Upstream Emissions from Electric Vehicle Charging

Carnegie Mellon
Vehicle Electrification Group

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CMU Vehicle Electrification Group

- Founded in 2009
- **Research areas:**

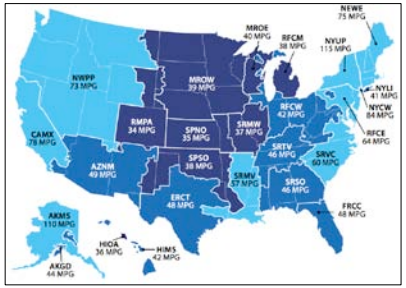
1. **Technology:** Vehicle, battery, and electric power systems, design, control and optimization
2. **Life-cycle:** economic, environmental, and energy security implications
3. **Consumer behavior:** technology adoption and driver behavior
4. **Public policy:** policy-relevant technical findings and policy analysis

Emissions Accounting Depends on Question

"What emissions are PEVs responsible for?"

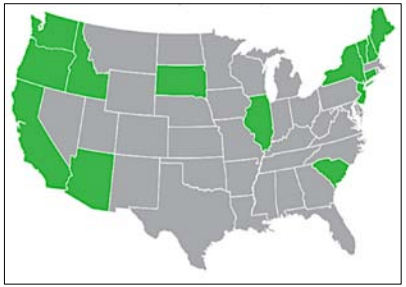
- Allocation question
- Requires a value judgment
- Different allocations yield different implications

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

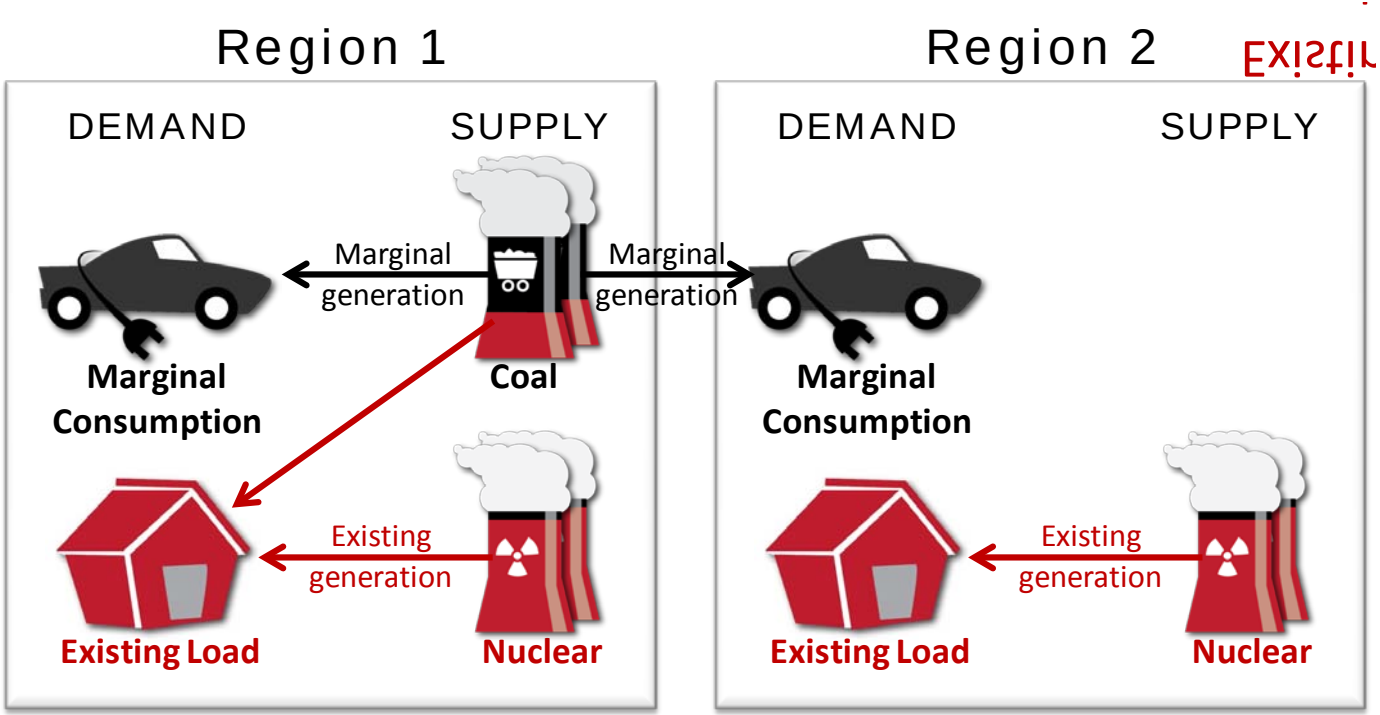


Green: Nissan Leaf is lower emitting
Gray: Toyota Prius is lower emitting

"What are the emissions implications of PEV adoption?"

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

Consequential Effects ≠ Avg. Generation



Two Approaches to Consequential Estimation

Empirical

- Marginal emission factors estimated via regression on past data
- **Pros:**
  - Represents real power plant operation in practice
- **Cons:**
  - Historical only
  - For marginal load changes only
  - Correlation ≠ causality

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

Empirical Approach

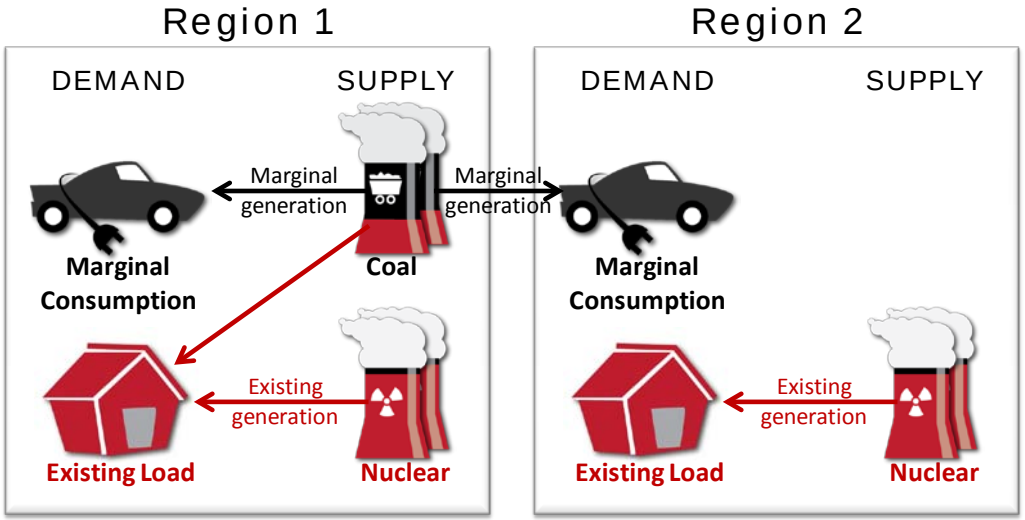
Tamayao, M., J.J. Michalek, C. Hendrickson and I. Azevedo (2015) "Regional variability and uncertainty of electric vehicle life cycle CO2 emissions across the United States," *Environmental Science and Technology*, 49 (14) p8844-8855.

