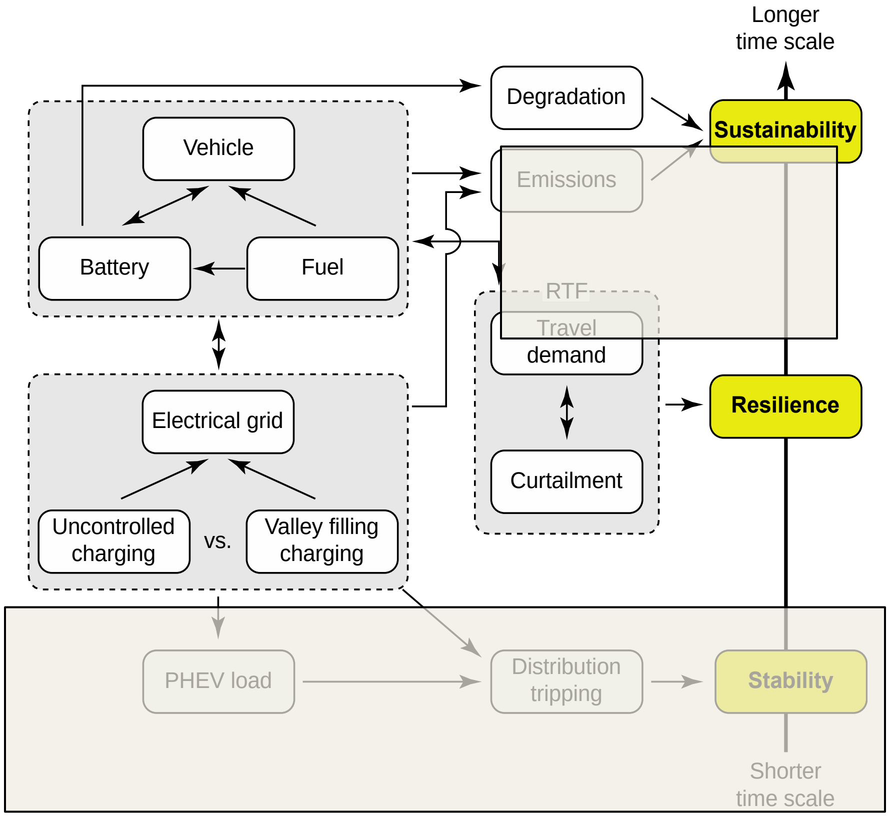
Case Study: Grid stability



- **Major finding:** Grid stability seems safe at low PHEV/EV penetration regardless of charging algorithm, but at high penetration an adaptive control algorithm should be investigated.

Case Study: Resilience

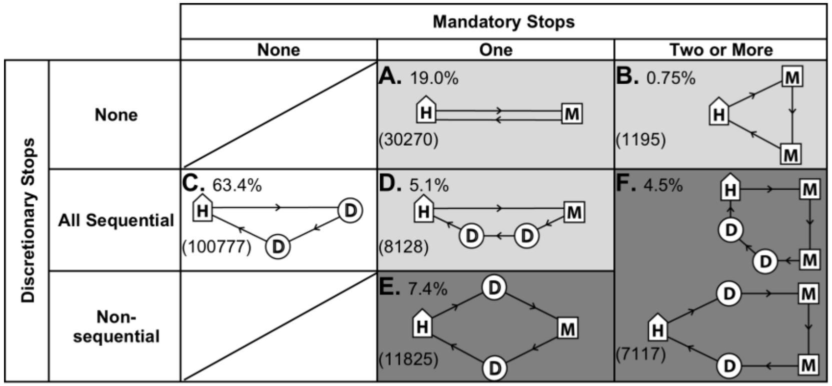
- Investigate the ability to fulfill travel demand
- Occurs at the daily to weekly timescale
- How many mandatory trips can be made during a gasoline outage that lasts several days

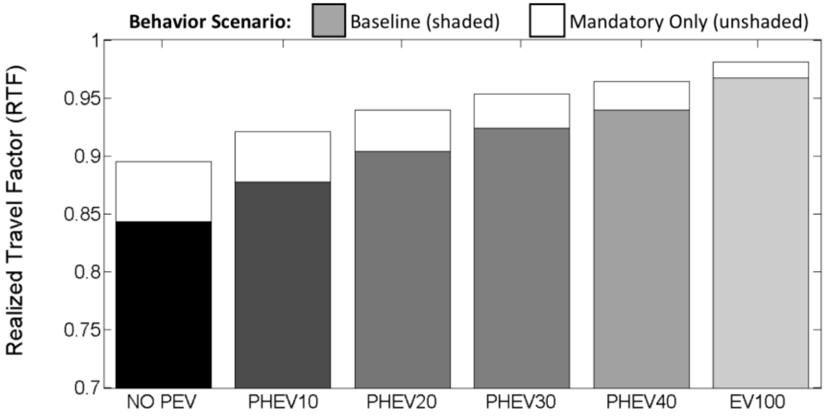


Case Study: Resilience

- Based on known trip information (NHTS) identify “mandatory” trips
- Curtail “discretionary” tours in events of massive disruption

