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 technology to reduce emissions of greenhouse gases and other pollutants by using electricity instead of petroleum, and by improving electric system efficiency by providing vehicle to grid (V2G) services. We use an electric power system model to explicitly evaluate the change in generator dispatches resulting from PHEV deployment in the Texas grid, and apply fixed and non-parametric estimates of generator emissions rates, to estimate the resulting changes in generation emissions. We find that by using the flexibility of when vehicles may be charged, generator efficiency can be increased substantially. By changing generator dispatch, a PHEV fleet of up to 15% of light-duty vehicles can actually decrease net generator NO_x emissions during the ozone season, despite the additional charging load. By adding V2G services, such as spinning reserves and energy storage, CO_2, SO_2, and NO_x emissions can be reduced even further.

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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 batteries depending on the cost of conventional generation and the need for ancillary services.

In this paper, we use a power system model that includes detailed generating unit constraints to simulate the operation of the Texas power system with PHEV fleets of varying sizes, with and without V2G services. The model captures the incremental emissions impacts of PHEVs and examines the changes in generator and vehicle emissions of CO_2, NO_x, and SO_2 in each fleet scenario. We explicitly model the limited flexibility in the operation of generating units (including minimum load constraints, ramping limits, and minimum up and down times), that can often force power system operators to use less efficient generators to serve a portion of the load. Our model includes detailed empirical driving pattern data, which determines battery depletion during trips 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, while ensuring generators and vehicles are all operated within their constraints, and that there is sufficient generating capacity available to serve the system's fixed and PHEV-charging loads. The operational costs modeled include all costs associated with PHEV operations (such as gasoline costs from vehicle driving, vehicle recharging costs, and costs associated with reductions in battery 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

Our analysis of the emissions impact of PHEVs charging loads and V2G services focuses on the three pollutants, CO_2, SO_2, and NO_x. Emissions of CO_2 and SO_2 are tracked on an annual basis, while NO_x emissions (an ozone precursor) are tracked during two periods: an ozone season (May through September) and a non-ozone season (the remaining months).

Generation-related emissions are broken down into generator emissions, and upstream emissions from fuel extraction and transportation. For estimating generator emissions, we use input-based emissions rates in our analysis, which give the mass of each pollutant released per unit of fuel burned. This use of an input emissions rate (as opposed to an output emissions rate, which gives mass of emissions per unit of electricity generated) allows our estimates to account for differences in generating efficiencies from part-load operation, as well as the fuel used and emissions released when generators are started up. Although generator emissions are often estimated as a single rate (*9*), this approach does not capture differences in emissions rates from part-load operations. Because PHEV charging loads and V2G services can result in shifting loads between generators, the emissions rates of generators can change noticeably when the vehicle fleet is added, beyond the impacts of heat rate variation. To capture the impact of input emissions rate variation, we use fixed and variable emissions rate estimates in our analysis. In addition to capturing variation in input emissions rate, we also differentiate NO_x emission rates (derived from CEMs data) between ozone and non-ozone seasons, to capture any seasonal differences in power plant emissions control operation and performance. The fixed rates are computed for each generator by dividing total emissions by the heat content of fuel burned, using CEMs data reported to the U.S. Environmental Protection Agency (EPA) for 2005. The variable rates are estimated using a nonparametric regression (*10*)

(*11*), which gives the emissions rate as a function of the heat content of fuel burned. Figure 1 shows actual NO_x rate data for the AES Wolf Hollow 1a combined-cycle gas unit during ozone season, along with the fixed and nonparametric rate estimates. The example highlights the fact that while the fixed rate estimate correctly captures the NO_x input emissions rate for fully-loaded operation, the actual NO_x rate is much higher for part-load operations and is not reflected in the fixed rate estimate. We use emissions rate estimates reported by Ventyx for generators that do not appear in the EPA's CEMs data. Table 7 through Table 9 in the supporting information summarize the range of emissions rates used in our analysis.