Tamayao, M., T. Yuksel, I. Azevedo, C. Hendrickson and J.J. Michalek (2015) "Effect of regional grid mix, driving patterns and climate on the comparative carbon footprint of electric and gasoline vehicles," working paper.

Two Variants in Literature

1. Marginal Consumption

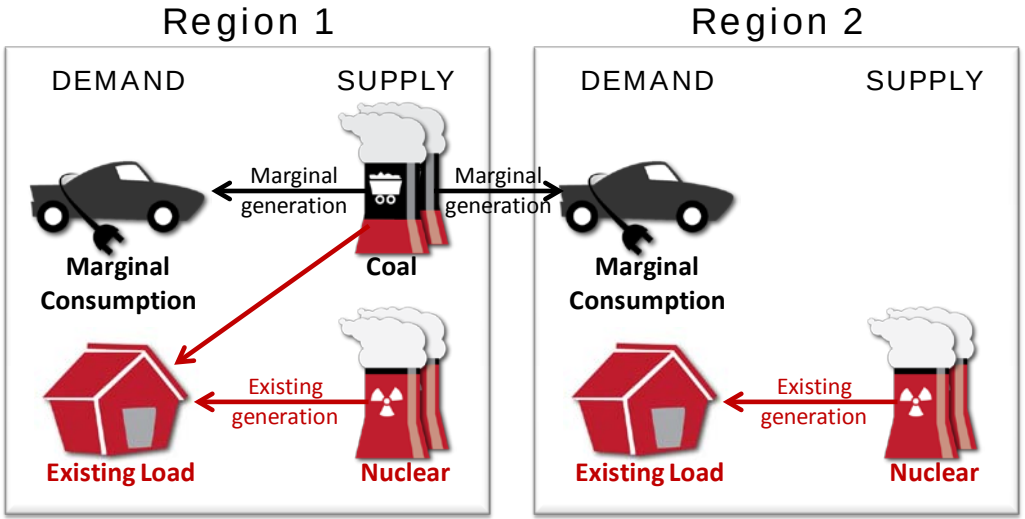
- Graff Zivin et al. (2014) regress interconnect emissions on NERC region consumption
  - Correct conceptually, but correlation vs. causality a significant source of error
  - Esp. for hydro, wind, etc.



Two Variants in Literature

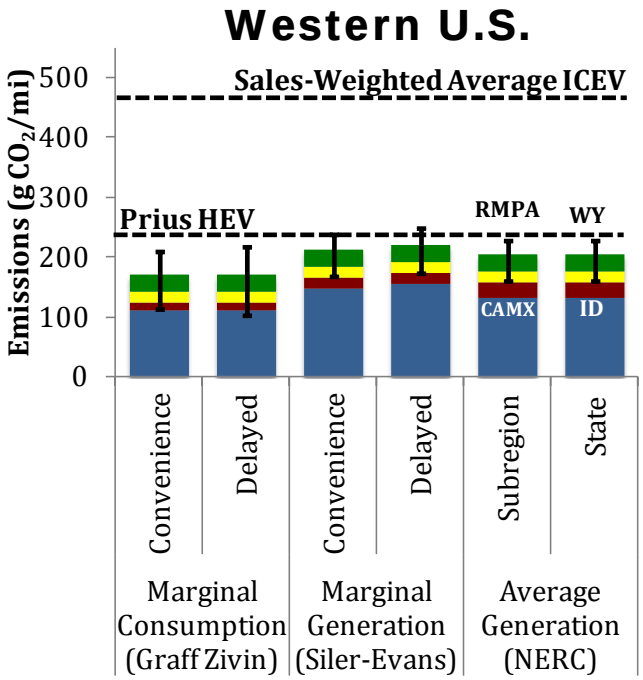
2. Marginal Generation

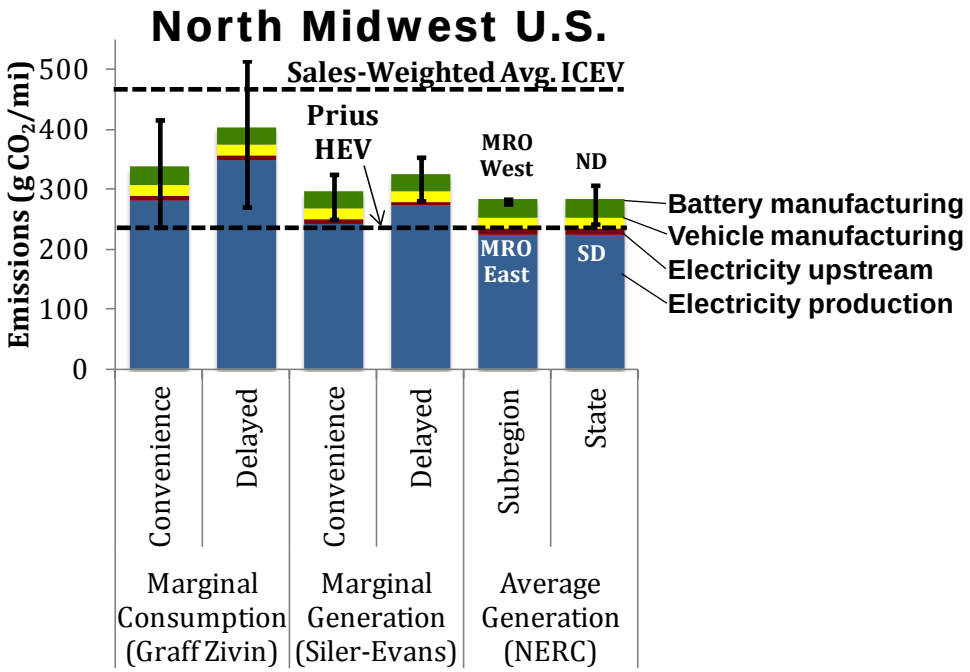
- Siler-Evans et al. (2012) regress change in fossil fuel generators vs. change in load for each NERC region
  - Mitigates correlation/causality issue but misses interregional trade and regionally varying efficiency