Findings at household level

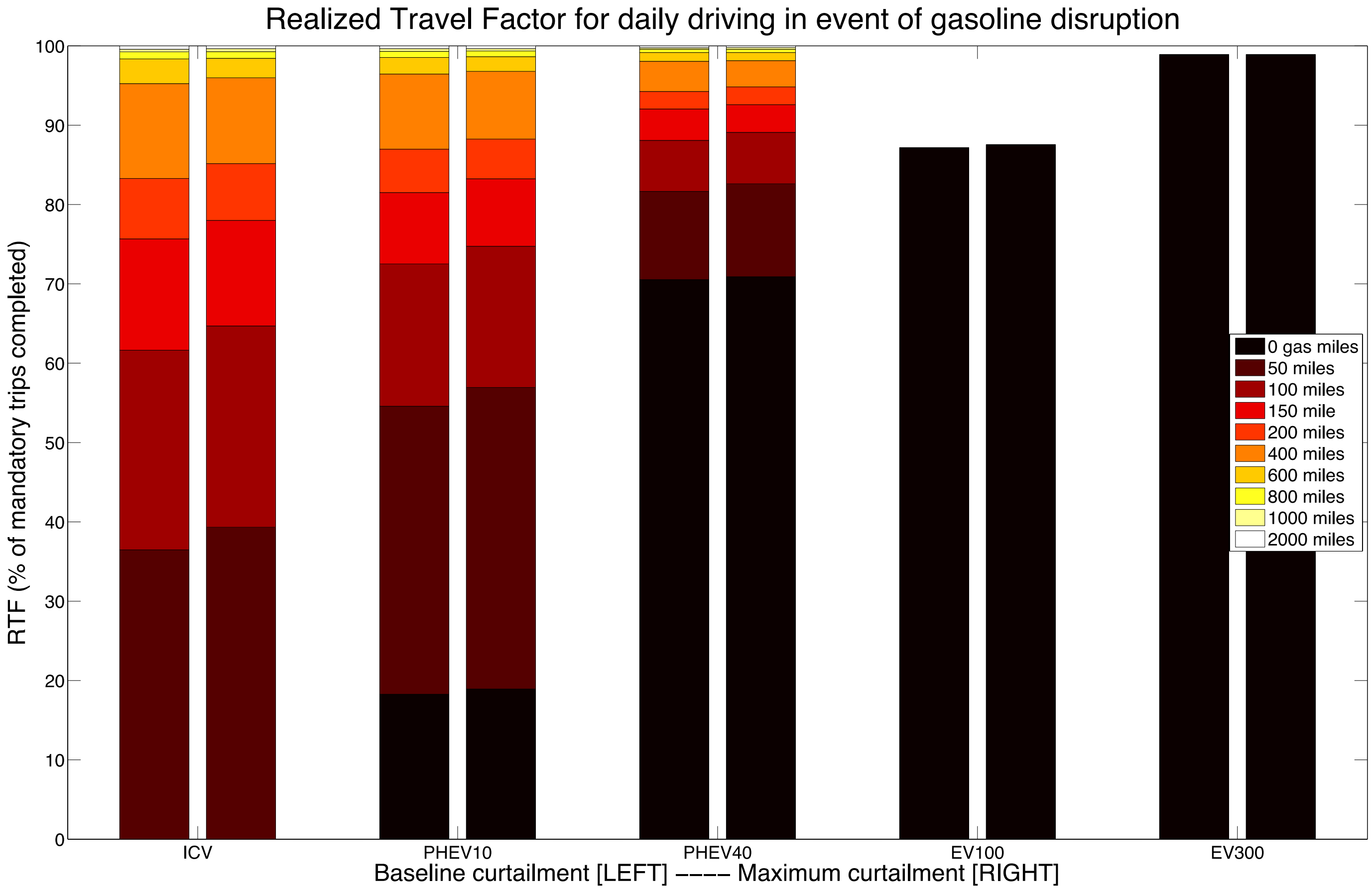




Case Study: Resilience

- Previous work based on household level, current study looks at vehicle level only
- Curtailment outlook strategies:
  - Take all trips as normal
  - Consider only current day
  - Consider full outage duration
- Includes charging algorithms
- Initial gasoline budget: 0-2000 miles
- PHEV penetration: 2 – 100 % of fleet