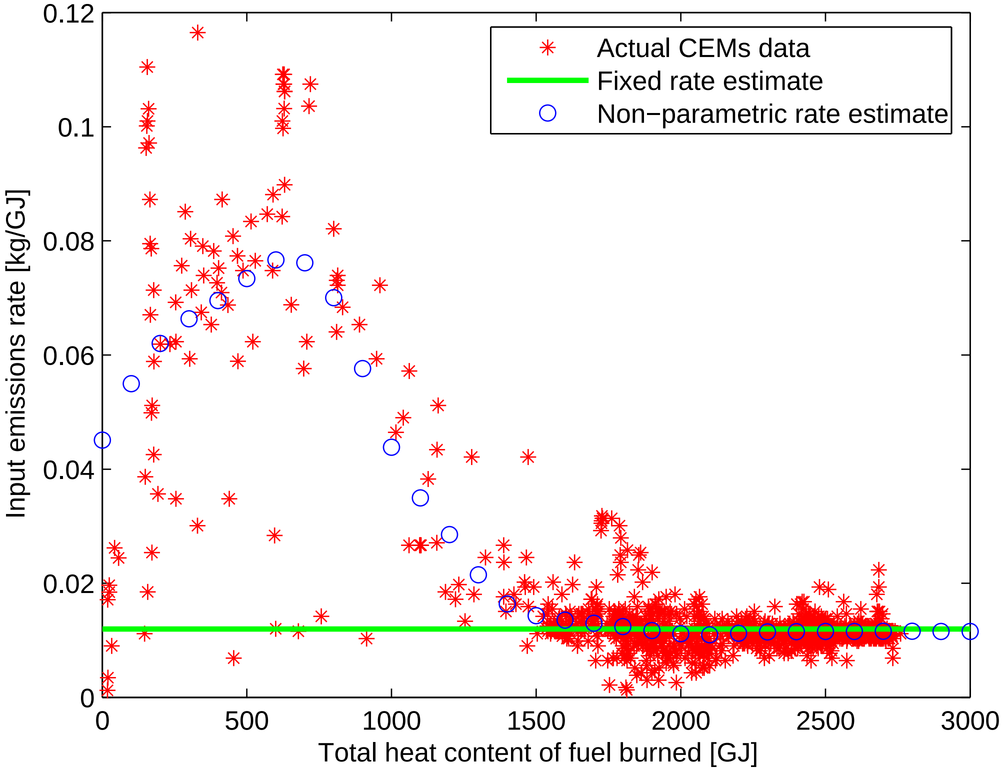


Figure 1: Comparison of fixed and non-parametric input based emissions rate estimates of NO_x for the AES Wolf Hollow 1a combined-cycle gas unit during ozone season.

Upstream generator emissions are based on estimates of CO_2, SO_2, and NO_x emissions from the extraction and transportation of coal and natural gas given in (*12*) and (*13*). It is worth noting that the CO_2 emissions given for natural gas extraction are actually CO_2 equivalent emissions, the bulk of which consist of methane losses in the extraction and transportation process.

Vehicle emissions are broken down into tailpipe emissions, which are pollutants released from 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 shows that although there is a net total increase in generation of 100354 MWh during ozone season, the shifting of load from less efficient to more efficient generators results in a decrease in the average incremental NO_x emissions rates of generators that are used (the average incremental emissions rate is the change in emissions between the 0% and 1% PHEV fleet sizes divided by the change in the heat content of fuel burned). It is important to note that the load shifting between the 0% and 1% PHEV penetration levels is done purely on an economic basis (*i.e.* without consideration of generator emissions), with the loads shifted to generators with lower heat rates. Much of this load shifting is from expensive 'peaking units' to less-expensive intermediate units, which could not be used without the flexibility inherent in PHEV charging loads due to operating constraints. The reduction in NO_x emissions is due to the economic efficiency gains—peaking unit tends to have higher emissions rates than the intermediate units to which their load is shifted. Indeed, Table 1 shows that NO_x emissions increase during non-ozone season. This is because the lower loads between October and April do not require the use of as much peaking generation and NO_x emissions rates are not reduced from load-shifting during non-ozone season.

Table 1 shows that NO_x emissions during ozone season decrease until a 1% PHEV penetration level, at which point they begin to increase. This is due to the fact that above the 1% PHEV penetration level many of the opportunities for efficiency gains from load-shifting are exhausted, as observed in (*8*). It is important to note, however, that despite this incremental increase in NO_x emissions above the 1% PHEV fleet size, NO_x emissions during ozone season with a 15% fleet size is still 1.0% lower than without any PHEVs, despite a 1.2% increase in generating loads.

