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The effectiveness of plug-in hybrid electric vehicles and renewable power in support of holistic environmental goals: Part 1 – Evaluation of aggregate energy and greenhouse gas performance

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HIGHLIGHTS

- Integration of PHEVs can increase renewable utilization under certain conditions.
- PHEV environmental benefit depends on grid renewable percentage.
- Combined benefits are maximized when PHEV/renewable synergies are realized.
- Additional complementary technologies are still needed to meet environmental goals.

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ABSTRACT

A study that analyzes the effectiveness of plug-in hybrid vehicles (PHEVs) to meet holistic environmental goals has been performed across the combined electricity and light-duty transportation sectors. PHEV penetration levels are varied from 0 to 60% and base renewable penetration levels are varied from 10 to 45%. Part 1 of the study focuses on CO_2 emissions, fuel usage, and the renewable penetration level of individual and combined energy sectors. The effect on grid renewable penetration level depends on two factors: the additional vehicle load demand acting to decrease renewable penetration, and the controllability of vehicle charging acting to reduce curtailment of renewable power. PHEV integration can reduce CO_2 emissions and fuel usage and increase the aggregate renewable energy share compared to the no-vehicle case. The benefits of isolated PHEV integration are slightly offset by increased CO_2 emissions and fuel usage by the electric grid. Significant benefits are only realized when PHEVs are appropriately deployed in conjunction with renewable energy resources, highlighting important synergies between the electric and light-duty transportation sectors for meeting sustainability goals.

1. Introduction and background

1.1. Introduction

Concerns regarding the impact of energy usage on the physical and economic environments have motivated the development of broad-context sustainability goals. These goals include promoting energy security, mitigating the effects of air pollution, climate change, and resource depletion. Each resource sector has set individual sustainability goals for their respective performance in order to contribute towards reaching the larger sustainability goals.

The electricity sector in many countries and states has set targets for meeting increasing fractions of electricity demand with renewable resources to promote a shift towards a low-carbon, low-pollutant emission grid mix. For example, California is mandated to provide 33% of all retail sales of electricity from renewable resources by the year 2020. Other states in the U.S. also aim to reach similar goals to larger or smaller extents [1]. Hawaii has set one of the most aggressive targets at 40% renewable electricity by 2030 [1,2]. Each region will attempt to make the best use of its local renewable resource types to meet these goals while still providing satisfactory electrical service to all customers.

The transportation sector in many regions also has individual sustainability goals. Reductions in greenhouse gas emissions, criteria pollutant emissions, and energy consumption can be achieved through the use of alternative fuels to meet the transportation demand, as measured in vehicle miles traveled (VMT). For

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example, California Executive Order B-16-2012 aims to put 1.5 million zero emission vehicles (ZEVs) on state roads by 2025 [3]. For ZEVs to be effective, fuel supply chain impacts, infrastructure impacts, and consumer demand behavior must be considered.

Unlike the diverse sources of energy used for electricity generation, however, the light-duty transportation sector has historically relied on a single primary energy source in the form of petroleum, limiting options for meeting sustainability goals. This has forced transportation to rely solely on energy efficiency as a means of reducing energy consumption and GHG emissions. A shift toward alternative fuels, specifically electricity, grants the light-duty transportation sector a degree of flexibility beyond simple efficiency improvements. This shift, however, will place an extra burden on the electric power system in the form of increased load. If implemented inappropriately, plug-in electric vehicles (PEVs) may impede the ability of the electricity sector to meet its own sustainability goals and reduce the ultimate environmental benefits of PEVs. But, if implemented appropriately, this integration can create synergies that aid each sector to extents that are not possible individually.

In California, the total transportation sector composes about 39% of the state's total energy consumption. California also consumes 11.8% of the transportation sector energy of the entire U.S. [4]. This mix is dominated by the use of gasoline and diesel for light and heavy duty road vehicles, but also includes fuel use in other vehicles such as ships and aircraft. Correspondingly, if a significant fraction of future vehicles rely on electricity, there may be a significant increase in electric load that must be managed within the constraints of the electric power system. Compounding on this effect is the fact that the VMT demand of the light-duty transportation sector is expected to grow with population in the same manner as the electric load demand [5]. One possible implication of the integration of electricity and transportation may be difficulty for the electricity sector to meet its renewable energy procurement goals. Renewable portfolio standards are based on the percentage of retail electricity sales supplied by renewable resources. With a significant increase in the electric load demand beyond standard growth projections due to the addition of transportation, even more intermittent renewable capacity will need to be installed and managed to meet RPS targets.