Case Study: Resilience

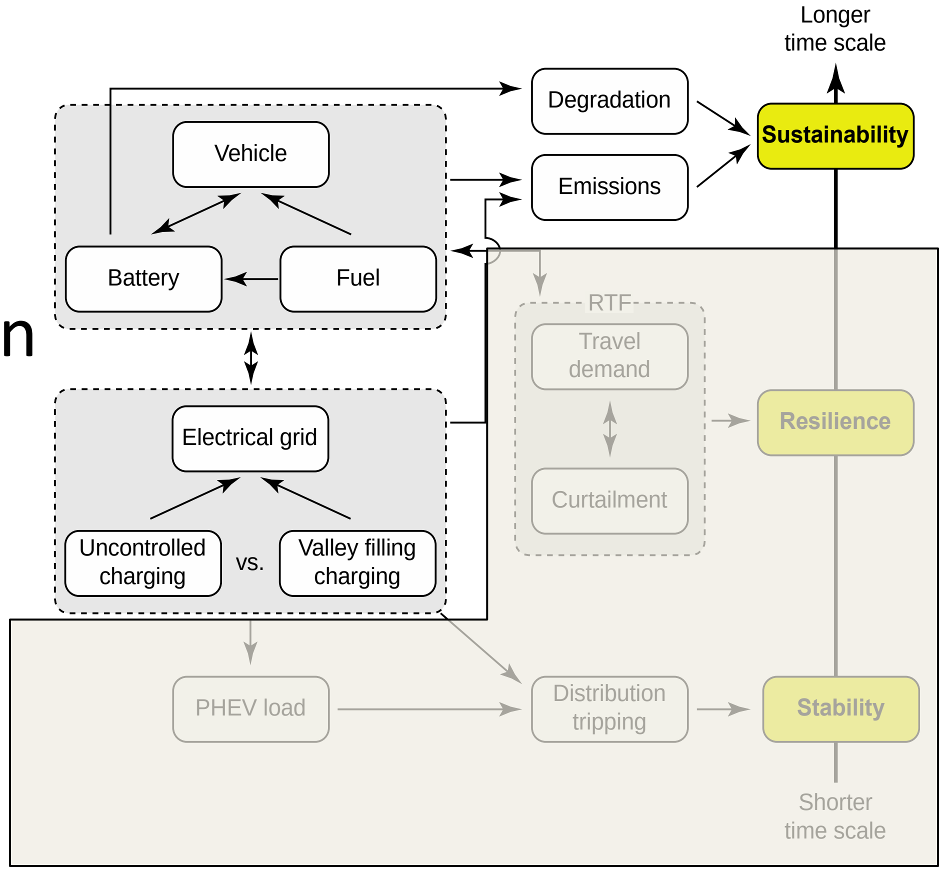


- **Major finding:** Technology provides greater increases in RTF than the behavior modifications considered in this study. Penetration level has little effect on RTF.

Case Study: Sustainability

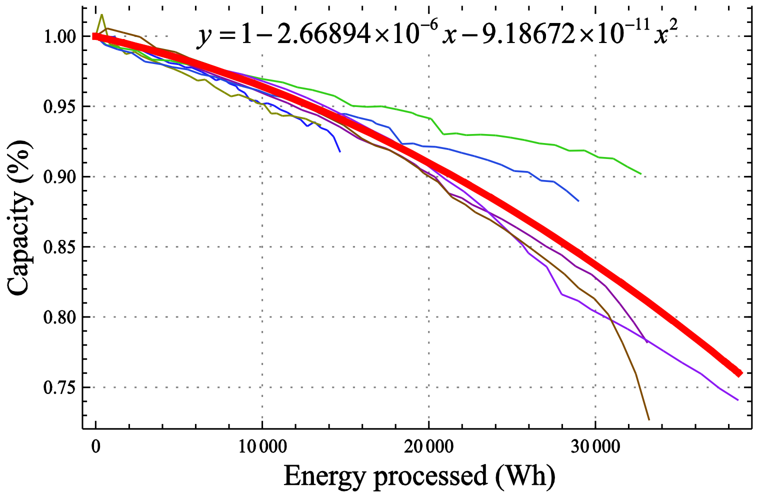
- Occurs over long timescale (vehicle lifetime)

