# Emissions from Electric Vehicle Charging in the U.S.


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Vehicle Electrification Group


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# Emissions Accounting Depends on Question

**"What emissions are EVs responsible for?"**

- Allocation question
- Value judgment

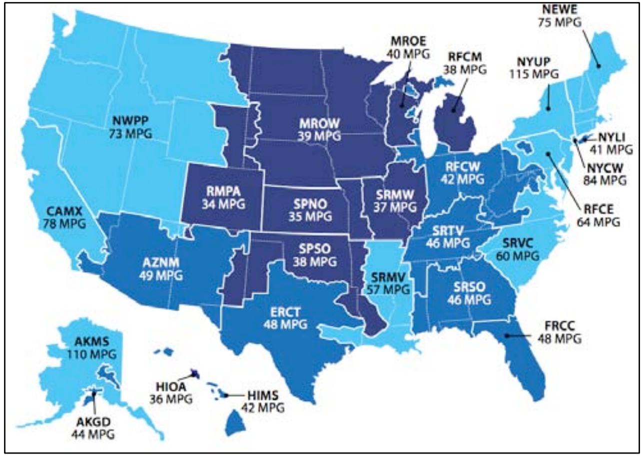
**"What are the emissions implications of EV adoption?"**

- Consequential question
- Need to know how the grid will change in response to new EV load

# Emissions Accounting Depends on Question

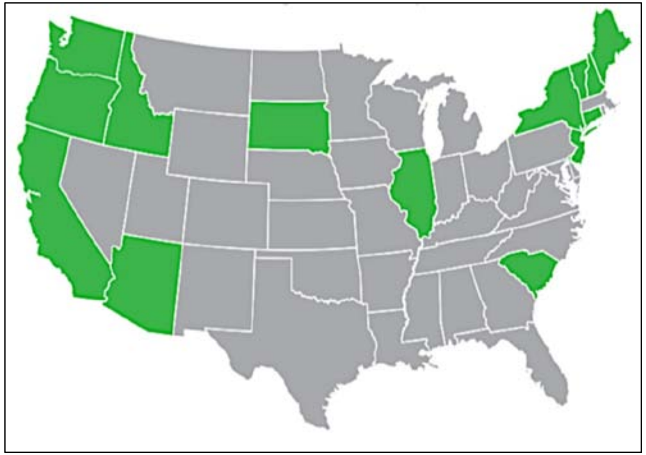
- Past studies used regional average generation emissions rates
- Easy, but doesn't assess emissions implications of EV adoption
  - Also depends on regional boundaries used

**Union of Concerned Scientists**




**Dark:** EV comparable to 31-40 mpg
**Medium:** EV comparable to 41-50 mpg
**Light:** EV comparable to 51+ mpg

**Climate Central**



**Green:** Nissan Leaf is lower emitting
**Gray:** Toyota Prius is lower emitting

# Two Approaches to Estimate Grid Response

## Top down

- **Empirical** marginal emission factors estimated via regression on past data
  - Graff Zivin et al. (2014), Siler-Evans et al. (2012)
- **Pros:**
  - Represents real power plant operation in practice
- **Cons:**
  - Historical only
  - For marginal load changes only
  - Correlation ≠ causality

## Bottom up

- **Normative** grid operations modeled as cost minimization using constrained optimization
- **Pros:**
  - Can model future scenarios
  - Can assess large load changes
- **Cons:**
  - Limited scalability – unable to model full interconnection (missing trade)
  - Unable to model all possible considerations that affect dispatch in practice

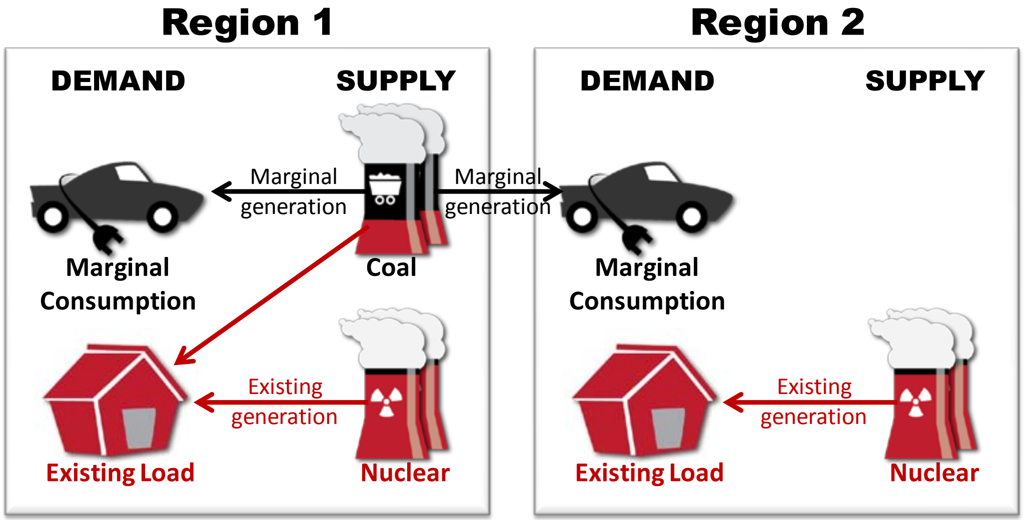
# Top Down Approach

Tamayao, M., J.J. Michalek, C. Hendrickson and I. Azevedo (2015) "Regional variability and uncertainty of electric vehicle life cycle $CO_2$ emissions across the United States," *Environmental Science and Technology*, in press.
Tamayao, M., T. Yuksel, I. Azevedo, C. Hendrickson and J.J. Michalek (2015) "Electric vehicle life cycle greenhouse gas emissions vary across the United States due to electric power grid emissions, driving patterns, and climate," working paper.