Comparison

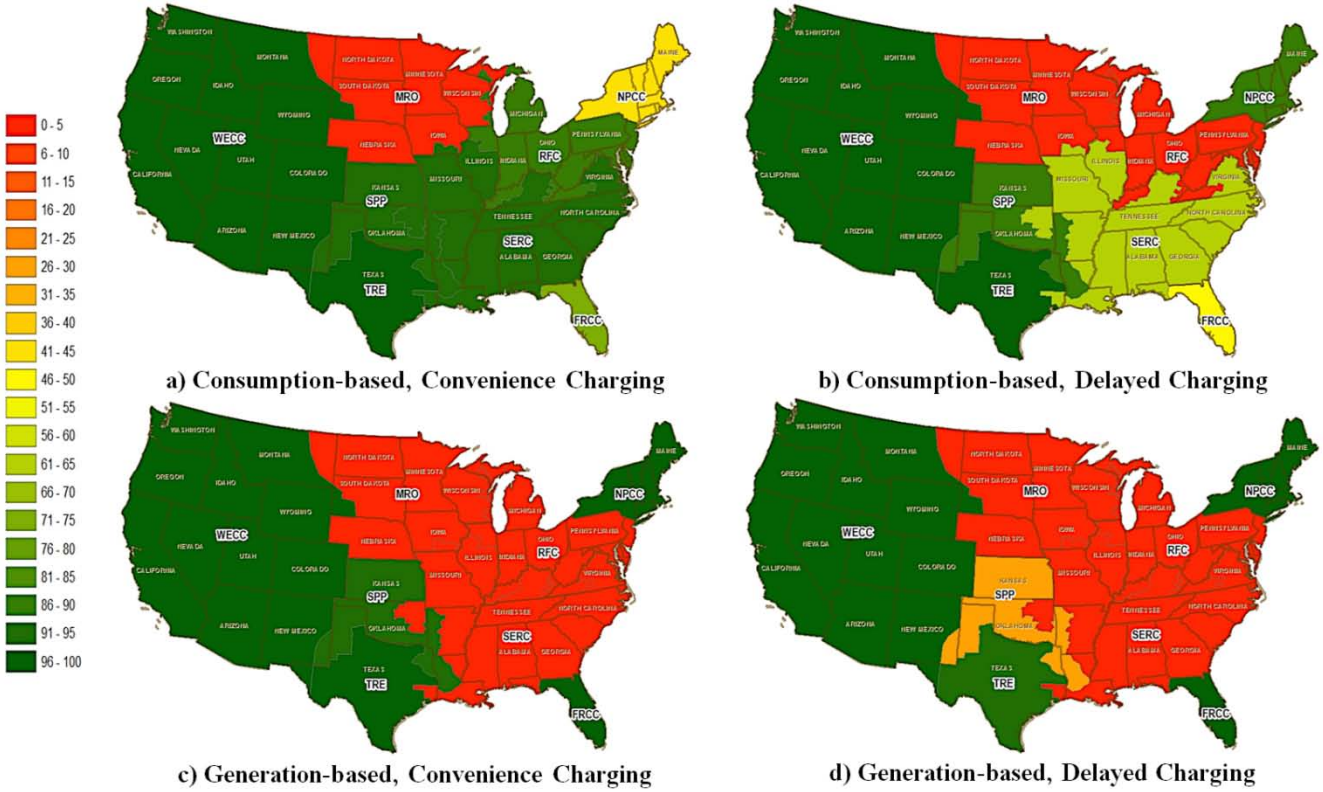
- Nissan Leaf GHG emissions using different grid emission factors





Leaf Wins in West & Texas, Prius in North

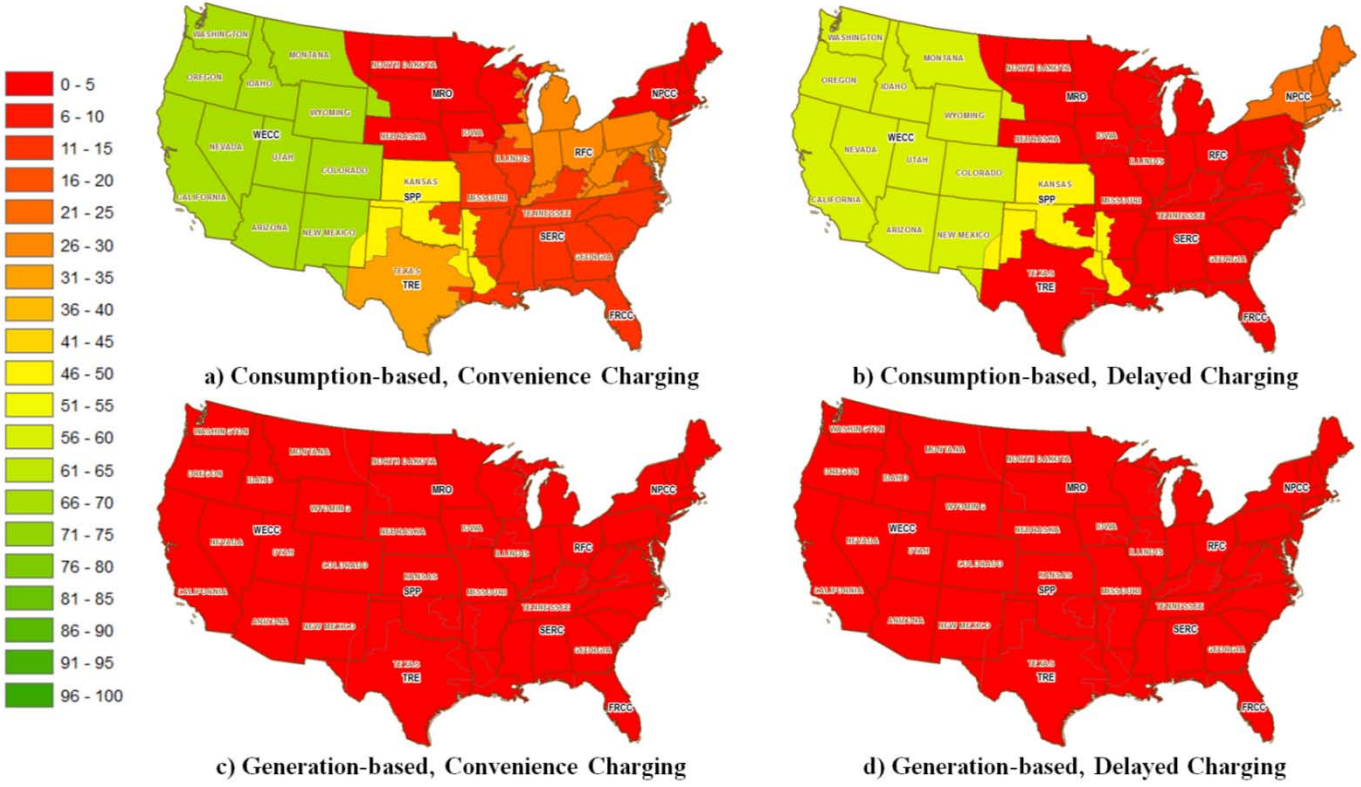
- Probability that a **Nissan Leaf** BEV is lower GHG emitting than a **Toyota Prius** HEV