Table 1: Total annual coal and natural gas burned [PJ] and emissions of pollutants from generators with different-sized PHEV fleets without V2G services provided by the PHEV fleet (CO_2 is reported in kilotonnes, SO_2 and NO_x in tonnes). Emissions estimates assume a fixed input emissions rate, with a different NO_x emissions rate for ozone and non-ozone seasons.

PHEV Penetration	Fuel Burned		Generator Emissions			
	Coal [PJ]	Natural Gas [PJ]	CO_2 [kt]	SO_2 [t]	NO_x [t]	
					Ozone	Non-ozone
0%	1422	1087	194387	453251	65441	64652
1%	1423	1090	194602	453510	64526	64691
5%	1426	1095	195183	454648	64617	64938
10%	1428	1102	195808	455627	64630	65177
15%	1430	1110	196461	456423	64812	65434

Table 2: Net change in generation [MWh], heat content of fuel burned [GJ], and NO_x emissions [t] during ozone season for generators with a net increase and decrease in generation between a 0% and 1% PHEV fleet size. Average incremental input and output NO_x emissions rates (g/GJ for input and g/MWh for output rates) are also given for the two groups of generators.

	Net Increase Generators	Net Decrease Generators
Δ Generation [MWh]	3392234	-3162030
Δ Heat Content of Fuel [GJ]	39033312	-35452629
Δ NO_x Emissions [t]	1014	-1891
Input NO_x Emissions Rate [g/GJ]	26.0	53.3
Output NO_x Emissions Rate [g/MWh]	299.0	598.0

Effect of Differences in Input Emission Rates From Part-Load Operation of Generators

Because the estimated reduction in NO_x emissions is critically dependent on the shifting of loads from less- to more-efficient generators, an important consideration is whether differences in input emissions rates between partially and fully loaded generators would impact this observation. Figure 1 gave an example of a generator with a much higher NO_x emissions rate when it is operated at part-load. Thus, the load shifting effect of PHEV charging loads could result in a higher NO_x emissions rate from generators that have their generation reduced. SO_2 emissions could also differ between full and partial operation, since some emissions control technologies may not work as efficiently at different generator operation levels. Table 3 summarizes annual SO_2 emissions and NO_x emissions during ozone and non-ozone season from generators, assuming the PHEV fleet does not provide V2G and that the SO_2 and NO_x emissions rates of generators could vary as a function of their operating points. As discussed before, we use a nonparametric normal kernel estimator to fit the emissions rate function to historical CEMs data. Table 3 shows similar results to Table 1. The absolute amount of SO_2 and NO_x emissions are estimated to be different than our estimates with a fixed emissions rate, due to different emissions rates from partially loaded generators, however the trend in emissions is similar. While SO_2 emissions increase with the PHEV fleet, NO_x emissions during ozone season show the same results by decreasing despite increased PHEV charging loads. Emissions decrease up to the 10% PHEV penetration scenario and increase thereafter. The increase in incremental emissions between the 1% and 5% scenarios results from the differences 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 with part load operation. Therefore the only effect on CO_2 emissions rates from changes in operation is variation in the efficiency of the power plant (*i.e.* the amount of fuel needed to generate a MWh of electricity), which is captured in the simulations through our use of input as opposed to output emissions rates.

Impacts of V2G Services on Generator Emissions

Results in the previous section consider a 'charge-only' scenario where vehicles do not provide V2G services. Table 4 summarizes generator emissions with the vehicle fleet providing V2G services. Since we believe the varying input emissions rates better captures actual emissions performance, results in this section use the non-parametric (variable) estimates of SO_2 and NO_x emissions rates. We again allow for NO_x emissions rates to vary between ozone and non-ozone seasons. Comparing these results to Table 1 and Table 3 shows that V2G services reduce generator emissions of CO_2 and SO_2, and can also reduce generator emissions of NO_x beyond the reductions achieved through load-shifting. Table 5 summarizes the generator emissions impacts of V2G services by showing the reduction in emissions when PHEVs provide V2G services as a percentage 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	Generator Emissions			
	CO_2 [kt]	SO_2 [t]	NO_x [t]	
			Ozone	Non-ozone
0%	194387	449306	71258	69604
1%	194547	449629	69708	69656
5%	194940	450911	69591	69658
10%	195509	452098	69634	69783
15%	196063	452990	69581	69970