# Two Variants in Literature

## 1. Marginal Consumption

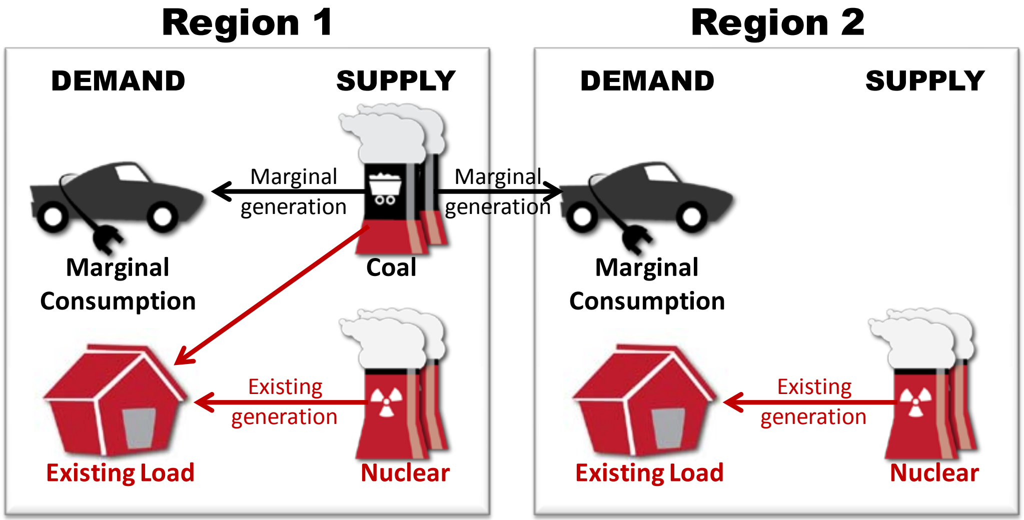
- Graff Zivin et al. (2014) regress interconnect emissions on NERC region consumption
  - Correct conceptually, but correlation vs. causality a significant source of error
  - Esp. for hydro, wind, etc.



# Two Variants in Literature

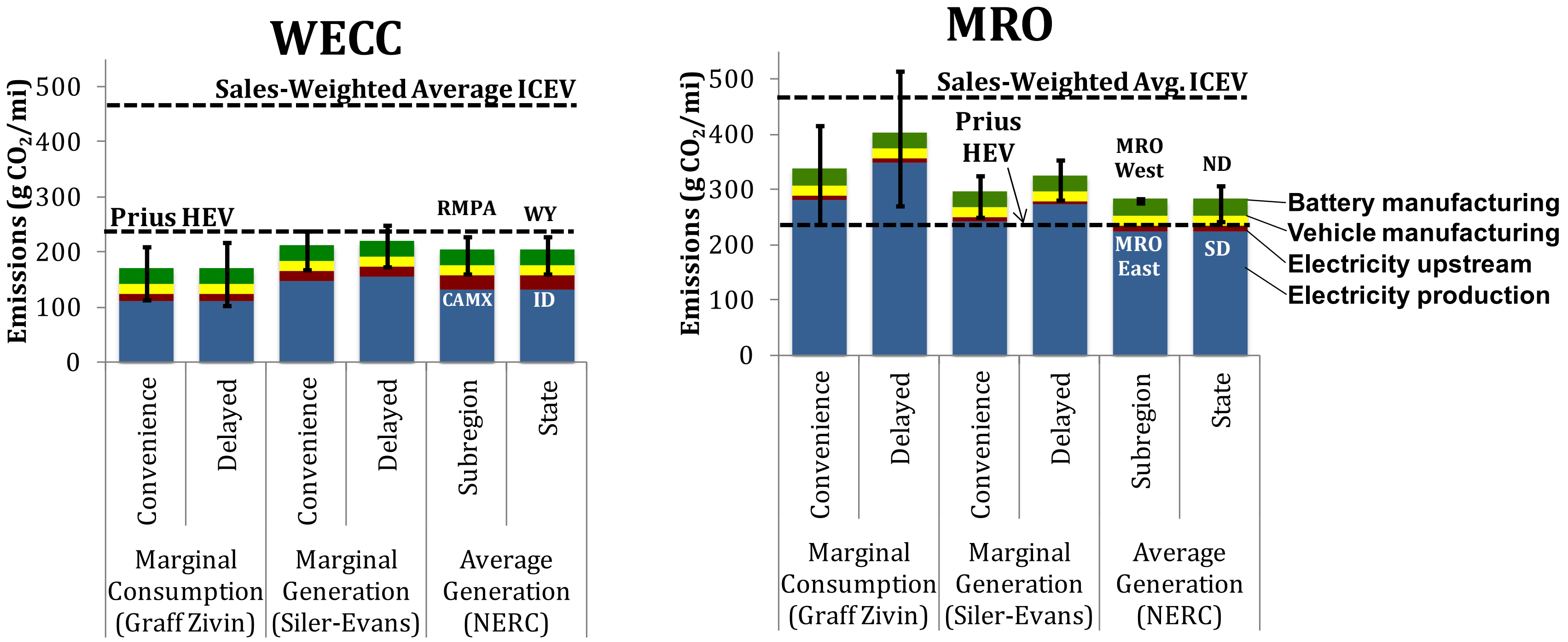
## 2. Marginal Generation

- Siler-Evans et al. (2012) regress change in fossil fuel generators vs. change in load for each NERC region
  - Mitigates correlation/causality issue but misses interregional trade and regionally varying efficiency



