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Optimizing plug-in electric vehicle and vehicle-to-grid charge scheduling to minimize carbon emissions

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ABSTRACT

Electric vehicles are an emerging technology with significant potential for reducing carbon dioxide emissions. Yet strategies to minimize carbon dioxide emissions by strategically charging during different times of day have not been rigorously explored. To identify possibilities for minimizing emissions from plug-in electric vehicle use, daily optimized charging strategies over each electricity reliability region of the United States are explored. Optimized schedules of plug-in electric vehicle charging for standard and vehicle-to-grid use were compared with pre-timed charging schedules to characterize the potential for carbon dioxide emission reductions across charging characteristics, regional driving, and marginal energy generation trends. It was found that optimized charging can reduce carbon dioxide emissions over pre-timed charging by as much as 31% for standard use and 59% for vehicle-to-grid use. However, some scenarios of vehicle-to-grid participation were found to increase carbon dioxide emissions by up to 396 g carbon dioxide per mile by displacing stored energy from more carbon-intense energy generation periods. Results also indicate that plug-in electric vehicle charging emissions can vary widely for a given energy efficiency rating. Current energy efficiency ratings may lead to incorrect assumptions of plug-in electric vehicles emissions compared to conventional gasoline vehicles due to varying regional and temporal emissions. To coincide with the push for lower greenhouse gas emissions from transportation, charging times for plug-in electric vehicles should target periods where charging promotes carbon dioxide reductions, and electric vehicle energy efficiency ratings should be reconsidered in order to promote sustainable plug-in electric vehicle use moving forward.

1. Introduction

Electric vehicles (EVs) are an emerging technology with significant potential for reducing carbon dioxide (CO_2) emissions. Shifting from conventional gasoline vehicles (CGVs) to plug-in hybrid electric vehicles (PHEVs) could reduce the gasoline consumption by up to 52% of the US petroleum imports [1] and could reduce carbon emissions in some cases by up to 60% in compared to conventional hybrid vehicles [2]. EV registrations have exceeded 500,000 units worldwide, and the registration rate was estimated to have doubled every seven to eight months from December 2010 to May 2014 [3]. With technology advancements and financial incentives, EVs will likely continue to see increased market penetration in the near future and become increasingly competitive with CGVs. Tax rebates of up to $7500 dollars and fuel costs as low as $0.04 per mile make EVs an attractive alternative to CGVs [4]. EVs use Lithium-ion batteries almost exclusively and production costs are declining. According to a 2015 study, production costs of Lithium-ion batteries are between $300/kWh to $410/kWh, and their production costs from 2007 to 2014 have dropped by approximately 14% annually with projections to continue declining [5]. With the EV market share on the rise and continuing developments in battery technology, EV use is likely to continue to develop and expand. Yet EV deployment strategies to ensure CO_2 reductions remain largely undefined.

Emissions from EV use can vary widely depending on the region and time-of-day in which charging occurs. Marginal energy produced during nighttime periods may have higher CO_2 emissions than peak periods for some regions by as much as 65% (southwest region during summer) for generation-estimated marginal emissions [6] or approximately 91% (southeast region) for consumption-estimated marginal emission [7]. These extremes are due to high energy

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Nomenclature

List of Acronyms

CGV	Conventional Gasoline Vehicle
CO_2	Carbon Dioxide
EV	Electric Vehicle
kW	Kilowatt
kWh	Kilowatt-hour
MPG	Mile Per Gallon
MPGe	Mile Per Gallon equivalent
NERC	North American Electric Reliability Corporation; NHTS National Household Travel Survey; PEV Plug-in Electric Vehicle; PHEV Plug-in Hybrid Electric Vehicle
UDDS	Urban Dynamometer Driving Schedule
V2G	Vehicle-to-grid

Formulae terms

B_c	EV battery capacity, in kWh
C_e	The effective EV charge rate in kW
C_{L2}	Max achievable charge rate of the EV in kW
d_r	Average urban daily miles driven in region r
$E_{D,i}$	Extra energy being charged to later be discharged to the grid during peak hours
$E_{V2G,i}$	Total energy being charged or discharged by the V2G EV in hour i
E_i	Energy in kWh drawn from the grid to charge a given EV in hour i
$MER_{s,r,i}$	Marginal emissions rate in grams CO_2/kWh for season s in region r for hour i
η	Charging efficiency for level 2 charging
P_s	EV powertrain efficiency in season s, in kWh per mile
$X_{s,r}$	Daily CO_2 emissions, in grams CO_2 for a given EV in season s in region r
$Y_{V2G,s,r}$	CO_2 emissions in grams per kWh discharged