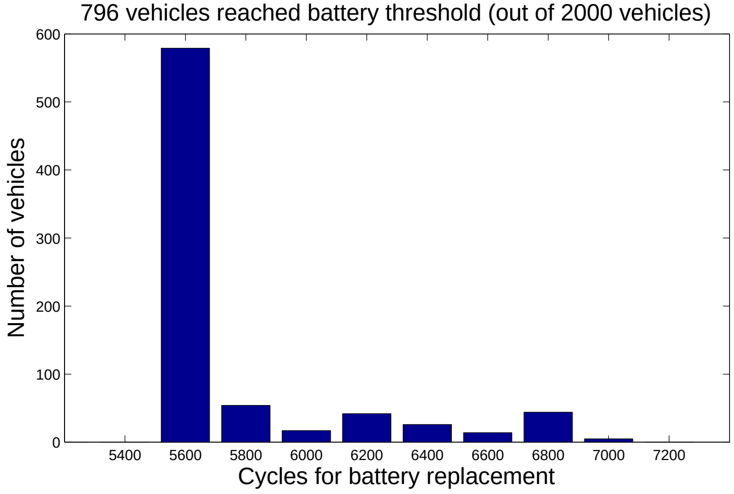
- Michigan grid profile
- Coal grid profile
- Natural gas profile
- Model battery degradation and replacement



Case Study: Sustainability

- Battery degradation modeled using lab test data
- Using NHTS data set, evaluate replacement profiles in PHEV10, PHEV40 and EV100
- 40% replacement in 5600 cycles (~8 years)
- Saturation effect due to battery daily capacity assumption

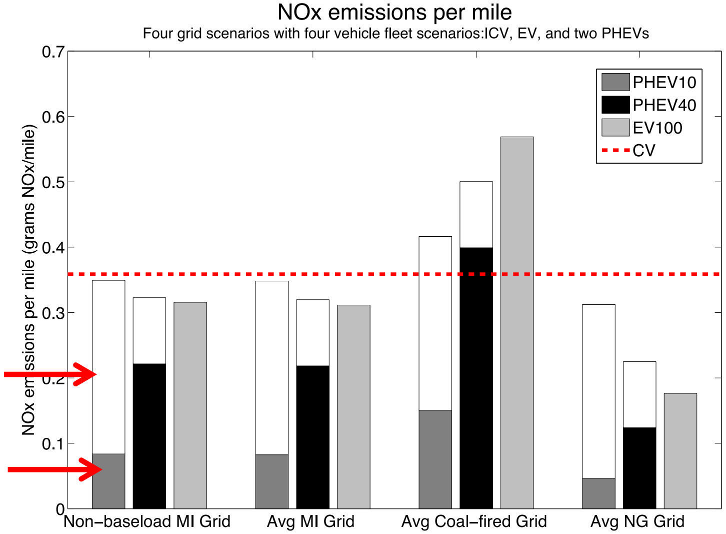




Case Study: Sustainability

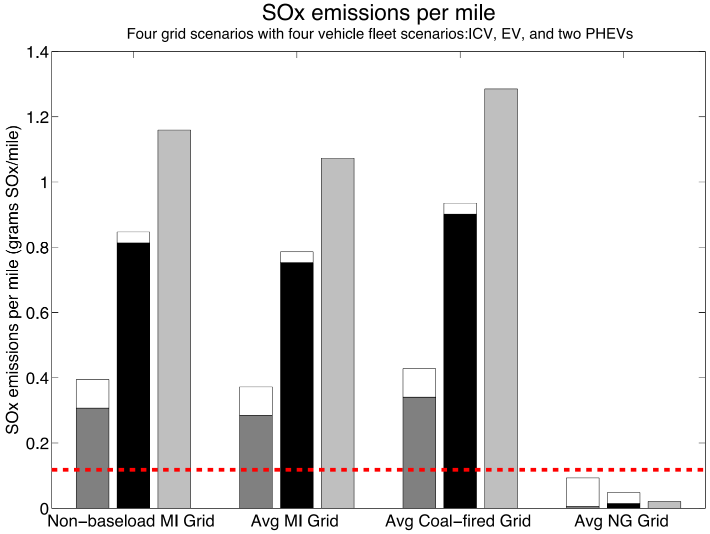
- Simulate vehicles over 2,000 different representative NHTS travel patterns
- Test over 10 years (7300 charge/discharge cycles)
- Use full vehicle life cycle assessment methodology
  - Includes: material extraction, manufacturing, operations and maintenance, and end of life
  - Use phase data obtained from EPA eGrid, upstream and end of life data from ANL GREET, and recent ANL battery life cycle study