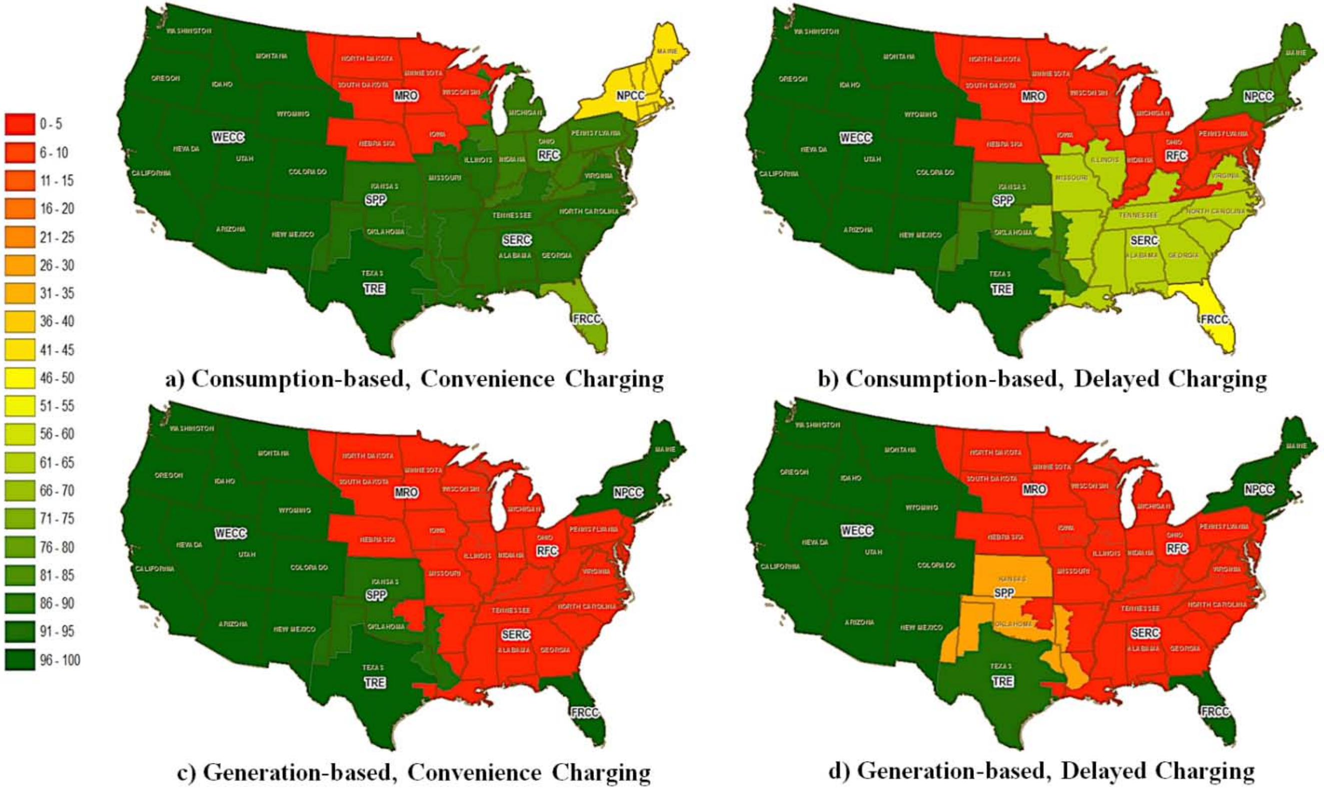
# Comparison

- Nissan Leaf GHG emissions using different grid emission factors



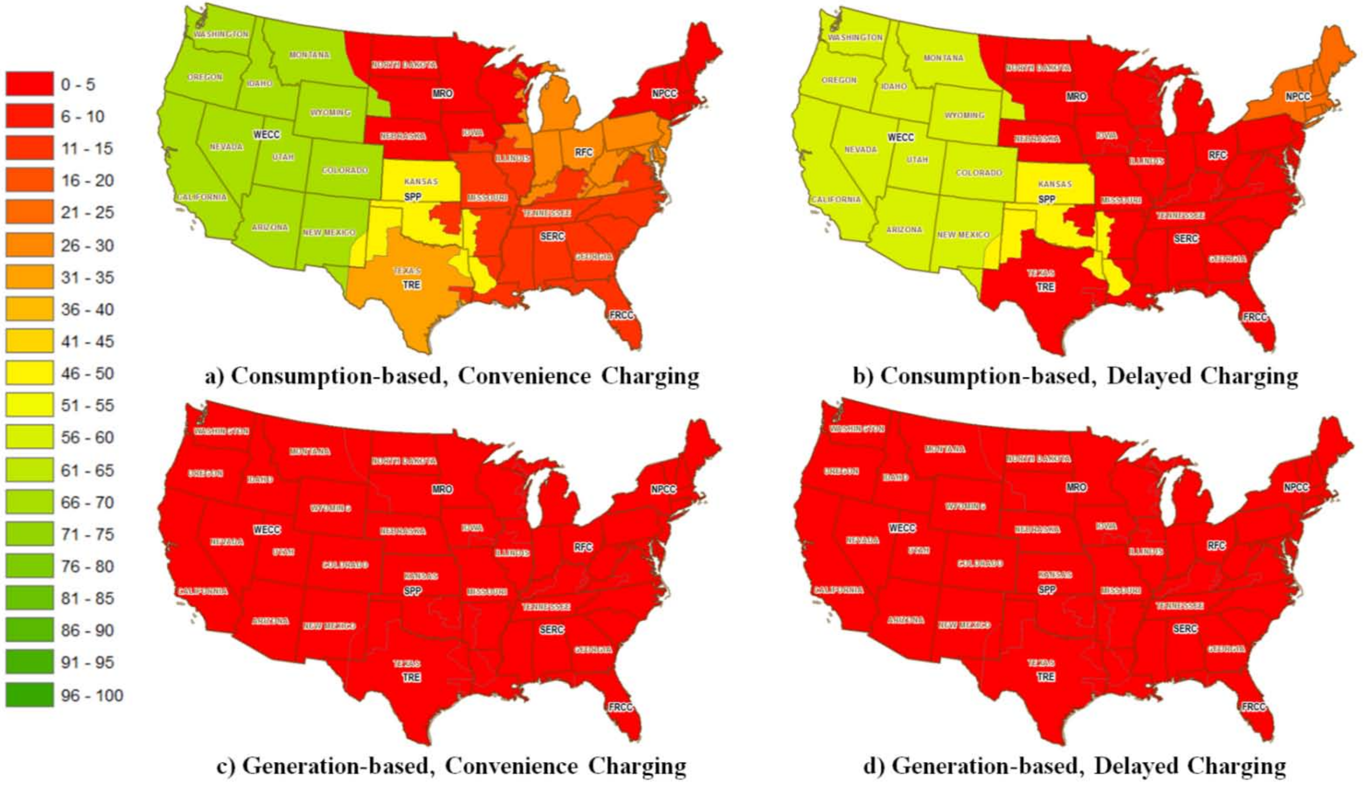
# Robustness

- Probability that a **Nissan Leaf** BEV is lower GHG emitting than a **Toyota Prius** HEV



# Robustness

- Probability that a **Chevy Volt** PHEV is lower GHG emitting than a **Toyota Prius** HEV




a) Consumption-based, Convenience Charging

b) Consumption-based, Delayed Charging

c) Generation-based, Convenience Charging