Estimated using EPA test vehicle efficiency and distribution of marginal emissions estimates produced by regresssions in Graff Zivin et al., Siler-Evans et al.

Prius Beats Volt Overall, Uncertain in West

- 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

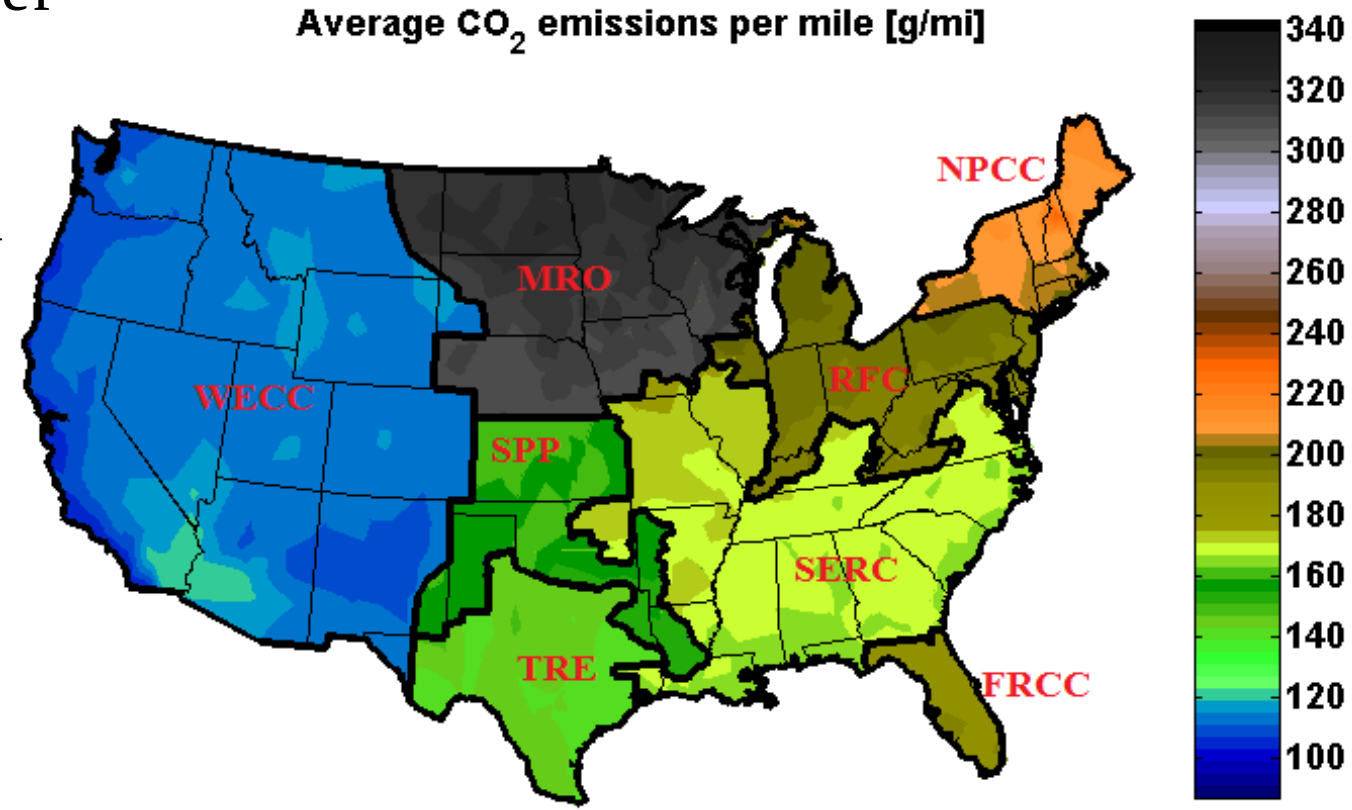
c) Generation-based, Convenience Charging

d) Generation-based, Delayed Charging

Estimated using EPA test vehicle efficiency and distribution of marginal emissions estimates produced by regresssions in Graff Zivin et al., Siler-Evans et al.

Using Marginal Consumption Emissions

- 2× to 3× higher emissions in northern Midwest than West Coast



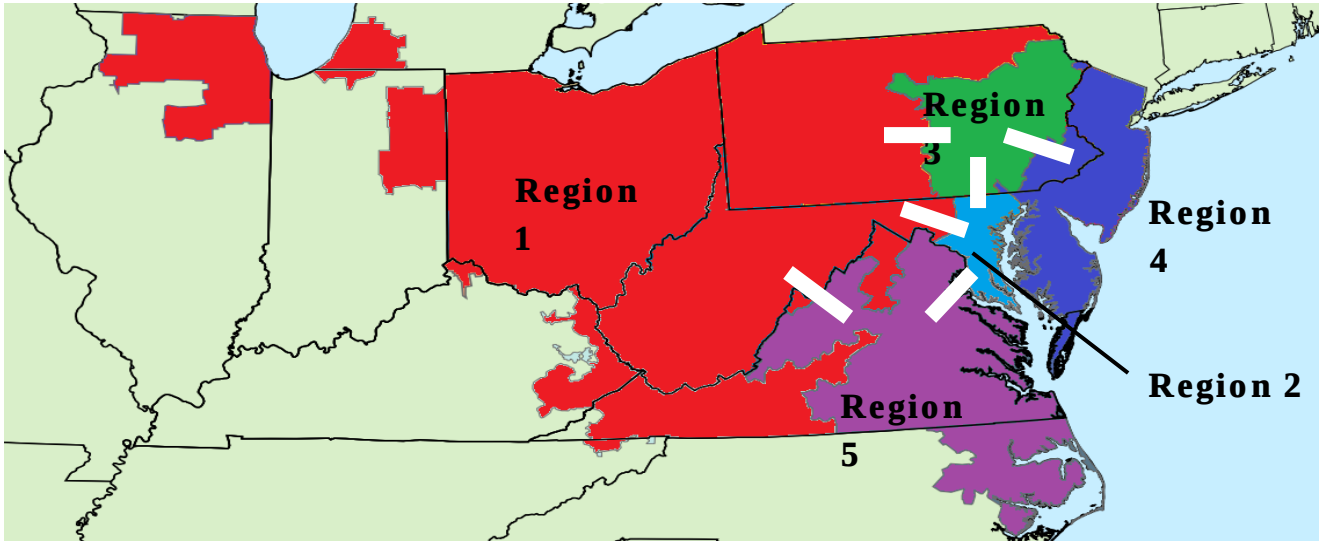
GHG emissions estimated using on-road Nissan Leaf efficiency at various temperatures (FleetCarma) and NERC region marginal grid mix (Graff Zivin et al.)

