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Comparing the emissions benefits of centralized vs. decentralized electric vehicle smart charging approaches: A case study of the year 2030 California electric grid

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HIGHLIGHTS

- Ideal & practical smart charging approaches are compared for environmental benefits.
- Effects on electric grid CO_2 and NO_x emissions are modeled and compared.
- Well-designed practical approaches can closely match ideal emissions benefits.
- Frequent grid communication is required to practically realize ideal emissions benefits.
- Lack of frequent grid communication reduces smart charging emissions benefits.

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ABSTRACT

Grid communicative "smart" charging of electric vehicles can provide significant benefits for maximizing the emission reductions provided by the large-scale use of these vehicles. While decentralized approaches to smart charging can be practical to implement in real systems, it is unclear whether these provide the same benefits for the electric grid as those identified by centralized approaches in the literature. This study compares the CO_2 and NO_x reduction benefits, and cost and grid capacity benefits, achieved by decentralized and centralized electric vehicle smart charging by modeling two different smart charging algorithms in battery electric vehicles and characterizing their effect on the operation and dispatch of electric grid resources and subsequently electric grid CO_2 and NO_x emissions. Decentralized approaches were found to provide the same CO_2 emissions benefits and within 2% of the NO_x emissions benefits achieved with centralized approaches, but only if the frequency of communication between vehicles and the electric grid is sufficiently high (less than 60 min). The difference in NOx emission is associated with the increased load variability caused by less frequent communication in decentralized smart charging resulting in higher power plant startup events. Finally, costs and grid capacity needs are increased without frequent grid communication.

1. Introduction

In the previous few decades, worldwide greenhouse gas emissions have risen significantly as population growth and increasing per-capita energy use have driven increased demand for fossil fuels. By 2014 worldwide greenhouse gas emissions have increased by 90% relative to year 1970 levels [1]. The United States (U.S.) is considered one of the largest emitters of greenhouse gas (GHG) emissions, totaling 14% of global emissions [2]. In the U.S., the transportation sector comprises 27% of the U.S. total [3]. The state of California which comprises one of the largest domestic automobile markets produced about 160 million tonnes CO_2 equivalent (CO_2e) from its transportation sector alone, accounting for 37% of California's GHG emissions in 2015 [4]. To combat rising GHG emissions, California has enacted a series of policies which establish GHG emission reduction targets for the state. Assembly Bill 32 (AB32) mandates that California reduces its GHG emissions to 1990 levels by 2020 [5]. Senate Bill 32 (SB32) expands on AB32 and requires that California reduce GHG emissions to 40% below 1990 levels by 2030 as an intermediate goal towards eventually reaching 80% below 1990 levels by 2050, making this the most stringent standard set by any

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Nomenclature – acronyms

3G	3rd Generation (wireless mobile telecommunications standard)
AB32	Assembly Bill 32
BAU	Business-*as*-Usual
BEV	Battery Electric Vehicle
CO2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
DC	Direct Current
DSL	Digital Subscriber Line
EV	Electric Vehicle
GE	General Electric
GHG	Greenhouse Gas Emissions
HiGRID	Holistic Grid Resource Integration and Deployment model
ICE	Internal Combustion Engine
kW	Kilowatt
kWh	Kilowatt-hour
LCOE	Levelized Cost of Electricity
LTE	Long Term Evolution (wireless mobile telecommunications standard)
MMBTU	Million British Thermal Units
MMT	Million Metric Tons
MW	Megawatt
MWh	Megawatt-hour
NHTS	National Household Travel Survey
NOx	Nitrous Oxides
NSRDB	National Solar Radiation Database
PEV	Plug-in Electric Vehicle
PG&E	Pacific Gas & Electric
PHEV	Plug-in Electric Vehicle
PLC	Power Line Communication
SB32	Senate Bill 32
SOC	State of Charge
U.S.	United States
VMT	Vehicle Miles Traveled
WWSI	Western Wind and Solar Integration (project name)