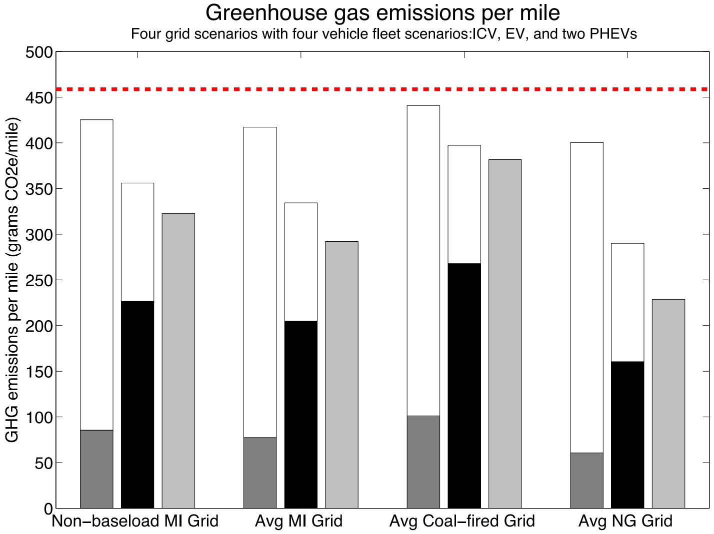
Case Study: Sustainability



Gasoline emissions

Electric emissions





- Major finding: Vehicle electrification reduces NO_x and GHG emissions, but increases SO_x (except in NG only grid), even with excepted battery replacement profiles. Coal heavy grid increases all emissions above ICV.

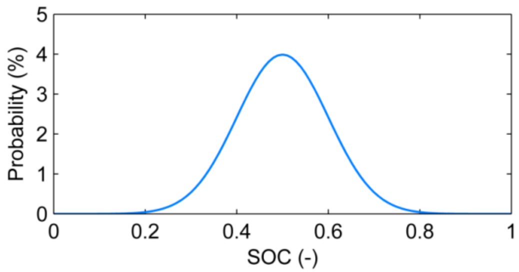
Conclusion

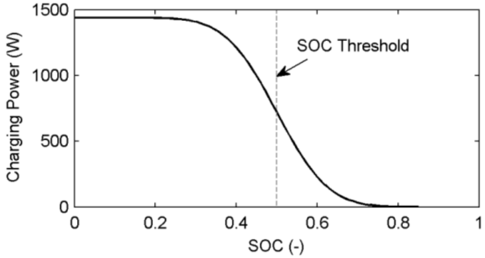
- Plug-in vehicles connect transportation and grid together and offer challenges/opportunities.
- PEV helps grid frequency regulation with no sacrifice of charging quality
- PEV also can also be used as ESS to mitigate wind intermittency—the required capacity is very small
- Finally, wind and PEV should be implemented together for synergy
- Significant sustainability and resilience effects—results depends on underlying assumptions

Appendix

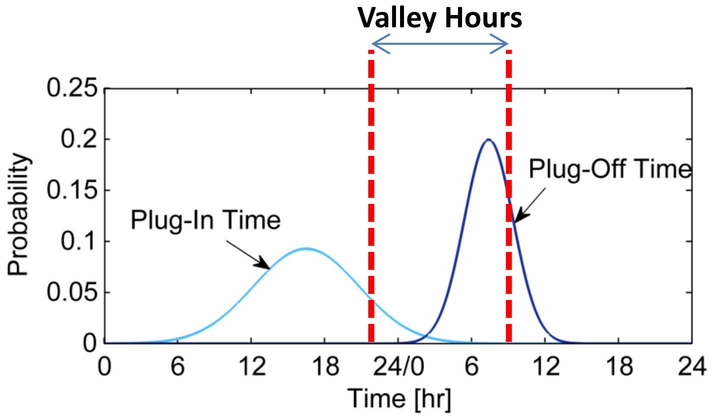
Details of Slide 11: Charging Control

1. Set a SOC threshold to control fundamental charging power





2. Scale it according to plug-off time and end of valley hour



$$\text{Scaling Factor} = \max\left\{ 1\ , \ \frac{T_{\text{end}} - T_{\text{start}}}{(\text{Plug-Off Time}) - T_{\text{start}}} \right\}$$