Table 5: Reduction in PHEV charging emissions of CO_2, SO_2, and NO_x from V2G services. Reductions reported as a percentage of the increase in generator emissions from introducing the PHEV fleet, without V2G services. 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	Generator Emissions Reductions			
	CO_2 [%]	SO_2 [%]	NO_x [%]	
			Ozone	Non-ozone
1%	25.8	8.0	20.2	29.7
5%	30.5	4.6	34.5	76.6
10%	21.0	0.1	25.4	53.0
15%	19.2	-0.2	48.0	39.0

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

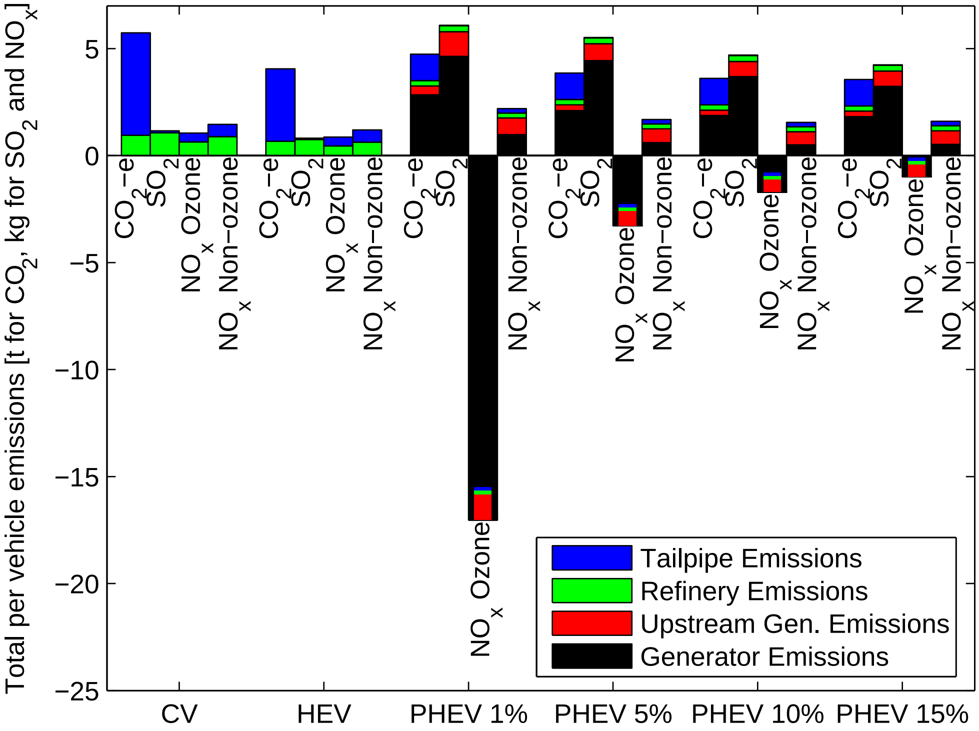
The estimated PHEV charging emissions can be combined with estimates of tailpipe and certain upstream emissions to compare the net impact of PHEVs with CVs and HEVs. Figure 2 and Figure 3 compare total annual per-vehicle emissions of CO_2-equivalent greenhouse gases (GHGs), SO_2, and NO_x from PHEVs to those from CVs and HEVs. The emissions are broken down between direct and upstream generation, refinery, and tailpipe sources. Direct generation emissions are calculated from the unit commitment model. Upstream generator emissions are derived from previous life-cycle analyses (*12*) (*13*) and include non-CO_2 GHGs, primarily methane leaks from natural gas extraction and delivery. It should be noted that this analysis is not intended to be a complete 'life-cycle' analysis and does not include emissions from power plant construction, maintenance, etc.

The generation emissions attributed to the PHEV fleet is calculated based on the incremental change in total generator emissions compared to the 0% PHEV fleet size, divided by the size of the PHEV fleet. The reductions in generator emissions of NO_x are attributed to the vehicle fleet, since these stem from the flexibility of battery recharging. Thus, PHEVs have a negative net NO_x emissions impact during ozone season. It is important to note, however, that tailpipe and refinery emissions of NO_x from PHEVs are both positive (as shown in the figures), making the PHEV 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*) (*18*), and assumed the CVs and HEVs are in the same vehicle class as the PHEVs with a fuel economy of approximately 11.1 km/l (26 miles/gallon).