For the electrification of the light-duty transportation sector to be holistically beneficial, it must be implemented in a manner which provides a benefit to the electric power system, and provides affordable, reliable, and timely electric fuel for vehicle drivers. The use of "smart charging" strategies for plug-in electric vehicles (PEVs) offers one method of integration that should be mutually beneficial. The extent of these benefits is examined in this study. Plug-in hybrid electric vehicles (PHEVs) are a subset of PEVs which use electricity stored in a battery and a chemical fuel stored in an on-board tank for propulsion. The battery can be charged by 'plugging-in' the vehicle to the electric grid. Electric drive is typically prioritized, with the chemical fuel being used when the battery is depleted or when additional power may be required. In this study, PHEVs using gasoline as the chemical fuel are considered since these vehicles can take advantage of the environmental benefits of electric drive while still providing sufficient range for all consumers to meet their transportation needs.

1.2. Background

Due to increasing interest in the development of alternative fuel vehicles over the past few years, much work has already been conducted to explore the interaction between plug-in electric vehicles and the electric grid.

A study performed by Jansen [6] provided some insight into the increase in the electric demand for the state of California due to plug-in vehicles, using a 40% penetration of PHEVs with a 40 mile all-electric range and uncontrolled charging behavior. The total electric load demand of a typical day was found to increase by 5–10% between the hours 9 am to 9 pm, and suggested an increased reliance on peaking power plants during this period. Similar parameters analyzed in New York show smart charging can reduce electricity system costs [7].

The integration of plug-in electric vehicles can also affect criteria pollutant emissions from conventional power plants. A previous study found that PHEV integration would increase grid-average CO and non-methane organic compound emission intensities by 4% and 7% respectively between 9 am and 9 pm, and reduce the NO_x average emission intensity by about 3% between 5 pm and 9 pm. The total emissions of criteria pollutants of stationary and mobile sources combined, however, is expected to decrease as increases in power plant emissions are offset by reductions in mobile source emissions due to lower gasoline use. The translation to improvements in air quality is dependent on the time of day when emissions are decreased [8].

The facets of this interaction within the context of renewable integration have also been addressed to some extent.

Dallinger [9] conducted a study which examined the role of grid-connected vehicles in improving the integration of renewable energy sources in California and Germany. This study compared the regional differences between these systems, as well as the effect of different charging strategies: last trip charging, time of use tariff charging, and demand side management charging. The study found that last trip charging resulted in a reduced electric driving share, increased net load ramp rates, and contributed only a small amount towards balancing renewable resources. Time-of-use tariff charging was found to balance renewable power generation only if the net load profile was regular and periodic. With non-periodic renewable generation, time-of-use tariff charging did not provide enough flexibility to gain benefits. Demand-side management charging was found to reduce net load ramp rates and was able to provide the most contribution towards managing intermittent renewable resources. This strategy was found to be more effective in California compared to Germany due to the characteristics of the load and renewable generation in that region.

Denholm [10] examined the benefits of an interaction between plug-in vehicle integration and solar PV deployment, specifically. This study found that mid-day charging of electric vehicles with solar PV can increase the amount of miles traveled using low-cost electricity and reduce the required battery size in plug-in vehicles. PHEV charging was found to provide a flexible source of electric load that can maximize the use of solar PV, especially during low load periods. Solar PV was also found to meet the burden of increased peak generation requirements due to mid-day charging. Overall, the study concluded that solar PV and PHEVs have important complementary characteristics. A case study in Brazil by Soares [11] examined the use of plug-in electric vehicles to maximize intermittent renewable integration. This study was conducted in anticipation of large wind power capacity that will be installed in the region in future years. It was discovered that a fleet of 500,000 PHEVs by 2015 and 1.5 million PHEVs by 2030 with overnight charging would allow the region to eliminate the onset of excess wind generation and reduce the need to significantly modify the electric power system.

Querini et al. show that GHG emissions are almost always reduced for PEVs utilizing renewable electricity compared to traditional gasoline or diesel vehicles, regardless of the manufacturing location or manufacturing techniques of the renewable technologies [12]. However, the study does not consider