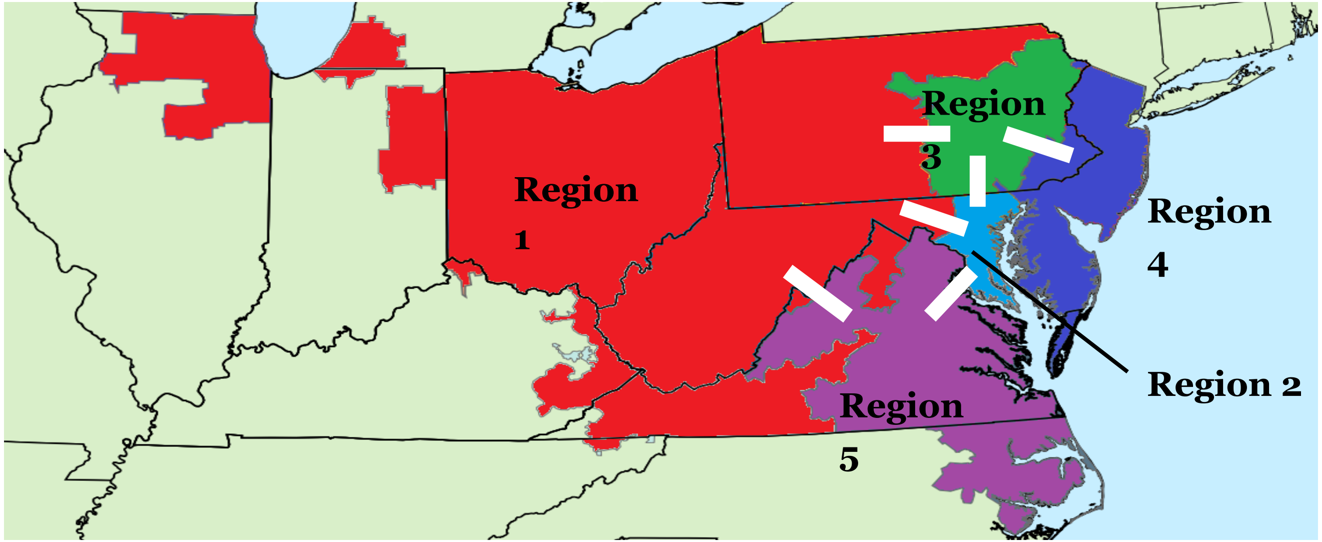
d) Generation-based, Delayed Charging

# Bottom Up

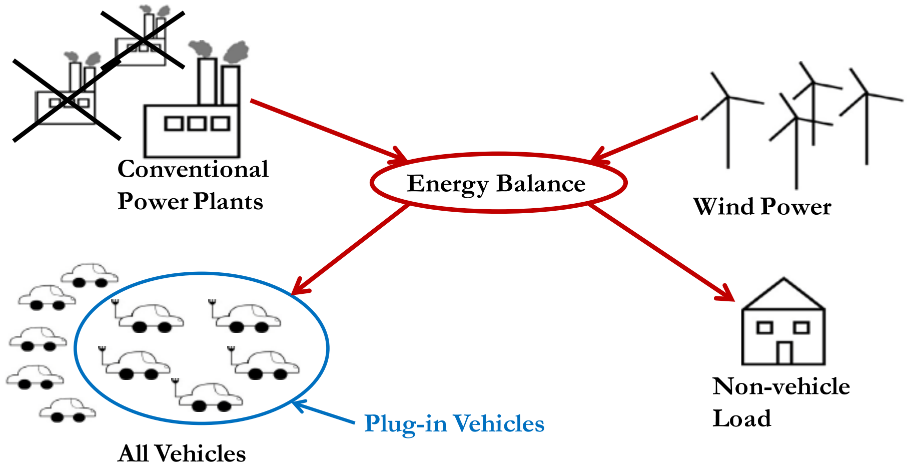
Weis, A., P. Jaramillo and J.J. Michalek (2014) “Estimating the potential of controlled plug-in hybrid electric vehicle charging to reduce operational and capacity expansion costs for electric power systems with high wind penetration,” Applied Energy v115 p190-204.
Weis, A., P. Jaramillo and J.J. Michalek (2015) "Life cycle implications of plug-in electric vehicles in the PJM interconnection," working paper.