The increased SO_2 emissions from PHEVs, compared to CVs and HEVs, is due entirely to the increase in generator emissions of SO_2 from vehicle charging loads. This increase in generation emissions of SO_2 can be further attributed to the use of coal-fired generators to serve the PHEV charging loads, since natural gas has extremely low sulfur content. In all of the PHEV scenarios analyzed, coal-fired generators provide between 22% and 33% of the incremental load. As such, the marginal output emissions rate of SO_2 ranges between 0.14 kg/MWh and 0.38 kg/MWh. Other studies of the emissions impacts of PHEVs have analyzed systems with different generation mixes, and have in some cases reported PHEVs reducing SO_2 emissions compared to CVs and HEVs (*3*). It is important to note, however, that because SO_2 emissions in the United States are capped, any increase in SO_2 emissions from PHEV charging loads would have to be offset by a decrease in SO_2 emissions elsewhere.

Comparing Figure 2 and Figure 3 shows a drop in generator emissions of PHEVs with V2G services, which stems from the reduction of emissions due to PHEVs providing spinning reserves. There is also a slight reduction in tailpipe and refinery emissions, which is caused by more conventional generating capacity being available for midday recharging of PHEV batteries. (*8*) noted that because the spinning reserves provided by the PHEV fleet reduces the need to procure AS from conventional generators, generators that are online have more capacity available with which to recharge PHEV batteries. This midday recharging of PHEVs allows for more miles on subsequent trips to be driven in charge-depleting mode (using electricity stored in the battery as the primary source of energy), further reducing tailpipe and refinery emissions.

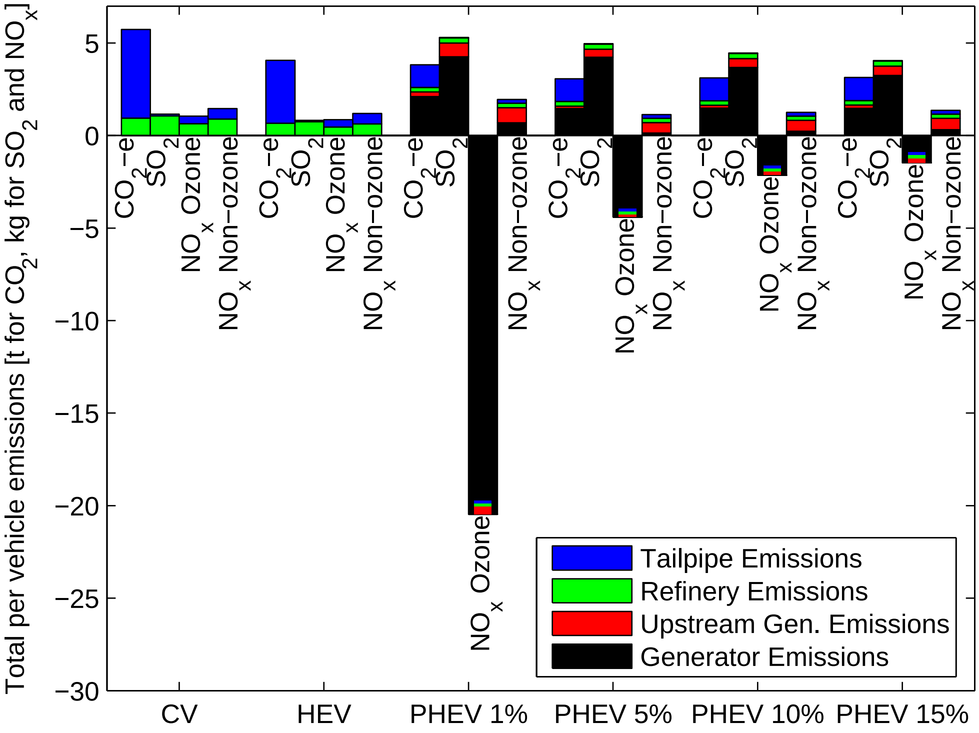
Figure 2: Total annual per-vehicle tailpipe, refinery, and generation emissions of pollutants with different-sized PHEV fleets, without V2G services provided by the PHEV fleet (CO_2-e is in t, SO_2 and NO_x in kg). Estimate assumes a fixed input emissions rate for CO_2-e and SO_2 and a variable input emissions rate for NO_x, with a different NO_x emissions rate for ozone and non-ozone seasons.



