***Life Cycle Air Emissions Externality Implications of Electric Vehicle Adoption in the U.S.: A Comparison of Empirical and Normative Approaches***

Paulina Jaramillo, Carnegie Mellon University, (412)268-6655, paulina@cmu.edu

Jeremy Michalek, Carnegie Mellon University, (412)268-3765, jmichalek@cmu.edu

Allison Weis, Carnegie Mellon University (now at Tesla Motors), kazakia@gmail.com

Inês Azevedo, Carnegie Mellon University, (412)268-3754, iazevedo@cmu.edu

Mili-Ann Tamayao, Carnegie Mellon University (now at University of the Philippines), mamtamayao@gmail.com

Chris Hendrickson, Carnegie Mellon University, (412)268-1066, cth@cmu.edu

## Overview

Emissions accounting for electric vehicle charging is handled differently depending on the question being asked. The question “What emissions are EVs responsible for?” is an allocation question that requires a value judgement; prior studies have decided that electric vehicles should be responsible for emissions associated with the average or marginal generation mix in the vehicle’s state, balancing region, NERC region, eGRID subregion, interconnect, or country. In contrast, the question “What are the emissions implications of EV adoption?” is a consequential question for which the analyst must assess how the power grid will change in response to new EV load at a particular location and time.

We compare empirical top-down and normative bottom-up approaches to answering the latter question in the United States on a life cycle basis.

## Methods

Top-down empirical approaches to estimating consequential emissions use regression on past data to understand how emissions change as load changes in practice; however, (1) these approachs addresses only the historical grid, which is arguably not relevant for future adoption of vehicles with lifetimes greater than a decade; (2) the approach addresses marginal load changes only; and (3) the approach assesses correlations that do not necessarily imply causality for supporting counterfactual analysis.

Existing regression-based studies include Graff Zivin et al. (2014), which regresses interconnect emissions on NERC region consumption (marginal consumption emission factors), and Siler-Evans et al. (2012), which regresses changes in fossil fuel generators vs. change in load for each NERC region (marginal generation emission factors). Graff Zivin is more conceptually correct – we are interested in the effect of consumption in one location on net emissions across the grid – however correlation vs. causality is a significant source of error in use for counterfactual analysis, particularly for generators like nuclear, hydro, and wind plants that typically do not change net output in response to variation in load. Siler-Evans mitigates this issue by focusing on fossil fuel plants but misses interregional trade and regional variation in efficiency. We compare regional emissions estimates and identify robust findings.

In contrast, bottom-up normative appraoches model grid operations, such as unit commitment and dispatch, as a constrained optimization problem, assessing how the grid should operate to minimize costs. Such approaches can model future scenarios and assess large load changes; however (1) such models have limited scalability, making it difficult to model a long time scale or a large interconnection and limiting the ability to model trade across sub-regions; and (2) it is generally not possible to model all possible considerations that affect grid operations in practice. We model the PJM interconnection using five transmission regions, optimize the system to minimize cost subject to generation/load, spinning and non-spinning reserves, generation level, ramp rate, runtime, downtime, transmission, vehicle charge rate and battery state of charge constraints. We monetize air emission externalities using the APEEP (AP2) and EASIUR models in addition to estimates of the social cost of carbon.

## Results

For the empirical models, we find that some conclusions are robust to variations in model and charge timing: The electric Nissan Leaf is lower GHG-emitting than the gasoline Toyota Prius in the western U.S., Texas, and likely in Florida and New England, but it is higher emitting in the northern Midwest. In other regions the comparison depends on which marginal emission factor estimates are used and/or charge timing. In contrast, the plug-in hybrid Chevrolet Volt is higher emitting than the gasoline Toyota Prius in most of the U.S., but the comparison in the western U.S. varies based on the emissions estimates used and charge timing. All three vehicles emit fewer GHGs than most of the U.S. vehicle fleet.

For the normative models, we find that for the recent PJM grid (2010, the most recent year for which all necessary data are available), the plug-in electric vehicles modeled cause higher emissions externalities than the gasoline hybrid electric vehicle. In a future grid (2018) with sufficient coal plant retirement (as predicted by the EPA) and wind penetration, externalities of plug-in electric vehicles could be marginally lower than gasoline hybrids.

Additionally, we find that utility-controlled charging of electric vehicles reduces generation costs by one quarter to one third in the recent PJM grid, but it does so largely by shifting load to coal-fired power plants, whose air emissions damages exceed generation cost savings. Nighttime charging also increases GHG emissions in most of the U.S., compared to convenience charging.

## Conclusions

In general, states with zero-emission vehicle (ZEV) mandates tend to be in regions where the electric Leaf has lower GHG emissions than the gasoline Prius, but the plug-in hybrid Volt often has higher emissions. State EV subsidies are partially misaligned with regions where plug-in vehicles offer the largest benefits.

In particular, PJM has several states that offer large state incentives for electric vehicle adoption on top of generous federal subsidies, including West Virginia, which offers the highest state subsidy: $7,500. But PJM air emissions benefits of electrification remain small (or negative) through 2018. While long term benefits of a transition to alternative fuel vehicles could potentially justify higher subsidies now, it is less clear that PJM is a good location for targeting adoption in the near term.

## References

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, 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.

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.