# Power System: PJM

- 2010 PJM power plants and 2010 fuel prices
- 5 transmission regions with power limited connections



# System Overview




- Estimate monetized air emission damages via
  - AP2
  - EASIUR
  - Social cost of carbon

- Optimize system to minimize cost subject to system constraints

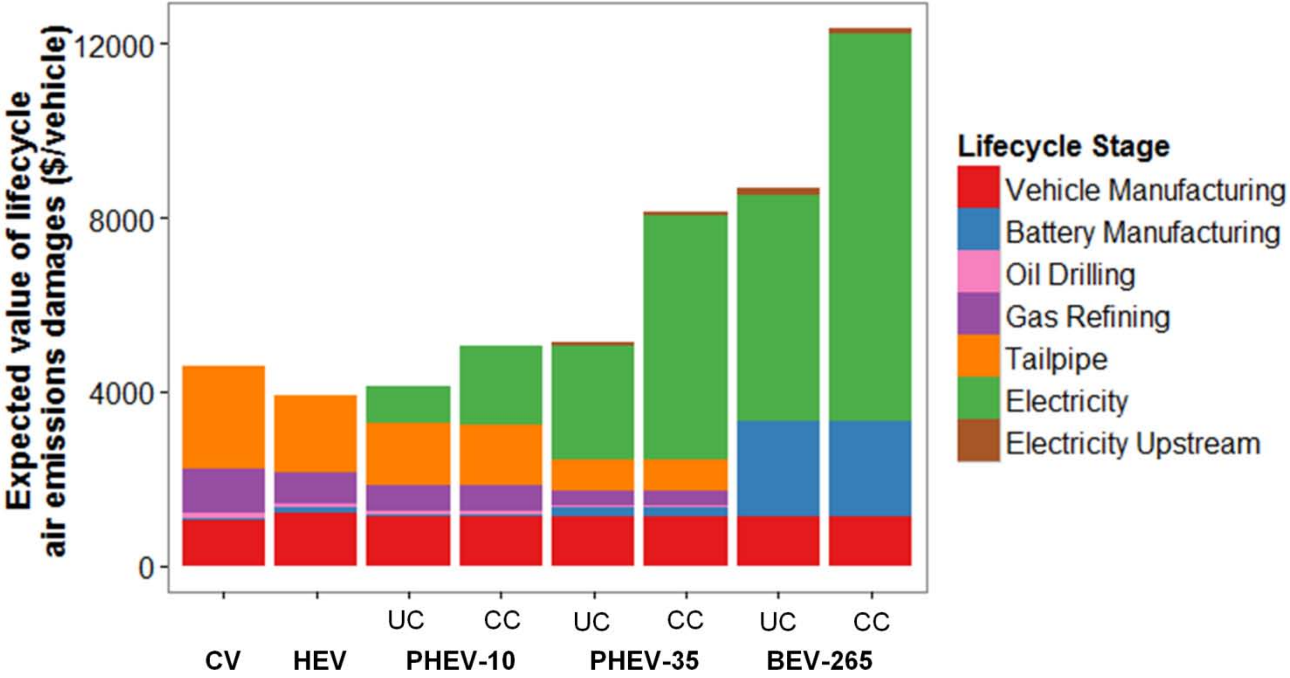
$$\text{minimize} \sum_{\text{time}} \sum_{\text{plants}} \left(\text{Fuel Costs} + \text{Startup Costs} + \text{Shutdown Costs}\right)$$

subject to:

- Generation = Load
- Spinning and non-spinning reserves
- Power plant constraints
  - Minimum and maximum generations levels
  - Ramp-rate limits
  - Minimum runtime and downtime
- Vehicle battery charging
  - Battery state of charge
  - Charge rate limits
- Transmissions constraints

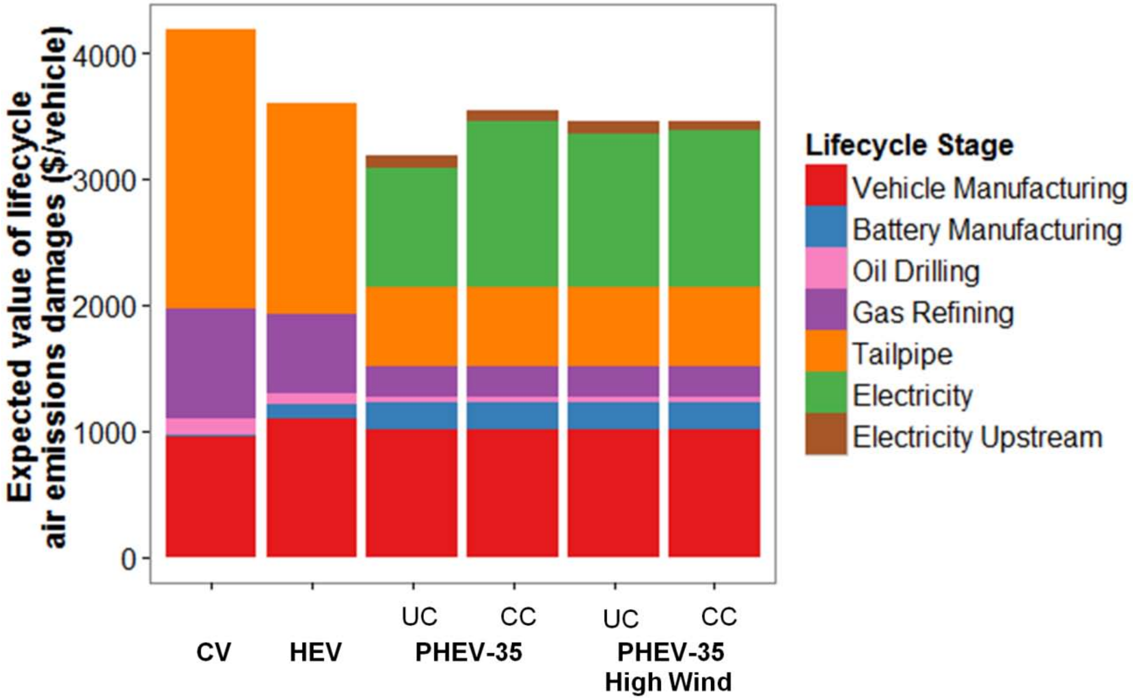
# Recent Grid (2010)