Discussion

The results of this analysis suggest that PHEVs can play a role in decreasing transportation-related emissions by using electricity as a source of energy, while the provision of V2G services can result in even more substantive emissions reductions. Moreover, the flexibility in choosing when to recharge PHEV batteries can have a noticeable impact on generator emissions—in the case of Texas reducing generator emissions of NO_x below the levels there would be without any PHEVs, despite the fact that generating loads are higher. Even more importantly, this reduction in NO_x emissions takes place during ozone season, when the environmental impact of NO_x tends to be highest. Our results showed that because coal-fired generation served at least a fifth of the PHEV charging loads, and due to the high SO_2 emissions rates of Texas coal generators, the net impact on SO_2 emissions would be an increase above emissions from CVs and HEVs. Other analyses of PHEVs, which have focused on other regions of the country, have shown that total net per-vehicle

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.



emissions of SO_2 can be reduced. For example, in a study of Colorado (*3*), with natural gas providing more than 80% of the charging energy, net SO_2 emissions from PHEVs are less than equivalent conventional vehicles (ignoring upstream generator-related emissions). This shows that the emissions impacts of PHEVs will be highly sensitive to the generation mix, and it may be prudent for future vehicle charging loads to be taken into account when generation investment is undertaken (as an example, a 2030 capacity expansion simulation for ERCOT (*1*) (*2*) found that new coal generation would be the most economic method of meeting large PHEV loads, increasing net emissions of PHEVs compared to the current grid modeled in this study). This also demonstrates the importance of detailed emissions impact studies for other power systems: ERCOT is a unique power system in that it has a great deal of natural gas and wind generation, and the emissions impacts of PHEVs may be different in other power systems.

Our analysis showed that V2G services can reduce generator emissions and make PHEVs more 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 dilution, chemical transformation, and deposition during long-range transport (*20*).

As discussed in the supporting information, our analysis made some simplifying assumptions in the unit commitment model. We assumed in the model that a PHEV must not be driven for an entire hour for it be connected to the grid and able to be recharged or provide V2G services. This assumption reduces vehicle availability by around 18% compared to how long PHEVs would be connected to the grid if we allowed vehicles to connect for less than an hour at a time. Conversely, this assumption may also overestimate the extent to which PHEVs would connect to the grid, since we implicitly assume charging stations are available for grid connections wherever PHEVs are parked and vehicle owners will always plug in their vehicles. Another assumption in the unit commitment model is that PHEV batteries will have a replacement cost of $3572, which is based on cost estimates in (*21*). Recent increases in battery-material costs suggest that these estimates may be too low. An increase in the cost of PHEV batteries will effect our analysis by increasing the cost of cycling a PHEV battery if it is used as an energy storage device. As discussed in (*8*), with the battery replacement cost of $3572 the cost of using a PHEV battery as an energy storage device is sufficiently high that PHEVs are very rarely used for energy storage. Thus, an increase in the battery replacement cost would have a negligible (if any) effect in reducing the use of PHEVs as energy storage devices, and would have a minimal effect on our results.

Another simplifying assumption made in our analysis of tailpipe emissions is that PHEV emissions of NO_x could be computed from HEV emissions assuming a linear reduction based on the reduction in gasoline consumption. This is a standard assumption that has been made in other emissions analyses of PHEVs (*2*) (*15*), largely due to the fact that commercial PHEVs are not currently available for emissions testing. This assumption may be underestimating tailpipe emissions of NO_x from PHEVs since extended electrical driving of a PHEV may result in more cold starts of the gasoline engine or longer catalyst light-off periods, which may result in higher NO_x emissions (*22*).

Importantly, the results of our analysis show that simple models that exclude generator and power system operating constraints may not properly capture the generation and net emissions impacts of PHEVs. To our knowledge, reductions in NO_x emissions due to increased load flexibility from PHEVs has not been observed in the literature. As such, many of these emissions impacts studies may understate the potential emissions reductions from introducing a PHEV fleet.

Acknowledgement

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-99GO10337 with the National Renewable Energy Laboratory. Any opinions and conclusions expressed in this paper are those of the authors and do not necessarily represent those of the Department of Energy or the National Renewable Energy Laboratory. The authors would like to thank Tony Markel and Armin Sorooshian for helpful suggestions and conversations. Tony Grasso of the Public Utility Commission of Texas provided invaluable assistance in gathering ERCOT market and system data.

