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A network-based dispatch model for evaluating the spatial and temporal effects of plug-in electric vehicle charging on GHG emissions

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ABSTRACT

The well-to-wheel emissions associated with plug-in electric vehicles (PEVs) depend on the source of electricity and the current non-vehicle demand on the grid, thus must be evaluated via an integrated systems approach. We present a network-based dispatch model for the California electricity grid consisting of interconnected sub-regions to evaluate the impact of growing PEV demand on the existing power grid infrastructure system and energy resources. This model, built on a linear optimization framework, simultaneously considers spatiality and temporal dynamics of energy demand and supply. It was successfully benchmarked against historical data, and used to determine the regional impacts of several PEV charging profiles on the current electricity network. Average electricity carbon intensities for PEV charging range from 244 to 391 gCO_2e/kW h and marginal values range from 418 to 499 gCO_2e/kW h.

Introduction

To meet long-term goals for greenhouse gas (GHG) emissions, most studies project a major role for electric drive vehicles, especially in the light duty transportation sector (Yang et al., 2009; IEA, 2010; Yeh et al., 2008). The well-to-wheel emissions associated with plug-in electric vehicles (PEVs), which include both battery only electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) that also rely on a gasoline engine, depend on the source of electricity available and the current non-vehicle demand on the grid. The main goal of this study is to establish a systems approach that can be used to evaluate the environmental and operational impacts of growing electric vehicle demand on the existing power grid infrastructure system (both generation and transmission assets) and energy resources. This requires a mathematical model that captures the spatial interaction and temporal dynamics of energy demand and supplies, as well as the interdependencies of the supporting infrastructure systems.

The key research questions to be answered are:

- How does PEV charging interact with the existing power grid infrastructure?
- How does spatiality of generation, demand and the transmission network affect the flow of power within the grid?
- How do the emissions for charging PEVs differ as a function of location and time?

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Many studies focused on the GHG impact of PEVs (Anair and Mahmassani, 2012; Axsen and Kurani, 2010; Elgowainy et al., 2010; Hadley and Tsvetkova, 2009; Kintner-Meyer et al., 2007; McCarthy and Yang, 2010; NRC, 2010; Samaras and Meisterling, 2008). However, as pointed out by Yang (2013), there is little agreement between the results of these studies, partially due to different modeling assumptions, and more critically due to different emission allocation approaches adopted. The methodology for estimating emissions in the electricity sector can be divided into three general categories: system average emission factors, load-following marginal analysis, and grid-system dispatch analysis (Callaway and Fowlie, 2009). The first approach estimates average emissions by dividing net system emissions by net generation. This approach is simple, but suffers poor temporal and spatial resolution – e.g. all power within California is represented by a single emissions rate – and is more suitable for national or international level analyses, such as the Union of Concerned Scientist report that estimated the average greenhouse gas emissions for plug-in vehicle charging in any city in the United States (Anair and Mahmassani, 2012) employing a multi-state regional average value. This approach also fails to account for changes in emissions rate that would result from adding PEV charging to the grid (Yang, 2013). The second approach uses historical data to estimate how system-wide emissions in the electricity market respond to changes in load. This approach is only appropriate for use in near-term evaluations where the power sector has not changed (Novan, 2011; Kaffine et al., 2011; Graff Zivin et al., 2012). It would not be appropriate in evaluating Renewable Portfolio Standard (RPS) or greenhouse reduction scenarios, for example, where the mix of generators would change significantly. In addition, this econometric approach cannot accommodate explicit modeling of the power transmission network, in case spatial interactions between different sub-regions need to be captured. The third approach is to develop a grid dispatch model that simulates the bid-based power grid operations by means of a least-cost optimization (Nelson et al., 2012) or long-term economic equilibrium approach (Bushnell, 2010). Examples include Oak Ridge National Laboratory's Competitive Electric Dispatch (ORCED) model for the entire United States (Hadley and Tsvetkova, 2009), the equilibrium model developed by Bushnell (2010), the UC Berkeley SWITCH model (Nelson et al., 2012) for the Western Electricity Coordinating Council (WECC) region, and UC Davis' EDGE-CA model (and its follow on model LEDGE-CA) for California (McCarthy, 2009).

The core of this research is the development of a network-based electricity dispatch model, which can be used to estimate the impacts of PEV charging on the power grid. The uniqueness of this research from above mentioned existing studies lies in the explicitly modeled spatial representation of the California electricity sector and the incorporation of transmission network to capture infrastructure interdependencies. In terms of spatial and temporal disaggregation, our approach is most similar to the Regional Energy Deployment System (ReEDS) model Martinez et al., 2013 recently developed by the National Renewable Energy Laboratory, which is the key model used in the Renewable Electricity Futures Study (Renewable Energy Laboratory, 2012). The main difference is: the ReEDS model assumes a single virtual transmission link between each energy source–destination pair, while our approach considers a general transmission network connecting these pairs.

Methodology

When considering the impact of additional demand such as plug-in electric vehicle charging on an existing power grid, one may immediately think of identifying which type of generation resource is on the margin. However, due to transmission constraints and losses, the lowest variable cost generator in the system may not necessarily be appropriate for meeting these demands. A systems approach for simultaneously determining dispatch and transmission parameters was needed to consider both spatial and temporal correlations involved in this study. To this end, we developed a linear programming model, named the Electricity Dispatch model for Greenhouse Gas Emissions for California transmission network (EDGE-NET), to determine the mix of generation resources operating at any given time to satisfy electricity demand. Upon validation, this model was then used to estimate the marginal emissions and costs that would result from additional electric load on the grid (e.g. from electric vehicles).

The analyses were based on the following assumptions:

- Only the existing power generation and transmission infrastructure is modeled. Future expansion of this infrastructure can be incorporated into our model, but is not included in this study.
- The power flow in the model is a simplified version of a transmission network with fixed efficiency rather than a full engineering treatment, for example a DC load-flow model, in which Kirchoff's Laws are enforced. While this model would not be appropriate for simulating physical performance of the electric transmission network itself, it is reasonable for considering bulk energy flows within the network (Nelson et al., 2012; Gil and Quelhas, 2003).
- A time step of one hour is used, as this is the discretization at which historical data is available.
- Rather than modeling power plants or units individually, power production (and storage) is aggregated into 10 different categories of power plant for each region.
- With the exception of transmission losses, no energy losses are modeled.

The variables and parameters used in the model are defined in Table 1.