- Most recent year for which all needed data are available
- EVs cause more damage



# Future Grid (2018)

- Using EPA plant retirement predictions
- EVs marginally better than HEVs

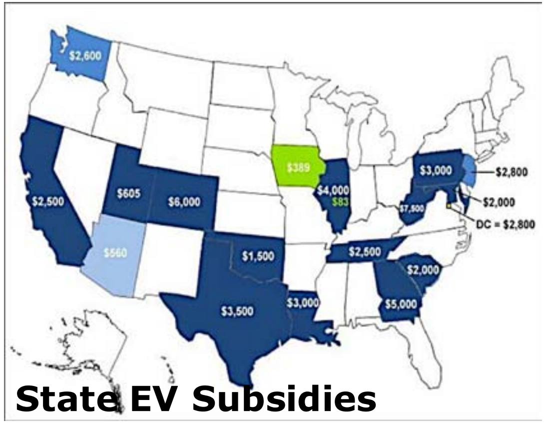


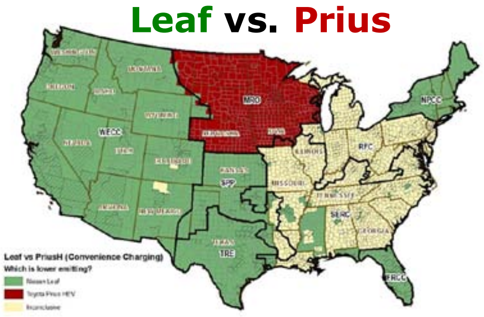
# Policy Implications

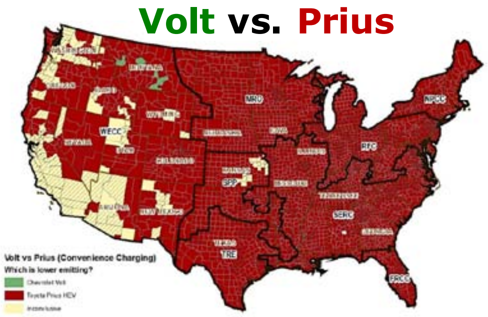
# Policy Implications

- ZEV (177) states are in areas where the Leaf has lower GHGs than the Prius, but the Volt does not.
- State EV subsidies are partially misaligned with regions where EVs are best.
- Grid improves over time, but effect on marginal emission factors is nonlinear.

**Regional Policy vs. GHG Benefits**

# Policy Implications

- Electric vehicles highly subsidized through federal and state incentives, but PJM air emission benefits remain small (or negative) through 2018
- Long term benefits of a transition might justify higher subsidies now (Greene et al.).
- But is PJM the best place for subsidies (or ZEV)?