Supporting Information Available

A more detailed explanation of the unit commitment model used in our analysis and a table summarizing model parameters. This material is available free of charge via the Internet at http://pubs.acs.org.

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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

Ramteen Sioshansi and Paul Denholm

6 Pages with 1 Figure and 4 Tables

Supporting Information

We describe the unit commitment model used in our analysis in more detail. The unit commitment model gives the hourly dispatch of all the generating units, as well as driving and battery data for the PHEV fleet. This PHEV data includes the state of charge (SOC) of the battery, whether the PHEV battery is being recharged or providing V2G services whenever it is connected with the grid, and the gasoline and battery usage in each hour in which the PHEV is driven. These outputs from the unit commitment model are then used to estimate generator, vehicle, and upstream refinery emissions. Figure 4 summarizes the flow of models.

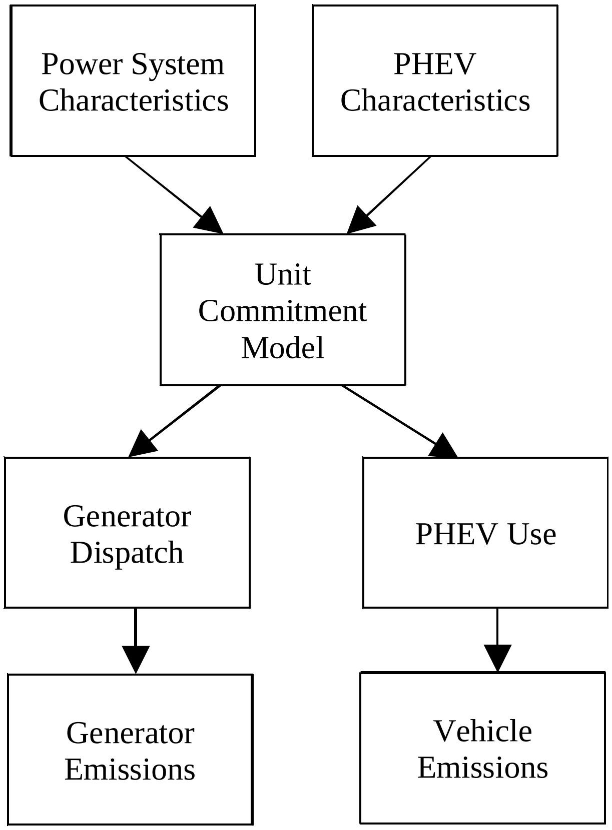

Figure 4: Flow of models in PHEV analysis.

Power System Data

Our model includes all conventional generators—consisting of thermal, hydroelectric, and wind generators—that were in operation in ERCOT in 2005. Conventional generator costs are modeled as consisting of three parts; a startup cost, which is incurred whenever a generator is started up; a spinning no-load cost, which is incurred whenever a generator is online; and a non-decreasing stepped variable cost function. Generation costs are estimated based on heat rates, fuel costs, and variable operation and maintenance costs data from Ventyx and Platts Energy. We also include the cost of SO_2 permits, but not CO_2 or NO_x prices, since they were not subject to a cap and trade program. Typical conventional generator constraints are modeled, including minimum and maximum generating output when a generator is online, minimum up and down times when a generator is started up or shutdown, ramping limits, and the amount of ancillary services (AS) a generator can provide. Constraint data were also obtained from Ventyx and Platts Energy. Hourly wind availability data was taken from a mesoscale model conducted by AWS Truewind for the Public Utility Commission of Texas. Table 6 through Table 9 summarize the heat and emissions rates for the generators in our data set.

Table 6: Number of units, total capacity [MW], and heat rate range [GJ/MWh] of different generator types.

Generator Type	Number of Units	Total Capacity [MW]	Heat Rate [GJ/MWh]		
			Minimum	Maximum	Average
Coal	28	16081	10044	13387	11289
Natural Gas	320	59717	7120	18991	10439
Hydroelectric	20	529	n/a	n/a	n/a
Wind	27	1880	n/a	n/a	n/a
Landfill Gas	7	44	10551	10551	10551

Table 7: Range of input-based emissions rates of CO_2 [kg/GJ] for different generator types.

