# Emissions Impacts and Benefits of Plug-in Hybrid Electric Vehicles and Vehicle to Grid Services

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**Abstract**

Plug-in Hybrid Electric Vehicles (PHEVs) have been promoted as a potential technologyNEV?s.2248.16e)]TJ 2he

# Introduction

Several studies (*1*), (*2*), (*3*), (*4*), (*5*) have found that when charged from the grid, plug-in hybrid electric vehicles (PHEVs) emit less $CO_2$ and certain other pollutants over their entire fuel cycle than conventional vehicles (CVs) and hybrid-electric vehicles (HEVs). Thus, PHEVs may reduce the emissions impacts of the transportation sector because in many regions grid electricity is effectively a cleaner source of transportation fuel than gasoline.

In addition to using a cleaner source of fuel, PHEVs may further increase the efficiency of electric generators and reduce overall emissions by providing two vehicle to grid (V2G) services (*6*), (*7*): energy storage and ancillary services (AS). As energy storage devices, PHEV batteries may be charged when the cost of generating electricity is low and discharged when it is high, decreasing the use of low efficiency, high emissions peaking generators. Ancillary services refer to the extra electricity capacity that power system operators must procure in order to balance electricity supply and demand in real-time. In this analysis we focus on the use of PHEVs to provide spinning reserves, capacity from generators that are online but reserved specifically to respond to unforeseen increases in electricity demand or generator outages. When PHEVs act as a source of spinning reserves, they allow the system to operate more efficiently, decreasing the emissions from peaking units and partially loaded power plants currently used to provide ancillary services. Our analysis assumes that the power system includes smart grid controls which will charge and discharge PHEV

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and when vehicles are available to connect to the grid to recharge or provide V2G services. The model further requires PHEV batteries be fully recharged each morning for the day's driving, but takes into account the flexibility in when a PHEV battery can be recharged and optimizes the timing of these charges to increase the efficiency of the generators that are used. We also capture the decreased use of generators that results from the PHEV spinning reserves and any associated reductions in emissions.

Modeling the changes in generation operation also allows for the potential to improve the accuracy of $SO_2$ and $NO_x$ emission rate estimates because those rates can vary with power plant load. We apply fixed emissions rates as well as emission rates that vary with the output of generators (both derived from historical continuous emissions monitors (CEMs) data) to estimate changes in $SO_2$ and $NO_x$ emissions.

Our results demonstrate that the flexibility in choosing when to charge PHEV batteries can result in significant generation efficiency gains by shifting load to more efficient generators. The generating efficiency gains that result from a PHEV fleet, either with or without V2G services, have the potential to reduce transportation-related emissions beyond currently reported estimates.

# Methods

Our analysis is based upon a unit commitment model of the Electricity Reliability Council of Texas (ERCOT) electric power system, the details of which are given in (*8*) and in the supporting information. The model simulates the commitment and dispatch of conventional generators as well as the dispatch of PHEVs to charge, discharge, and provide ancillary services when not being driven. The model dispatches the power system and PHEVs to minimize total operational costs, cycle life) as well as generation costs (both for serving PHEV and electric customer loads). Our analysis models vehicle and power system operations for the year 2005.

The supporting information, specifically Table 10, also describes assumptions regarding PHEV characteristics.

## Emissions Data

burning gasoline in the vehicle's engine, and upstream refinery emissions. Tailpipe emissions of $CO_2$ and $SO_2$ are determined based on the carbon and sulfur content of gasoline. While the carbon content of gasoline is fixed, the sulfur content depends upon the refining process and is generally subject to environmental regulation. We use the EPA's Tier2 requirement that gasoline sulfur content be below 30 ppm to estimate the tailpipe emissions rate of $SO_2$ (*14*). Tier2 also requires that tailpipe $NO_x$ emissions be less than 0.07 g per mile driven (0.043 g/km). In comparing tailpipe emissions of $NO_x$ from PHEVs to CVs and HEVs, we assume that CVs and HEVs will be designed to meet the Tier2 $NO_x$ requirements. Following (*2*) and (*15*) PHEV emissions are derived from HEVs emissions assuming a linear reduction in $NO_x$ based on the reduction in gasoline consumption. Upstream refinery emissions are estimated using the Greenhouse gases, Regulated Emissions, and Energy use in Transportation model (*16*).