**Current State Incentives in PJM (Source: EERE)**

# Acknowledgements


## Funding by:

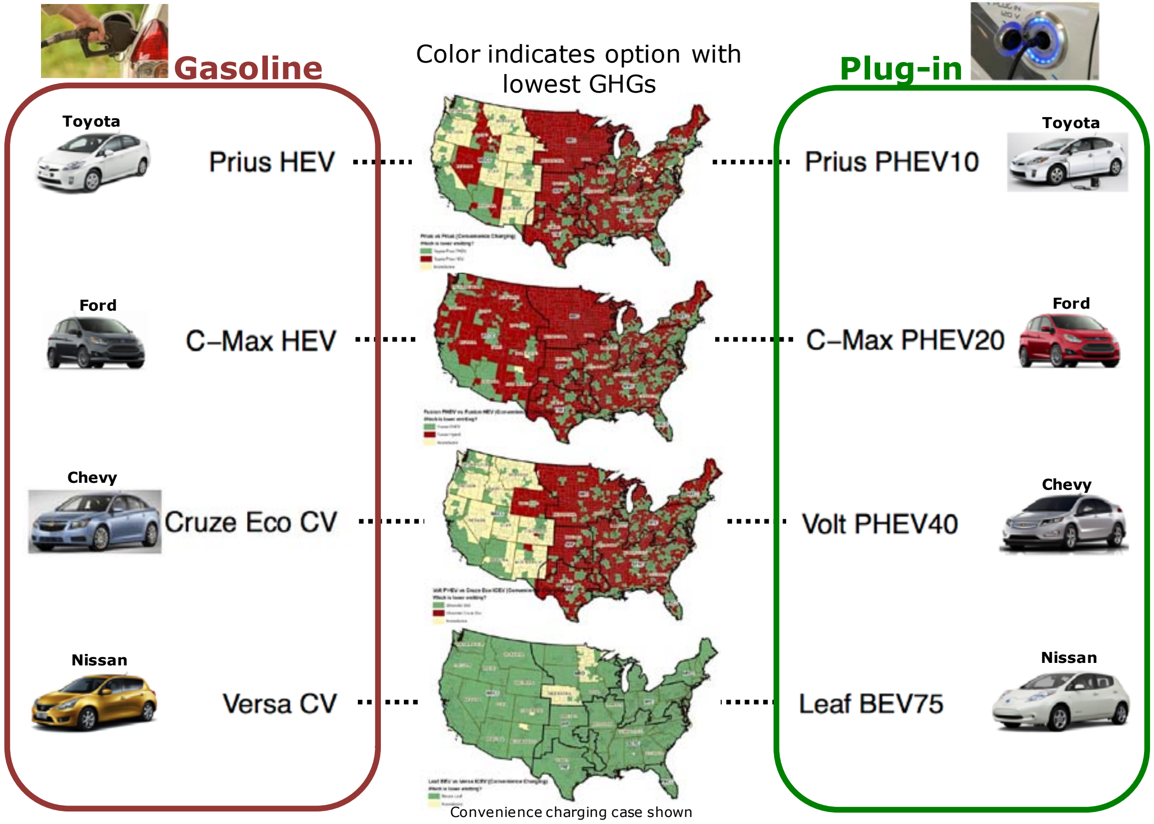
- Center for Climate and Energy Decision-Making
- Carnegie Mellon Electricity Industry Center through the RenewElec project
- Doris Duke Charitable Foundation
- Richard King Mellon Foundation
- Electric Power Research Institute
- Heinz Endowment
- National Science Foundation CAREER Award #0747911
- Toyota Motor Corporation
- National Science Foundation Graduate Research Fellowship Program
- Engineering Research and Development for Technology Scholarship Program at the University of the Philippines

# Backup

# Driving Conditions Also Matter

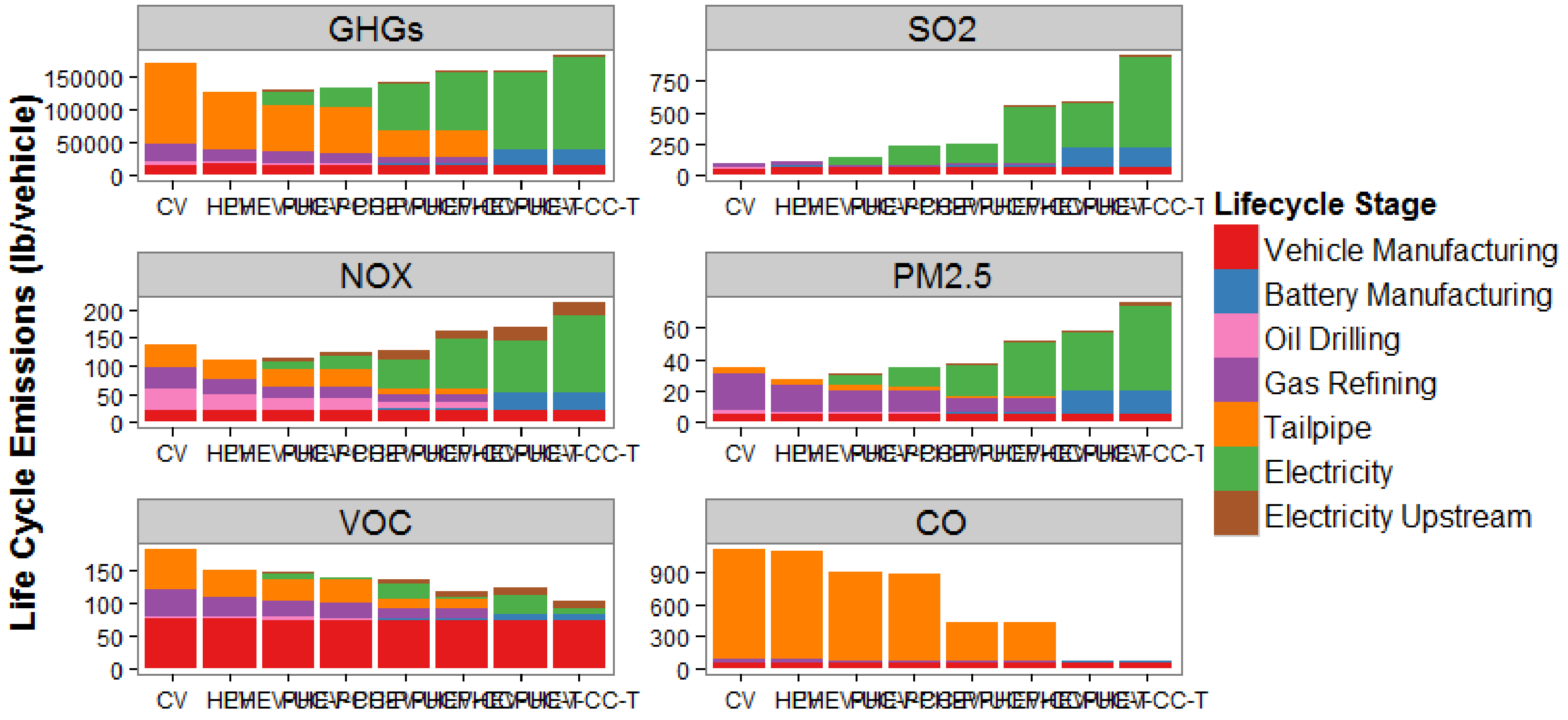
- Comparison of PEVs to their gasoline counterparts
- **Urban counties:** city test
- **Rural counties:** highway test
- **Suburban counties:** blend