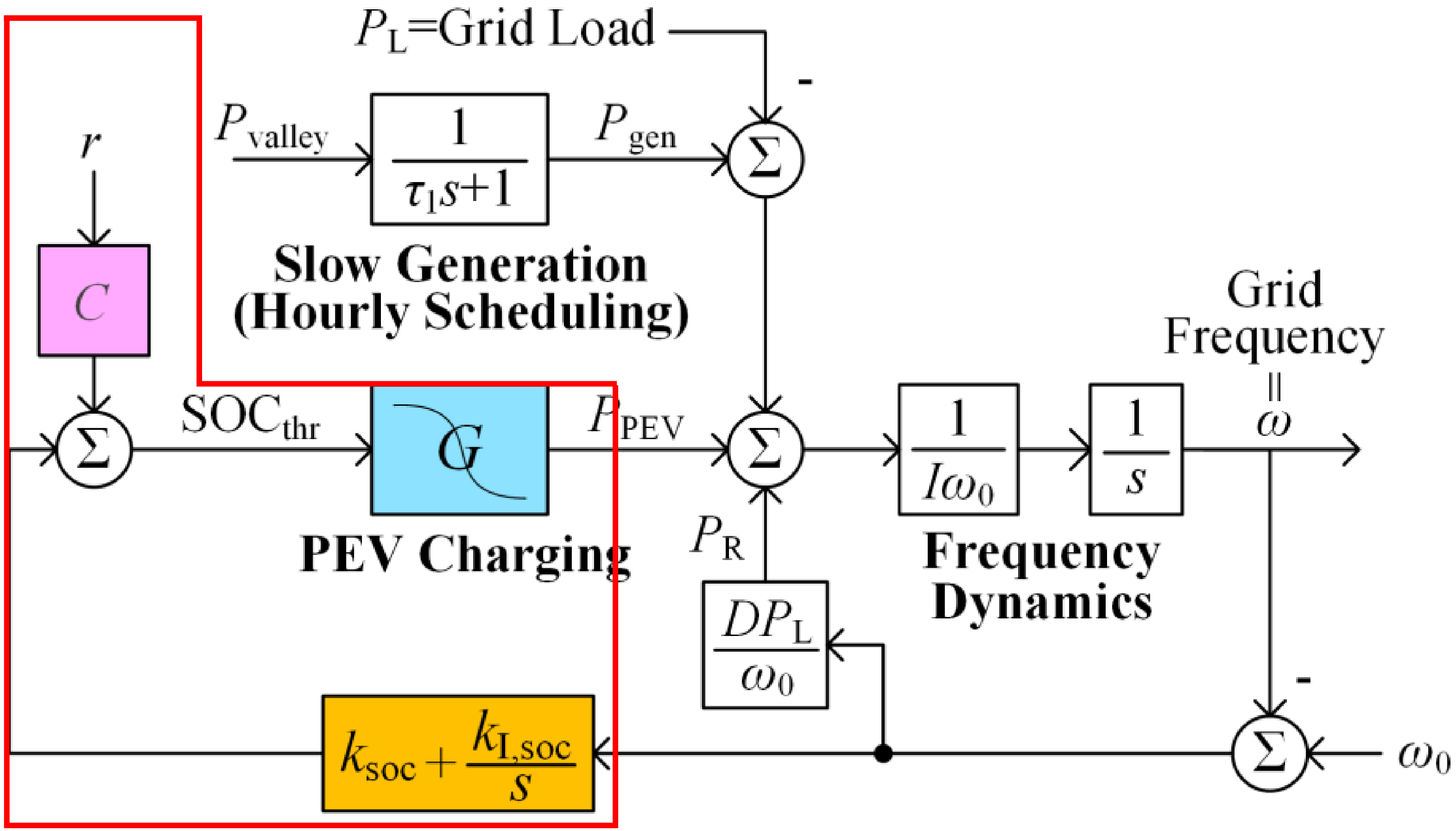
Charging Power = (Power Allocation) x (Scaling Factor)

3. Modify SOC threshold based on grid frequency

$$SOC_{\text{thr}} = SOC_{\text{thr,FF}} + [-k_{\text{soc}}(\omega - \omega_0) - k_{I,\text{soc}} \int (\omega - \omega_0) dt]$$