Generator Type	Input-Based CO_2 Emissions Rate [kg/GJ]		
	Minimum	Maximum	Average
Coal	87.95	93.57	90.6
Natural Gas	50.71	50.71	50.71
Landfill Gas	0	0	0

The model includes hourly load-based AS constraints. These constraints require that the total

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 online. 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 would be connected for charging and providing V2G services if we allowed vehicles to connect for less than an hour at a time. Depending on the SOC of a PHEV's battery the vehicle will either be driven in charge-depleting (CD) mode, in which case the battery is the primary energy source and the gasoline engine is used only on a supplemental basis for quick accelerations, or charge-sustaining (CS) mode, in which case the gasoline engine is used to maintain the same average SOC (as in an HEV). Table 10 summarizes the assumed characteristics of the PHEVs, with complete details of vehicle assumptions and simulations provided in (*18*). Using the Advanced Vehicle Simulator, described in (*17*), the driving pattern data was used to simulate the average gasoline and battery energy usage for each PHEV driving profile in both CD and CS modes. As is typically proposed in PHEV designs, we assume vehicles are driven in CD mode until the battery SOC reaches 30% of the battery's maximum storage capacity, at which point it is driven in CS mode and remains at 30% SOC unless recharged by grid-connecting. We assume each PHEV battery has an energy storage capacity of 9.4 kWh, which corresponds to an electric-only driving range of about 35.9 km (22.3 miles), depending on the vehicle class (see (*15*), (*21*), and (*27*) for estimates of energy storage needs for different PHEV classes with different electric-only driving ranges). We further assume that PHEVs always have sufficient gasoline to operate in either CS or CD mode.

Table 10: Assumptions on design characteristics of vehicles in analysis.

Characteristic	Value
Battery storage capacity	9.4 kWh
Vehicle mass	1488 kg
All-electric range	35.9 km (22.3 miles)
Average energy use over drive cycle	23 km/l and 59 Wh/km (54 miles/gal. and 95 Wh/mile)
CD-mode electric energy use	0.183 kWh/km (0.295 kWh/mile)

PHEVs have two constraints on their dispatch as V2G resources: the energy storage limit of the battery and the power capacity of the plug used in the charging station (*7*). As discussed above, we assume each PHEV battery has an energy storage capacity of 9.4 kWh and that they can only be discharged to 30% SOC. We assume that the plug in the charging station has a power capacity of 5 kW, making it an average of a standard 120 V home circuit and a 240 V appliance circuit (derated for continuous duty), and assume that recharging a PHEV battery results in 10% energy losses and 7% losses when discharging it for V2G services, based on estimates in (*3*) and (*28*).

Discharging a PHEV battery for V2G services results in three costs, all of which are modeled in our analysis. The first is the cost of recharging the energy drawn from the battery, which is modeled by enforcing a constraint that each PHEV's battery must be fully recharged each morning. In this way the energy replacement cost is captured by requiring any energy discharged be replaced by the following morning. The second cost is any increase in gasoline costs due to the PHEV driving more CS-mode miles on subsequent trips if the battery is depleted by providing V2G services without a midday recharging. This cost is captured by including the total gasoline costs of driving in the cost function of the unit commitment problem, which directly accounts for any increase in gasoline costs. The retail cost of gasoline is taken from historical weekly price reports for the state of Texas from the U.S. Department of Energy's Energy Information Administration. The third cost is the reduction in the usable cycle life of the PHEV battery. The lithium-ion batteries that are proposed to be used in PHEVs have a usable cycle life that is a decreasing function of how much the batteries are discharged. As such, the dispatch of a PHEV to provide energy imposes a cost on the vehicle owner in that it shortens the expected lifetime of the battery, thereby increasing battery replacement costs. We represent this cost by modeling the expected battery life lost from each discharging of a PHEV battery and the associated expected battery replacement cost. We assume a PHEV battery has a replacement cost of $3572, based on estimates in (*21*), and use battery cycle life estimates in (*27*). These costs are all modeled in the unit commitment to ensure that the use of V2G service trades off the cost of those services with the benefits provided. An important question is whether sufficient benefits from providing V2G services accrue to PHEV owners to ensure that they make their vehicles available for V2G. As discussed in (*8*), if PHEV owners are paid for energy and ancillary services based upon the marginal value of those services, these payments far outweigh any costs and PHEV owners are made better off by making their vehicles available for V2G.