# Results

Table 1 summarizes emissions of $CO_2$, $SO_2$, and $NO_x$ from generators with different-sized PHEV fleets (fleet sizes are given as the percentage of light-duty vehicles in ERCOT), without the fleet providing V2G services, assuming a fixed emissions rate. Our results show that the PHEV charging loads result in increases in generator emissions of $CO_2$ and $SO_2$, with marginal $CO_2$ emissions rates of between 582 kg/MWh and 935 kg/MWh and marginal $SO_2$ emissions rates of between 0.9 kg/MWh and 1.2 kg/MWh. $NO_x$ emissions from generators decrease during ozone season, however, due to the load-shifting and generation efficiency improvements caused by the flexibility in PHEV charging. Table 2 summarizes this effect by breaking down the generators into two sets—those which have a net increase in generation between a 0% and 1% PHEV penetration level, and those which have a net decrease in generation. The table show

in generator emissions due to partially loaded operation, and again demonstrates the sensitivity of emissions to shifting of loads between generators.

Table 3: Total annual emissions of $SO_2$ and $NO_x$ from generators [t] without V2G services provided by PHEV fleet, using a non-parametric estimate of the input $SO_2$ and $NO_x$ emissions rates. A separate non-parametric estimate is used for ozone and non-ozone seasons.

| PHEV Penetration | Generator Emissions | | |
|---|---|---|---|
| | $SO_2$ [t] | $NO_x$ [t] | |
| | | Ozone | Non-ozone |
| 0% | 449306 | 71258 | 69604 |
| 1% | 449657 | 69968 | 69678 |
| 5% | 450989 | 70019 | 69835 |
| 10% | 452100 | 69963 | 69985 |
| 15% | 452982 | 70126 | 70204 |

It is important to note that only fixed $CO_2$ input emissions rates are used in this analysis. $CO_2$ input emissions rates are dependent only on the carbon content of the fuel (typically about 50.7 kg/GJ for natural gas and 90.3 kg/GJ for coal) and do not vary w of the increase in emissions from introducing the PHEV fleet. For example, at the 1% level V2G services eliminate more than a quarter of generator emissions of $CO_2$ from introducing the PHEV fleet without V2G services. It is interesting to observe the large difference in the reduction of $CO_2$ and $NO_x$ emissions as compared to $SO_2$ emissions. The reason for this observation is that without V2G services, spinning reserves are typically provided by natural gas-fired generators, since their generation is more expensive than coal-fired generation. As such, if both a coal- and natural gas-fired generator have capacity available, it is more economical to reserve the capacity of the natural gas-fired generator and use the coal-fired generator to provide lower-cost energy. Thus, when PHEVs provide spinning reserves, they tend to reduce the need to keep natural gas-fired generators online. The low sulfur content of natural gas implies that V2G services will have more of an impact in reducing $CO_2$ and $NO_x$ emissions as compared to $SO_2$.

Table 4: Total annual emissions of pollutants from generators with different-sized PHEV fleets with V2G services provided by the PHEV fleet ($CO_2$ is reported in kilotonnes, $SO_2$ and $NO_x$ in tonnes). Estimates assume a fixed input emissions rate for $CO_2$, and a variable input emissions rate for $SO_2$ and $NO_x$, with a different $NO_x$ emissions rate for ozone and non-ozone seasons.