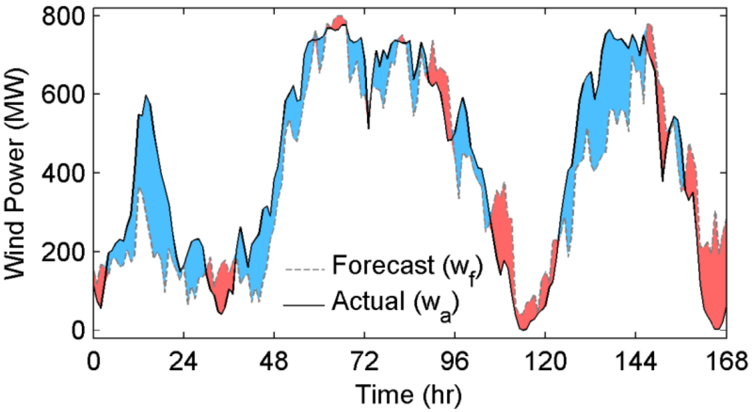
Details of Slide 11: Charging Control Final Form

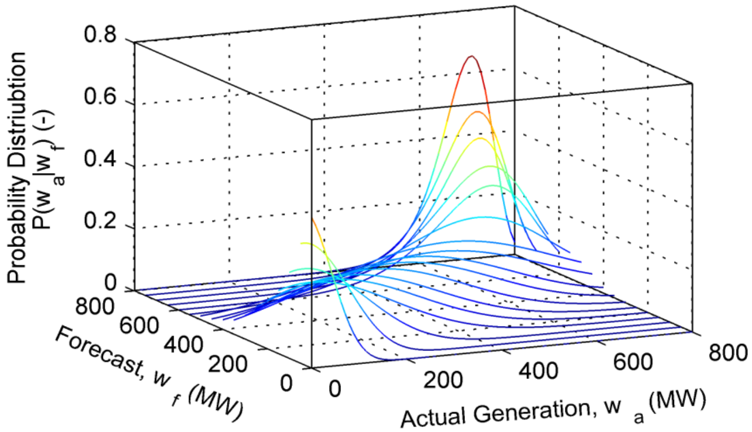
Return

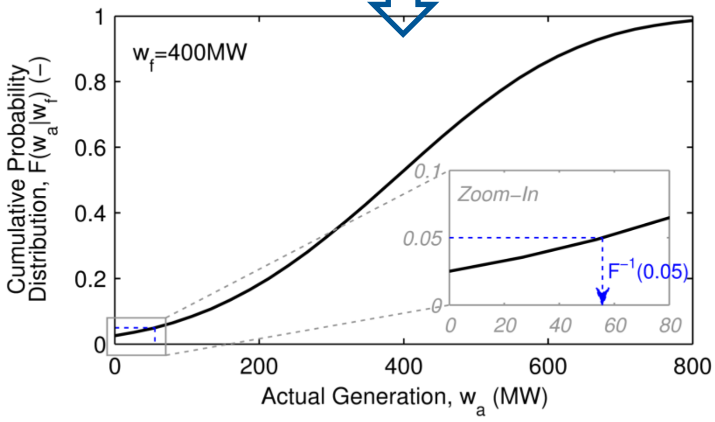


Wind Power Modeling

- Use PDF, $\mathbf{P}(w_{\mathrm{a}}|w_{\mathrm{f}})$ & CDF, $\mathbf{F}(w_{\mathrm{a}}|w_{\mathrm{f}})$ to quantify reserve requirements for wind







Reserve requirement:

$$R_{\mathrm{w,rqd}}(w_{\mathrm{f}},u)=[u-\mathbf{F}^{-1}(0.05)]^{+}$$

Expected wind deficit:

$$w_{\mathrm{d}}(w_{\mathrm{f}},u)=\mathbf{E}\{[u-w_{\mathrm{a}}]^{+}\}$$

(u: Scheduling of wind power)

Data source: National Renewable Energy Laboratory (NREL). Eastern Wind Dataset. http://www.nrel.gov/wind/integrationdatasets/eastern/methodology.html

Mitigate Wind Intermittency

Return

- To maximize profit for a wind farm owner:
  - With conventional reserves:

$$\min_{u} : J = \underbrace{-C_1 \cdot u}_{\text{Revenue (Sell } u \text{ units of wind power to the grid)}} + \underbrace{C_2 \cdot R_{\text{w,rqd}}}_{\text{Reserve Scheduling}} + \underbrace{C_3 \cdot w_{\text{d}}}_{\text{Expected Reserve Dispatch}}$$

u: Scheduling of wind power

Per unit price/cost: $C_1 = 1;\ C_2 = 1.03;\ C_3 = 1$

  - With battery energy storage & MPC:

$$\min_{\boldsymbol{u}} : J_k = \sum_{t=k}^{k+N-1} \Big[\underbrace{-C_1 \cdot u(t)}_{\text{Revenue}} + \underbrace{C_2 \cdot R_{\text{s}}(t)}_{\text{Reserve Scheduling}} + \underbrace{C_3 \cdot R_{\text{d}}(t)}_{\text{Expected Reserve Dispatch}}\Big] + C_N \cdot (x(k+N) - x_{\text{ref}})^2$$