consumption during peak hours in summer months in the southern Unites States. Energy generated for high demand periods is more costly on the margin but less carbon intense [8], therefore causing large variations in peak-to-nighttime marginal CO_2 emissions. As a result, EV charging during recommended nighttime hours can lead to higher CO_2 emissions. Zivin et al. [7] found that EV charging during nighttime hours (12am - 4am) in the Midwestern United States may result in higher CO_2 emissions than similar use of a CGVs or PHEVs. Tamayao et al. [9] found that nighttime charging of various EVs mostly resulted in higher emissions than charging during the evening. Much discussion of EV charging has focused on questions of when the technology breaks even with CGVs given regional grid mixes. While valuable, there remains limited knowledge of how charging should be scheduled across the US at different times of day to minimize CO_2 emissions. The opportunity remains to identify optimal charging strategies to minimize CO_2 emissions.

Much of the current literature investigating optimization of EV charging focuses on minimizing costs. Cao et al. [10] proposed methods to control EV charging loads with a focus on minimizing charging cost, and Korolko and Sahinoglu [11] investigated optimization of EV charging schedules in unregulated electricity markets to minimize overall costs. Yuksel and Michalek [12] estimated EV CO_2 emission variations from regional temperature differences, driving patterns and grid emissions factors. Weis et al. [13] examined the cost implications of controlled EV charging in a single region in the US. The findings indicate controlled charging using the current grid mix produces overall negative net social benefits due to increased coal generated energy utilized for vehicle charging even though operator costs were reduced by 23%–34%. Khayyam and Bab-Hadishar [14] modeled powertrain, driving factors and environment factors for PHEVs to develop an intelligent energy management system to improve the vehicles overall energy efficiency. Due to growth in EV market penetration, EV charging research remains focused on minimizing the strain on the electrical grid by minimizing costs for operators. Consideration of environmental impacts using grid emission factors has been considered in some EV scheduling research. However, reducing environmental impacts from EV charging has not been the motivation for optimizing charge schedules, even though controlling EV charging to reduce generation costs may produces negative net social benefits [13]. As a result, optimized charge scheduling motivated by reducing carbon emissions may expand the understanding of EV charging related emissions and the practicality of optimized charge scheduling.

In addition to EV charging, vehicle-to-grid (V2G) technology has been cited as a method of integrating renewable energy to the grid while also aiding in load balancing during peak hours by delayed discharging of excess EV battery energy [15]. Emerging V2G technologies utilize EV battery energy by discharging excess capacity during high demand hours to help regulate peak energy demands. Research indicates that V2G use could be adopted in the near future as a supplementary means for peak load regulation [16]. Fluctuating energy mixes by region and time-of-day could cause highly varied emissions when considering the energy displaced from V2G participation. Factors such as regional energy mix, charge schedule, and EV characteristics may all influence the emissions from V2G use.

Although there is potential for future V2G implementation in EVs, there is little discussion on the environmental effects from V2G charging. Most cases evaluate optimal scheduling of V2G use to focus on maximizing economic benefit or minimizing the strain to the energy providers, following the same trend as non V2G EV scheduling research. Implications of controlled and intelligent management of V2G use has been evaluated in a number of cases. Honarmand et al. [17] modeled realistic V2G charge and discharge schedules for implementation in an intelligent parking lot and found that optimal charging occurs when energy prices are lower and discharging occurs when energy prices are higher. With some exceptions, most research does not focus on the environmental impacts from the V2G implementation. Sioshansi and Denholm [18] found that V2G use could reduce generator CO_2 emissions substantially in Texas. Cardoso et al. [19] modeled the effects of V2G use at a large office building in San Francisco to find reductions in energy cost and CO_2 emissions when payback periods are small. Therefore, investigating the optimization of V2G charging-discharging by minimizing CO_2 emissions may provide valuable new insight.

If EVs can be positioned to minimize emissions from passenger vehicle use, optimal charging strategies should be identified that are sensitive to marginal time-of-day emissions and the regional electricity mix. This paper addresses three specific research questions: 1) Can optimized or strategic EV charging schedules reduce CO_2 emissions for EV and V2G use? 2) What EV charging and driving characteristics have the most influence on CO_2 emissions? and, 3) How might V2G use change CO_2 emissions relative to EV