## Adding Urban/Rural Drive Cycles by County

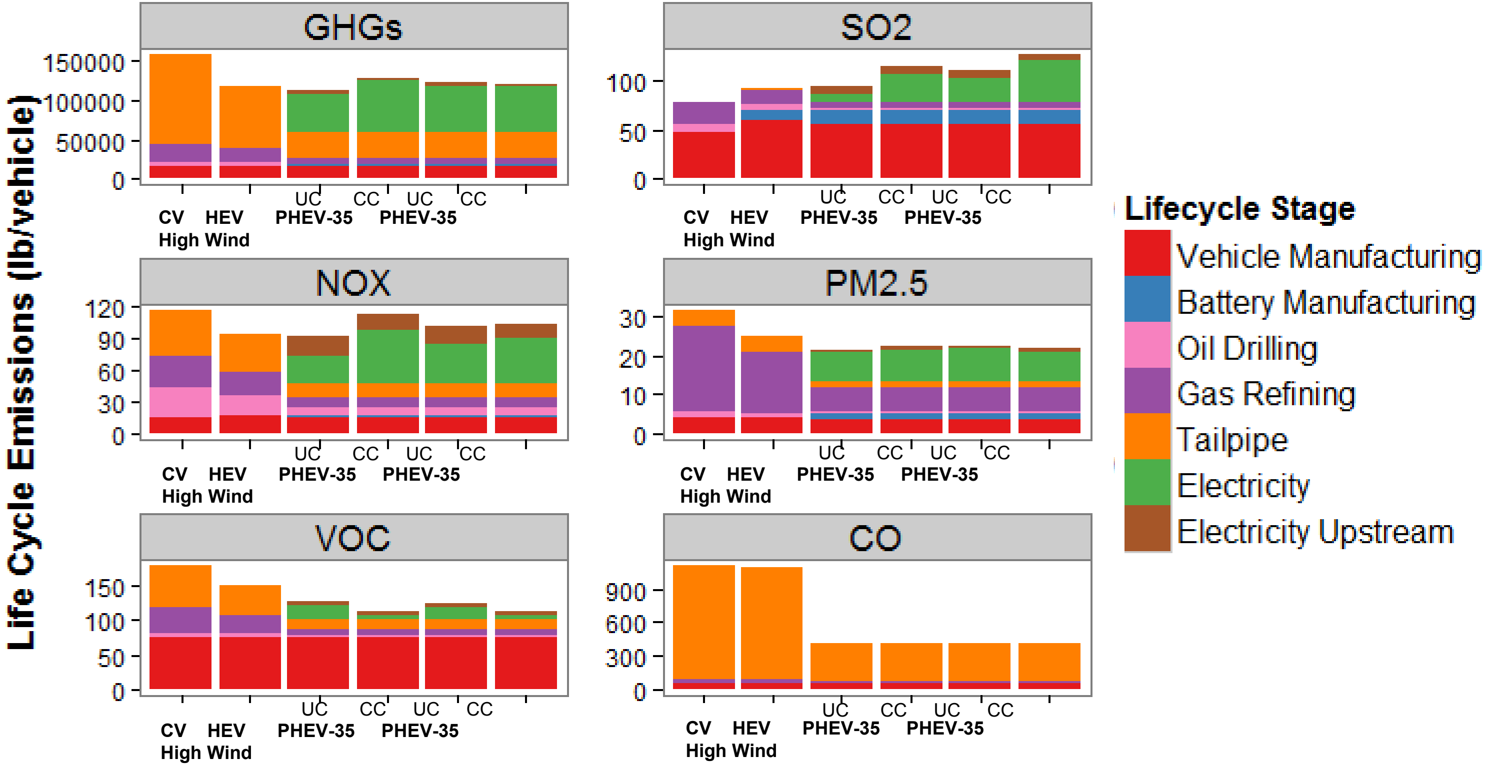



**Yellow = Inconclusive (different estimates disagree)**

# Recent Grid (2010)



# Future Grid



Life Cycle Emissions (lb/vehicle)
GHGs
150000
100000
50000
0
SO2
100
50
0
NOX
120
90
60
30
0
PM2.5
30
20
10
0
VOC
150
100
50
0
CO
900
600
300
0
UC
CC
UC
CC
CV
HEV
PHEV-35
PHEV-35
High Wind
Lifecycle Stage
Vehicle Manufacturing
Battery Manufacturing
Oil Drilling
Gas Refining
Tailpipe
Electricity
Electricity Upstream

# EVs Costly Now, Might Save a Little in Future

| PJM Scenario | Charging | Probability Damages Are Larger than for HEV's | Mean Change in Life cycle Damages Compared to HEV's |
|---|---|---|---|
| CV – Recent Grid | | 100% | $650 |
| PHEV-10 – Recent Grid | Uncontrolled | 81% | $210 |
| | Controlled | 98% | $1100 |
| PHEV-35 – Recent Grid | Uncontrolled | 95% | $1200 |
| | Controlled | 99% | $4200 |
| BEV-265 – Recent Grid | Uncontrolled | 99% | $4800 |
| | Controlled | 99% | $8400 |
| CV –Future Grid | | 99% | $580 |
| PHEV-35 – Future Grid | Uncontrolled | 4% | -$420 |
| | Controlled | 28% | -$60 |
| PHEV-35 – Future Grid with High Wind | Uncontrolled | 17% | -$150 |
| | Controlled | 18% | -$150 |