Normative Approach

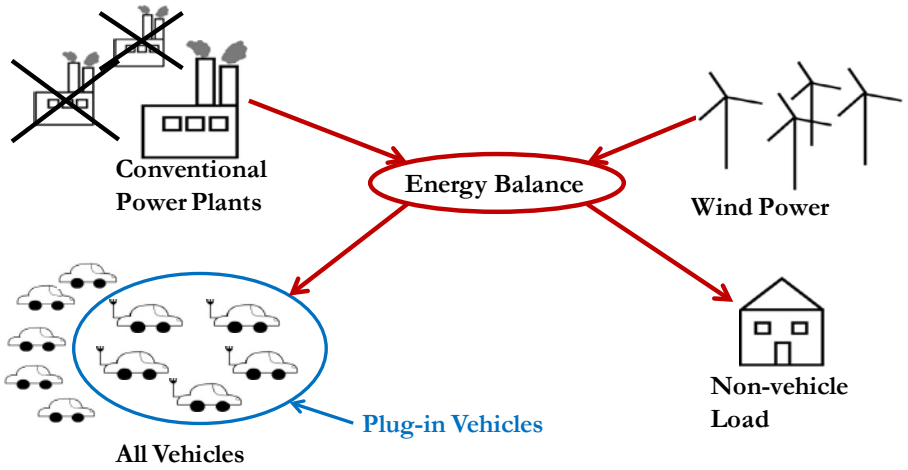
Weis, A., P. Jaramillo and J.J. Michalek (2014) “Estimating the potential of controlled plug-in hybrid electric vehicle charging to reduce operational and capacity expansion costs for electric power systems with high wind penetration,” Applied Energy v115 p190-204.
Weis, A., P. Jaramillo and J.J. Michalek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



- Optimize system to minimize cost subject to system constraints

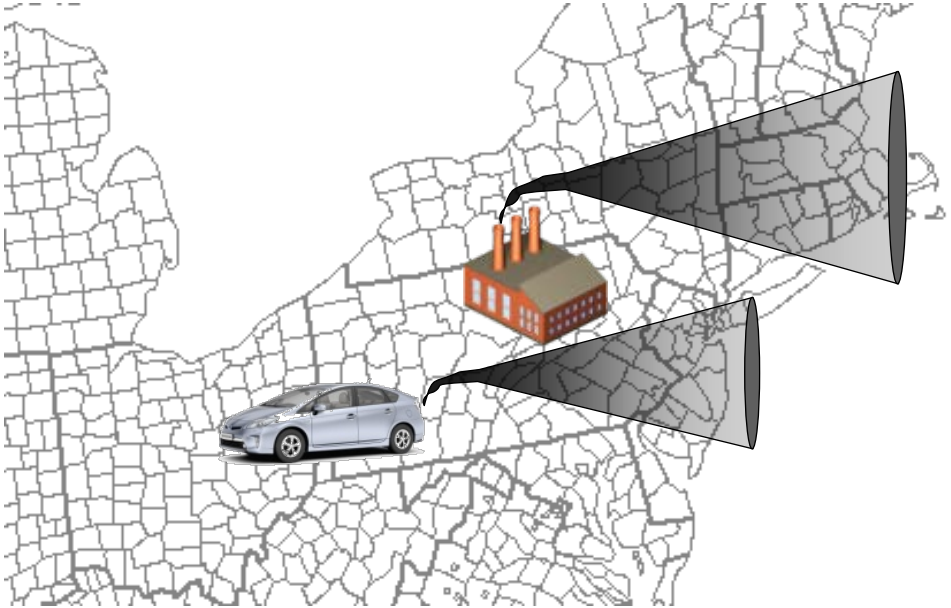
$$\text{minimize} \sum_{\text{time}} \sum_{\text{plants}} (\text{Fuel Costs} + \text{Startup Costs} + \text{Shutdown Costs})$$

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

Monetized Social Costs

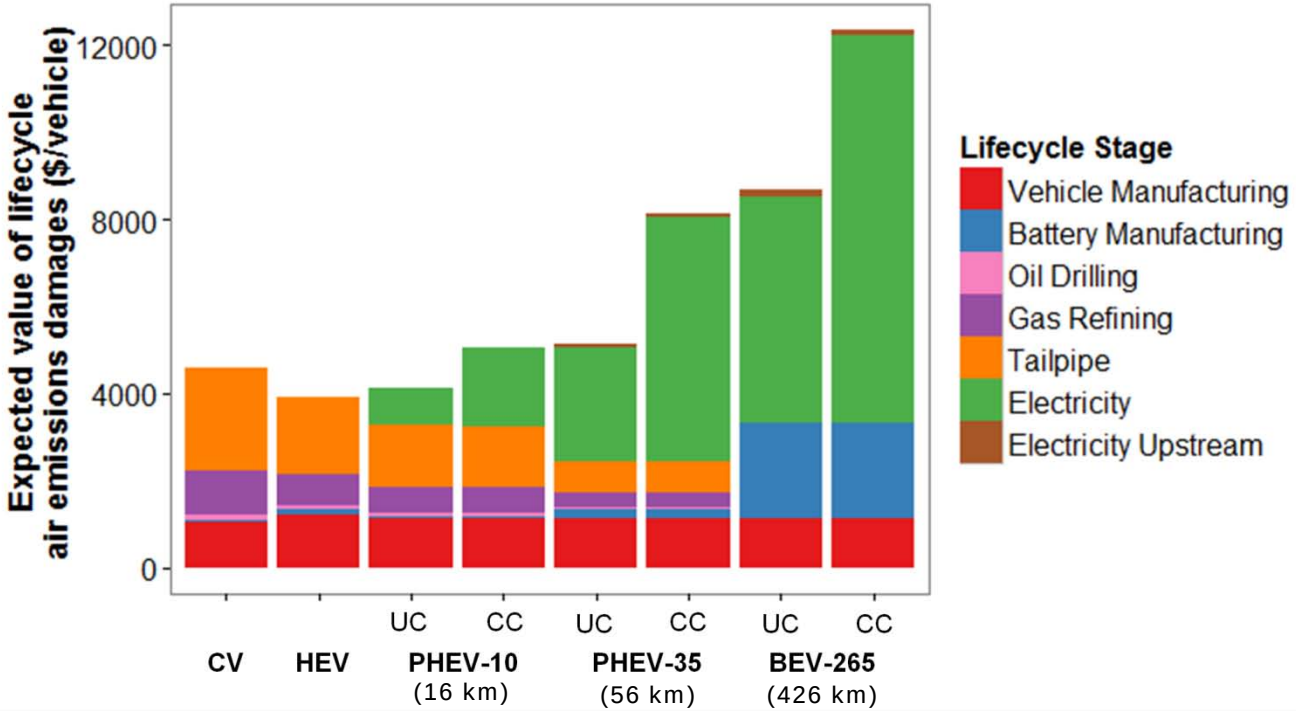
- Estimate monetized air emission damages via
  - AP2
  - EASIUR
  - Social cost of carbon