Nomenclature – equation variables

Δt	Time interval difference
Δt_{ij}	Dwelling period length
$\Delta t_n(t_i)$	Time for which the vehicle has been plugged in at time t_i
B	Total charging energy of all PEVs over 1 day
b_n	Charging energy of an individual PEV over 1 day
$C(t_i)$	Cost function value per kWh
$D(t_i)$	Net electric load at time t_i
$EF_{i,fuel,LF}$	The emissions factor for a pollutant type i per unit of fuel burned in a load-following power plant
$EF_{i,fuel,PK}$	The emissions factor for a pollutant type i per unit of fuel burned in a peaking power plant
$EF_{i,starts,LF}$	The emissions factor for a pollutant type i per start up event in a load-following power plant
$EF_{i,starts,PK}$	The emissions factor for a pollutant type i per start up event in a peaking power plant
$E_{gen,LF}$	The annual electricity generation from load-following power plants as calculated by the dispatch of generators in HiGRID
$E_{gen,PK}$	The annual electricity generation from peaking power plants as calculated by the dispatch of generators in HiGRID
$Em_{i,LF}$	Total annual emissions of a pollutant i from load-following power plants
$Em_{i,PK}$	Total annual emissions of a pollutant i from peaking power plants
f_{ij}	Charging cost function value per kWh during the jth hour in the ith dwelling period
$N_{starts,LF}$	The annual number of power plant start-up events by load-following power plants as calculated by the dispatch of generators in HiGRID
$N_{starts,PK}$	The annual number of power plant start-up events by peaking power plants as calculated by the dispatch of generators in HiGRID
P_{LF}	Power capacity of an individual load following power plant
P_{NL}	Net load profile
P_{load}	Electric load profile on the electric grid
P_{Ren}	Aggregate renewable generation profile
$P_{Solar,R}$	Rooftop solar photovoltaic electricity generation profile
$P_{Solar,C}$	Centralized solar electricity generation profile
P_{Wind}	Onshore wind electricity generation profile
P_{Geo}	Geothermal electricity generation profile
P_{Hy}	Hydropower electricity generation profile
$P_{NL,Final}$	Final net load profile
P_{EV}	Electric load from EV charging
$s_{k-1}(t_i)$	Aggregated charging profile at time t_i for update time step k-1
ta_n	Time at which the nth PEV arrives at home
t_i	Time interval i
T_k	Time when the cost function is updated
T_{step}	Time interval for updating the cost function
$X(t_i)$	Overall charging power at time t_i
x_{ij}	State of charge increase during the jth hour in the ith dwelling period
$x_n(t_i)$	Charging energy for vehicle n at time t_i
η	Charging efficiency

government in North America [6]. In order to meet these goals, the transportation sector will require major changes. The adoption of plug-in electric vehicles (PEV) is a forefront solution in reducing GHG emissions in the transportation sector.

PEVs can be classified into battery electric vehicles (BEVs), and plug-in hybrid electric vehicles (PHEVs). BEVs solely rely on the electric motor and the onboard battery, while PHEVs use an internal combustion engine (ICE) combined with an electric motor [7]. The utilization of PEVs has been shown to have significant advantages compared to ICE vehicles such as improved fuel economy, decreased oil consumption and imports, and reduced GHG and pollutant emissions [8]. As PEVs continue to proliferate, the demand for PEV charging infrastructure and subsequent electric demand will increase [9]. Previous studies have shown that enabling the ability to charge PEVs at home ranks as the most important infrastructure need for supporting PEV deployment, followed by enabling the ability to charge at workplaces [7]. This occurs since the dwell period of vehicles parked at home overnight typically exceeds the number of hours required for a PEV to obtain a full charge. If the entire PEV fleet charges at the same time, however, the electric load profile on the electric grid will be significantly altered [9]. Data from the 2009 National Household Travel Survey (NHTS) show that the majority of vehicles arrive home from work around 5 p.m. [10]. In California, this is typically when renewable generation ramps down and the net load ramps up, as seen in the California “duck curve” [11]. If strategies to manage the timing and magnitude of PEV charging are not implemented, PEV charging loads can introduce a large load which adds to the peak loads of the electric grid [8]. As PEV penetration increases, “smart” or controlled charging protocols will be necessary to