$\boldsymbol{u}$: Scheduling of wind power

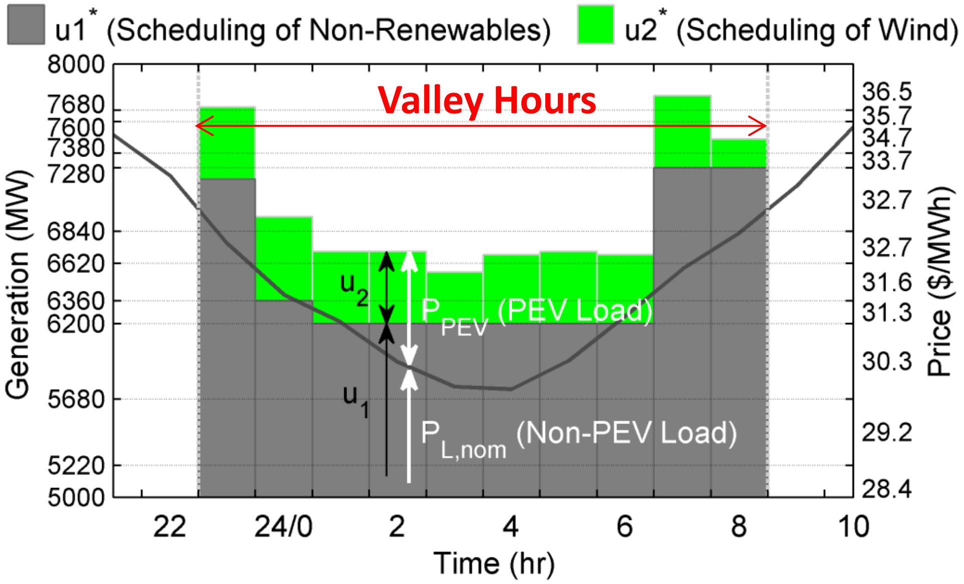
x: Battery state of charge

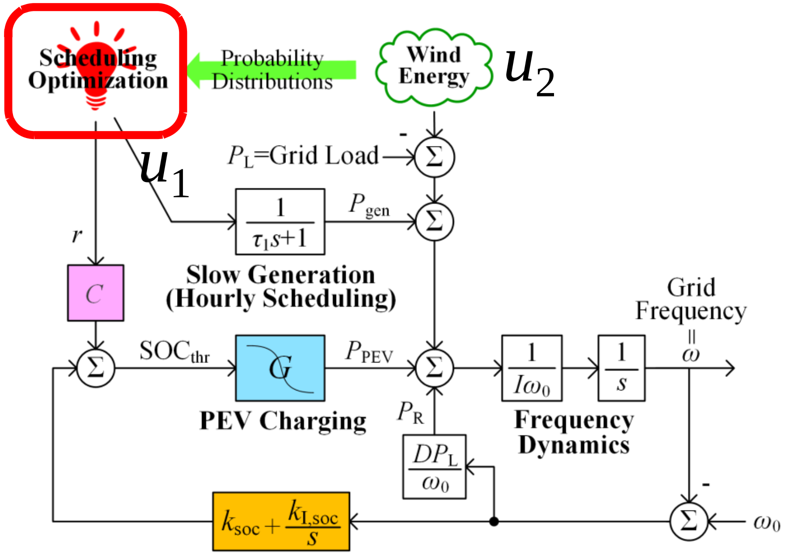
$$R_{\text{s}} = [R_{\text{w,rqd}} - P_{\text{dis,lmt}}]^+$$

$$R_{\text{d}} = [w_{\text{d}} - P_{\text{dis,lmt}}]^+$$

Integrate PEV Charging & Wind Scheduling

- 2 million PEVs & an 800 MW wind farm on the Michigan grid:
- Optimal generation scheduling:





Integrate PEV Charging & Wind Scheduling

- 2 million PEVs & an 800 MW wind farm on the Michigan grid: **Return**
  - Fully charge most PEVs
  - Use cheap generation capacities as much as possible
  - Grid frequency regulation