Models: APEEP2, EASIUR

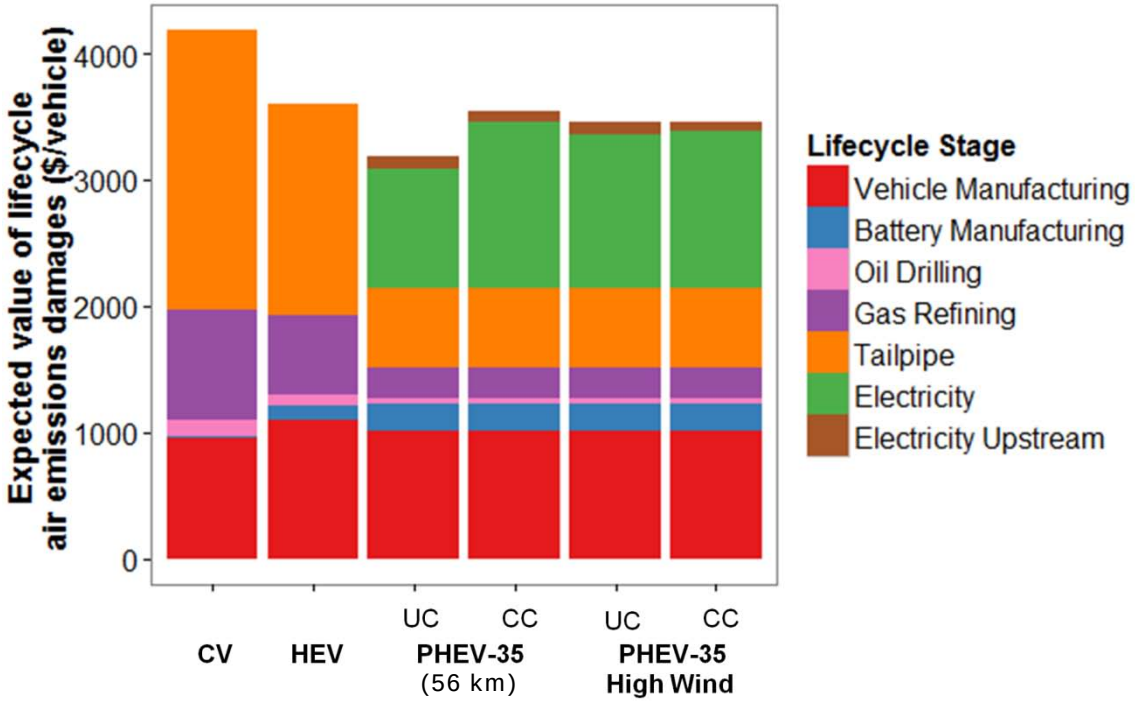
Recent Grid (2010)

- Most recent year for which all needed data are available
- PEVs cause more damage (BEV 2-3×)



Future Grid (2018)

- Using EPA plant retirement predictions
- PEVs comparable to HEVs

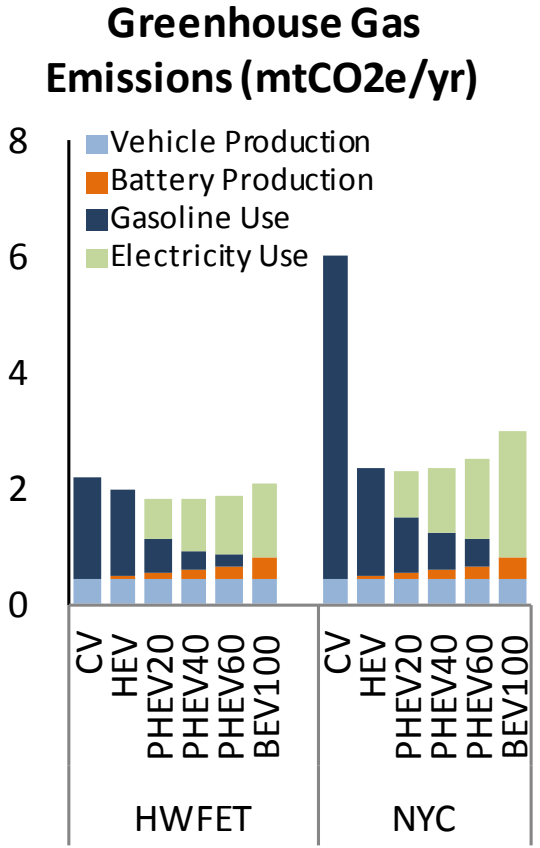


Other Regional Factors

Karabasoglu, O. and J.J. Michalek (2013) "Influence of driving patterns on lifetime cost and life cycle emissions of hybrid and plug-in electric vehicle powertrains," *Energy Policy*, v60 p445-461.
Traut, E.J., C.T. Hendrickson, E. Klampfl, Y. Liu, and J.J. Michalek (2012) "Optimal design and allocation of electrified vehicles and dedicated charging infrastructure for minimum life cycle greenhouse gas emissions and cost," *Energy Policy*, v51 pp 524-534.
Yuksel, T. and J.J. Michalek (2015) "Effects of regional temperature on electric vehicle efficiency, range, and emissions in the United States," *Environmental Science & Technology*, v49 n6 p3974-3980.
Yuksel, T., M. Tamayao, C. Hendrickson, I. Azevedo and J.J. Michalek (2016) "Effect of regional grid mix, driving patterns and climate on the comparative carbon footprint of electric and gasoline vehicles," *Environmental Research Letters*, v11 n4 044007.
Yuksel, T., J.J. Michalek and V. Viswanathan (2015) "Effects of air cooling on battery life in plug-in hybrid electric vehicles," working paper.