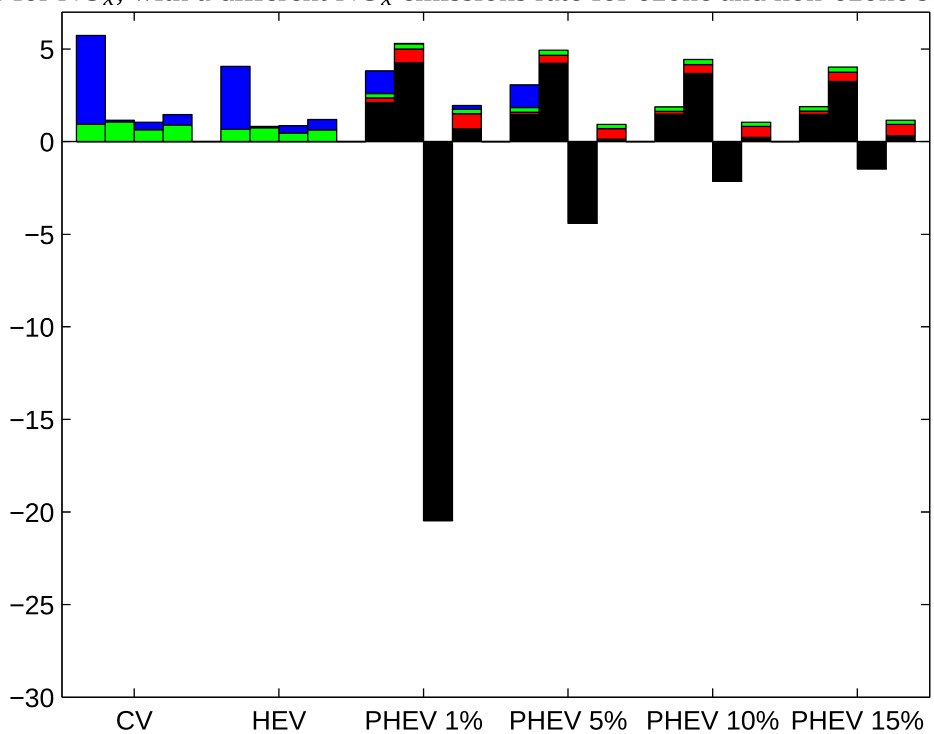
PHEV Penetration

As discussed in (*8*), the value and emissions reductions of V2G services stem mainly from their providing spinning reserves. The provision of spinning reserves from conventional generators requires part-load operations, resulting in efficiency losses as well as increased emissions. Thus, if a generator is online, it is more economical for it to generate electricity as opposed to holding some its capacity in the form of reserves. PHEVs, by contrast, do not need to be 'online' or incur any such cost when providing spinning reserves, thus they provide a costless source of capacity for the system. The emissions impact of V2G services is due to this same effect. Moreover, PHEVs do not burn any fuel idling if their battery capacity is used for spinning reserves. Our use of an input as opposed to an output emissions rate more fully captures this emissions impact of V2G services.

## Net Emissions Impact of PHEVs and V2G Services

The estimated PHEV charging emissions can be combined with estimates of tailpipe and certain upstream emissions to compare the net impact of PHEVs with CV emissions slightly less negative. The CV and HEV emissions assume the vehicles are driven with the same driving profiles used to simulate the PHEV fleet. CV and HEV fuel use were determined using the Advanced Vehicle Simulator (*17*) (

Figure 3: Total annual per-vehicle tailpipe, refinery, and generation emissions of pollutants with different-sized PHEV fleets, with V2G services provided by the PHEV fleet ($CO_2$-e is in t, $SO_2$ and $NO_x$ in kg). Estimate assumes a fixed input emissions rate for $CO_2$-e and $SO_2$ and a variable input emissions rate for $NO_x$, with a different $NO_x$ emissions rate for ozone and non-ozone seasons.



environmentally attractive in terms of total vehicle emissions. V2G services can substantially reduce generator emissions of $CO_2$, in some cases eliminating more than 80% of the increase in generator emissions of $CO_2$ from introducing the PHEV fleet. The impact of V2G on $SO_2$ is less than on $CO_2$, since most of the effect of V2G is to reduce the system's reliance on gas-fired generators, which have low $SO_2$ emission rates. Other potential applications of V2G services, such as frequency regulation (generators that automatically adjust their output on a second-by-second basis to ensure supply and demand are balanced), have not been considered in this study, due to some of the technical and market design complications raised in (*8*). Nonetheless, PHEV batteries and their extremely fast response times are very well-suited to frequency regulation applications, and market redesigns can make this application feasible. As such, the emissions reductions from V2G may be greater than the estimates given here.

The net changes in emissions and emissions rates presented here do not account for the shifting of emissions that may result from cap and trade programs or other environmental regulations. Increases in local $SO_2$ emissions from PHEVs must be compensated for by decreases elsewhere. Likewise, local decreases in $NO_x$ emissions from PHEV charging or V2G may result in excess permits that could be traded elsewhere (pending legal review of rules regarding $NO_x$ trading (*19*)).