Other Regional Factors: Driving Conditions

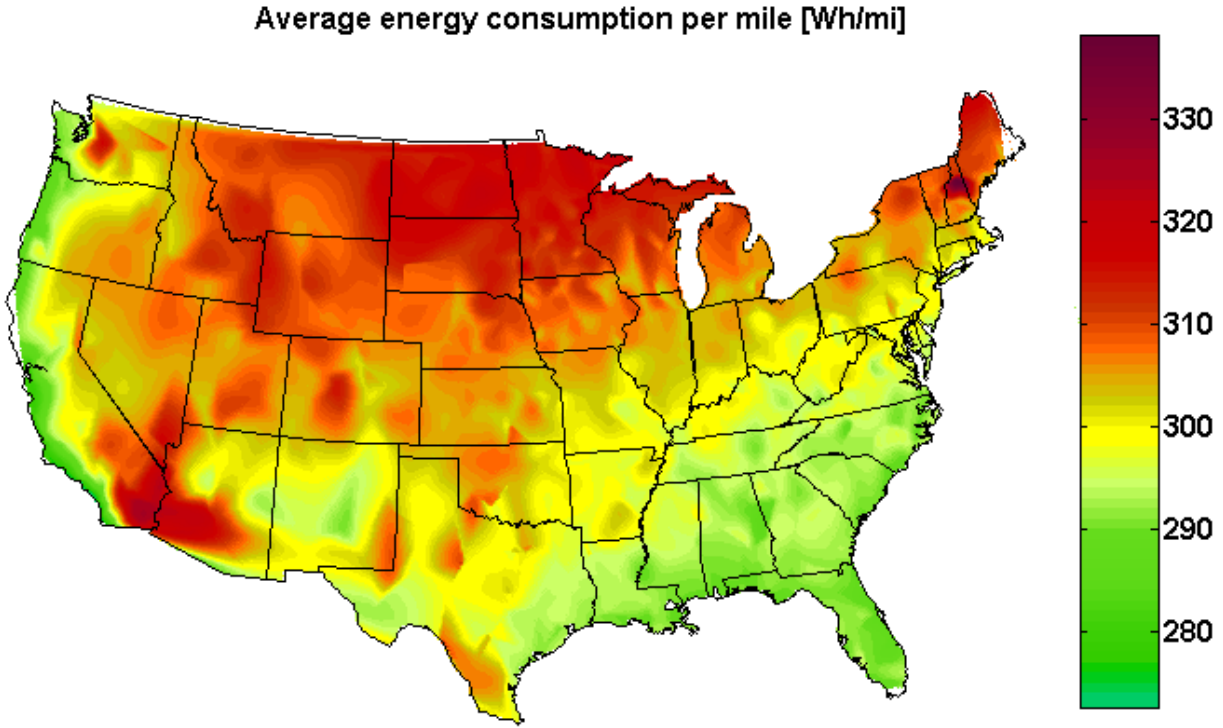
- **Heavy urban driving (NYC)**
  - Hybrid vehicles can cut GHG emissions in half while lowering lifetime cost
- **Light highway driving (HWFET)**
  - Hybrid and electric vehicles offer marginal GHG benefits (on average) at higher cost



Estimated using vehicle physics simulation PSAT and average U.S. grid mix

Other Regional Factors: Temperature

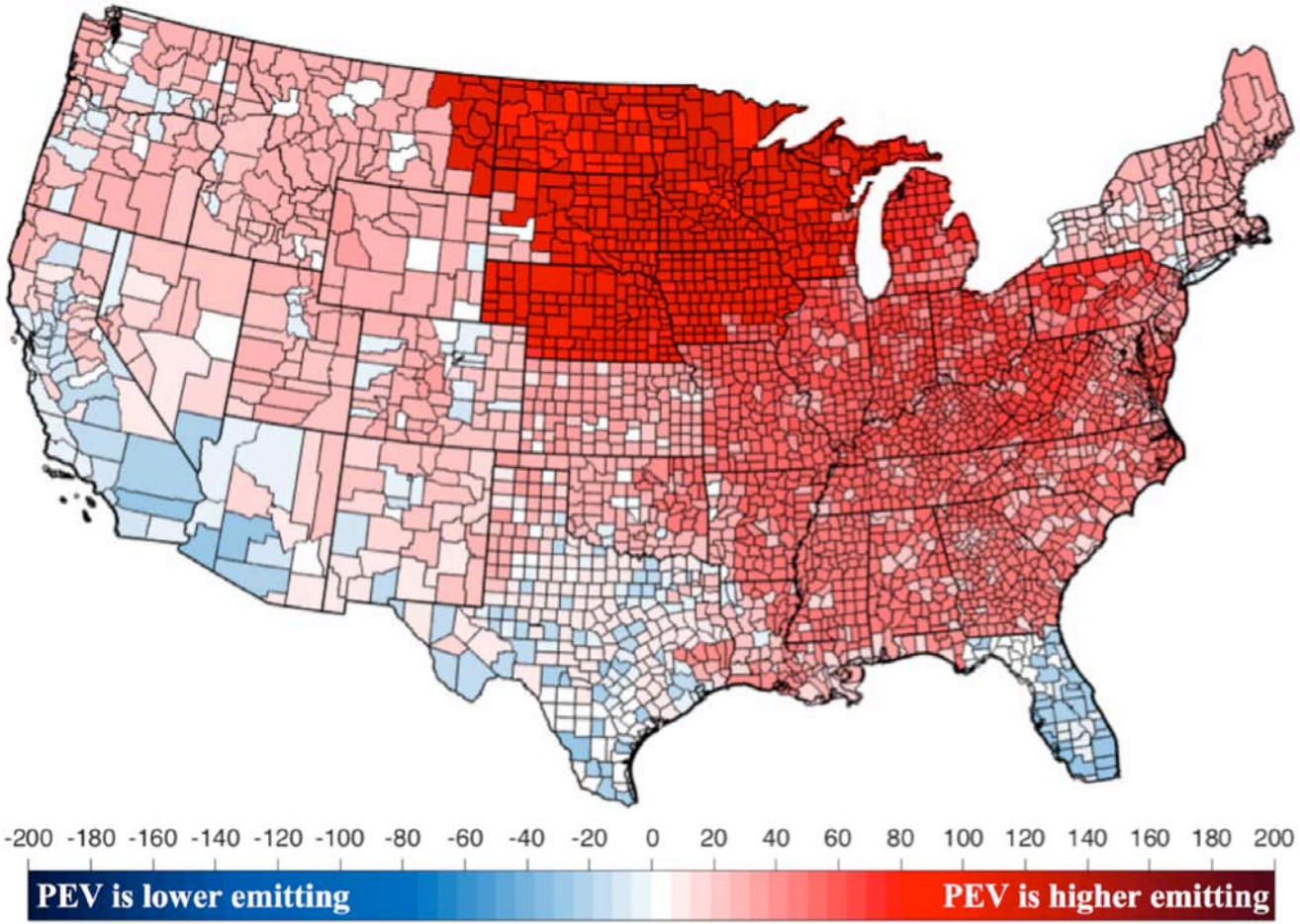
- PEVs consume 15% more electricity in hot/cold regions, on average



Estimated from on-road Nissan Leaf efficiency data (FleetCarma) and regional temperature patterns

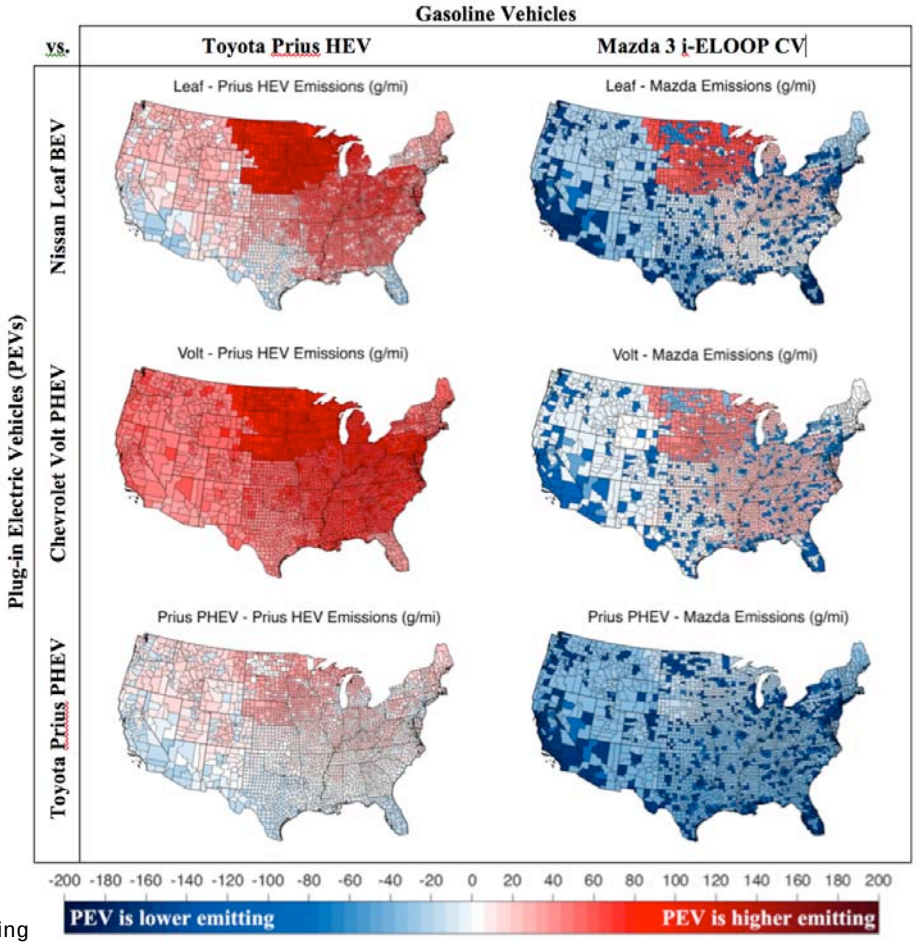
Combined Regional Effect (Leaf vs. Prius)

- Combined effect of regional grid mix, drive cycle & temperature
- Leaf produces lower GHG emissions than Prius in urban counties of the southwest, TX, & FL
- Prius better in midwest, south, and most rural counties



Combined Regional Effect

- Pairwise comparison of three PEVs to two gasoline vehicles
- PEVs are sometimes cleaner than gasoline vehicles but not always
  - PEVs typically best in urban counties of the southwest, TX, FL
  - PEVs typically worse in midwest, south, and rural counties
- Grid expected to get cleaner over time, reducing PEV emissions



Results shown using Siler-Evans marginal emissions estimates and convenience charging

Key Ideas

Average emissions

- Easy, but arbitrary
- Results vary substantially with choice of regional boundaries
- Ignores trade across boundaries
- Does not measure implications of increasing PEV load

Consequential emissions

- Assesses implications of changes in PEV adoption – relevant question for policy
- Can estimate, but impossible to know precisely in a heavily interconnected grid
  - Empirical and normative estimates have strengths and weaknesses

Key Ideas

- **Which power plants respond to changes in load?**
  - Varies regionally and temporally
  - Renewables and nuclear plants are almost never on the margin.
  - Fossil fuel plants dominate marginal generation even in a renewable-heavy region.
    - PEV emissions determined primarily by coal / natural gas ratio on margin
  - Except: under a binding RPS, increases in load should produce increases in wind generation.
- **Future Projections**
  - Grid changes over vehicle life
  - Future consequential emissions require projections of future grid, regulations, fuel prices, etc.
    - Estimates sensitive to assumptions
    - Projections certain to be wrong
  - Presence of PEVs could affect capacity expansion
- **Air Pollution**
  - With coal, PEV air pollution damages > social cost of carbon emissions
  - Binding SO2 caps reduce this substantially

What to do?

- Difficult to assign emissions to PEV load in a precise and meaningful way that stands up to scrutiny
- More effective to regulate emissions at the source
  - Economy-wide carbon price or cap-and-trade system
- If restricted to regulating emissions associated with PEV charging
  - All estimates have issues.
  - Should be grounded in data. But any past estimate has uncertainty and ignores future changes, and any future projection is bound to be wrong.