One factor not considered in our analysis is the locational shift in emissions and its effect on exposure. Our results show that PHEVs can reduce tailpipe emissions of pollutants, to which populations would be exposed, and shift those emissions to generators, which tend to be outside of population centers. Although these emitted species can be transported over regional scales, humans will be exposed to lower concentrations of these species as compared to emissions from vehicle tailpipes due to dilutionasn2948(r)1.762693.525(O)559E43505-2.4628I0993(8(t)-233.8(o)-222.699(b)-15593(e3

(15) Electric Power Research Institute.

(26) East-West Gateway Coordinating Council. *Household Travel Survey: Final Report of Survey Results*; EWGCC: St. Louis, MO, 2003.

(27) Electric Power Research Institute. *Batteries for Electric Drive Vehicle—Status 2005: Performance, Durability, and Cost of Advanced Batteries for Electric, Hybrid Electric, and Plugicl E21.fl4(m)-0.7*

Table of contents brief: We analyze the total emissions impact of a plug-in hybrid electric vehicle fleet in Texas, both with and without vehicle to grid services, and demonstrate the potential for significant emissions reductions.

# Supporting Information

## Emissions Impacts and Benefits of Plug-in Hybrid Electric Vehicles and Vehicle to Grid Services

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6 Pages with 1 Figure and 4 Tables

Table 8: Range of input-based emissions rates of $SO_2$ [kg/GJ] for different generator types.

| Generator Type | Input-Based $SO_2$ Emissions Rate [kg/GJ] | | |
|---|---|---|---|
| | Minimum | Maximum | Average |
| Coal | 0.04 | 0.8 | 0.29 |
| Natural Gas | 0.00026 | 0.00026 | 0.00026 |
| Landfill Gas | 0 | 0 | 0 |

Table 9: Range of input-based emissions rates of $NO_x$ [kg/GJ] for different generator types.

| Generator Type | Input-Based $NO_x$ Emissions Rate [kg/GJ] | | |
|---|---|---|---|
| | Minimum | Maximum | Average |
| Coal | 0.02 | 0.22 | 0.07 |
| Natural Gas | 0 | 0.425 | 0.054 |
| Landfill Gas | 0.02 | 0.06 | 0.03 |

excess generating capacity of generators that are online (spinning reserves) is sufficient to provide an additional 4.5% of the system's load. An additional 4.5% of the system's load must also be met by non-spinning reserves, but this requirement can be served by generators which are not on-line. The spinning reserves are meant to have capacity standing by and able to react quickly to fluctuations in electricity supply or demand, whereas non-spinning reserves are slower-responding capacity that provides additional system flexibility for a persistent change in supply or demand. Load data in the model is based on actual load measurements provided by the Public Utility Commission of Texas, and we assume transmission and distribution losses of 5% (*23*).

## PHEV Data

For each set of model runs, the PHEV fleet is assumed to consist of a fixed number of vehicles. The total vehicle fleet size (consisting of both PHEVs and non-PHEVs) is taken from 2005 Texas vehicle registration information reported by the U.S. Department of Transportation's Federal Highway Administration. We assume that of the total vehicles in Texas, 85% are driven within and interconnect with the ERCOT control area (based on the fact that ERCOT serves approximately 85% of Texas's retail electric customers (*24*)). We conducted a series of model runs, assuming that the PHEV fleet would account for between 1% and 15% of the total ERCOT vehicle fleet.

Vehicle driving patterns are based on a household travel survey that was conducted by the East-West Gateway Coordinating Council in the St. Louis, Missouri metropolitan area, which is detailed in (*25*) and (*26*). The vehicle survey tracked the second-by-second driving patterns of 227 vehicles over the course of a number of weekdays. We assume that the PHEV fleet in our simulations is evenly divided into the 227 types with driving profiles corresponding to the driving pattern data. Furthermore, we assume that all vehicles of each PHEV type are dispatched identically—that is all the vehicles within a PHEV type are charged, discharged, and provide the same amount of AS in each hour.

The driving data are used to determine the hours in which the PHEVs are driven and the total distance traveled in that hour. We assume that hours in which a PHEV is not being driven it is connected to the grid through a charging station and can be dispatched to charge or discharge its battery or provide AS. In doing so, we assume that a PHEV must not be driving for an entire hour for it to be considered 'grid-connected,' which best simulates standard wholesale electricity market rules. This assumption reduces vehicle availability by around 18% compared to how long PHEVs