The Value of Plug-In Hybrid Electric Vehicles as Grid Resources[☆]

Ramteen Sioshansi

Integrated Systems Engineering Department, The Ohio State University, Columbus, Ohio, United States
Phone: +1-614-292-3932

Paul Denholm

National Renewable Energy Laboratory, Golden, Colorado, United States

Abstract

Plug-in hybrid electric vehicles (PHEVs) can become valuable resources for an electric power system by providing vehicle to grid (V2G) services, such as energy storage and ancillary services. We use a unit commitment model of the Texas power system to simulate system operations with different-sized PHEV fleets that do and do not provide V2G services, to estimate the value of those services. We demonstrate that a PHEV fleet can provide benefits to the system, mainly through the provision of ancillary services, reducing the need to reserve conventional generator capacity. Moreover, our analysis shows that PHEV owners are made better off by providing V2G services and we demonstrate that these benefits can reduce the time it takes to recover the higher upfront capital cost of a PHEV when compared to other vehicle types.

Key words: Plug-in hybrid electric vehicles, unit commitment, electricity markets

1. Introduction

Over the past few years a number of automobile manufacturers have announced plans to produce plug-in hybrid electric vehicles (PHEVs). PHEVs are similar to hybrid-electric vehicles (HEVs) except that they have batteries with a larger energy storage capacity, which can be recharged from the electric grid, allowing PHEVs to be driven over moderate distances without needing to use their combustion engines. Most PHEV designs currently being discussed call for a battery capacity allowing the vehicle to be driven between twenty and forty miles using the battery only.[1]

Beyond reducing gasoline usage and emissions, PHEVs can also potentially benefit the electric power system by giving the system operator (SO) flexibility in timing the charging of vehicles, yielding generating efficiency gains, and by providing vehicle to grid (V2G) services when they are parked and not being driven. These services include acting as an energy storage device that can be charged off-peak and discharged on-peak as well as providing ancillary services, such as spinning reserves, thereby reducing the need of the system to rely on conventional generators. Kempton and Letendre (1997) present a hypothetical example in which if 20% of Southern California's vehicle fleet has an electric drive system and one-third of them are

---

[1]Depending on the specific driving patterns and habits of the vehicle user and the powertrain configuration, the combustion engine may be needed for short periods within the 'electric-only' range to provide supplemental power due to 'high-power' driving events such as quick accelerations or steep inclines.

available to provide energy, they could contribute two-thirds of the (at that time) forecasted 2010 peak load of Southern California Edison. In addition to potential cost savings for the electric power system, the provision of V2G services could also give PHEV owners a revenue stream, which would reduce their lifetime ownership costs. While PHEVs have lower driving costs than HEVs and conventional gasoline-powered vehicles (CVs), they also have considerably higher upfront costs, mainly due to the battery. Denholm and Letendre (2007) estimate that on the basis of driving cost savings alone, a PHEV will take between six to eleven years to pay for its upfront cost premium over HEVs and CVs, depending on gasoline prices.[2]

In this paper we develop and analyze a detailed unit commitment model of the Texas electric power system with a PHEV fleet to quantify the potential cost savings from using PHEVs as V2G resources, and the value to PHEV owners of making their vehicles available to the SO in exchange for energy and ancillary service payments. Our analysis assumes a controlled charging scenario, in which the SO co-optimizes the charging of PHEVs with power system operations, subject to some minimum service requirements. Section 2 describes our model in detail and the data underlying our analysis. Our results, which are summarized in section 3, show that a PHEV fleet can provide savings to the power system as a whole—with a more than $200 per vehicle annual savings in some cases. We show that most of these savings come from the provision of ancillary services, which reduces reliance on conventional generators for capacity and allows the SO to commit fewer generators.[3] In addition to these savings to the system as a whole, we also show that PHEV owners can reap significant value from making their vehicles available to the system for V2G services. This value stems from energy and ancillary service payments as well as reduced vehicle driving costs due to conventional generators having more capacity available to charge PHEV batteries during the day, since the SO does not have to rely on generators for ancillary services. We demonstrate that these value streams give PHEV owners significant savings in excess of the system value of V2G and would reduce the lifetime ownership cost of a PHEV as compared to other vehicle types and incent their purchase. Section 4 presents three sensitivity cases: (i) higher gasoline costs, (ii) different vehicle purchase costs, and (iii) uncontrolled PHEV charging (i.e. individual drivers making charging decisions); to show the impact on PHEV ownership and power system operations costs. Section 5 concludes.

Our work builds upon other analyses that have evaluated the use of PHEVs as V2G resources, such as Kempton and Letendre (1997); Kempton and Tomić (2005). Our analysis differs from these studies in that they use historical wholesale electricity market prices to determine the value of V2G services, assuming that PHEVs will have a negligible impact on these prices, whereas we simulate the commitment, dispatch, and operation of the entire system. While analyses based on historical prices are quite useful for small PHEV fleets, with the high PHEV penetration levels suggested by some, the assumption of a negligible impact on market prices may be unrealistic. Indeed, our simulations of grid operations with and without V2G result in non-trivial changes in both energy and ancillary prices—stemming from PHEV charging needs increasing loads and ancillary service requirements, and from their provision of ancillary services dampening spinning reserve prices.

2. Model and Data

Our analysis is based upon a unit commitment model of the Electricity Reliability Council of Texas (ERCOT) electric power system, which we formulate as a mixed-integer linear program (MILP) using the General Algebraic Modeling System (GAMS) and solve using the branch and cut algorithm in cplex 9.0. 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. Thus, our analysis assumes a controlled charging scenario, in which the SO co-optimizes power system operations and PHEV charging. As is typical of day-ahead electricity markets, the unit commitment model has a one-day planning horizon with an hourly timestep for the commitment and dispatch variables. Each day in the sample, which

---

[2]Their estimates analyzed undiscounted costs, and as such understates the cost recovery time of consumers who would discount future driving cost savings.

[3]As we discuss in section 2, due to economic and market design considerations we model spinning and non-spinning reserves only but not frequency regulation. As such, our estimates of the value of V2G services are likely understated.

consists of the 365 days in 2005, is simulated independently, except that the commitment and dispatch of each conventional generator and the charge level of each PHEV battery at the beginning of each day is fixed based upon the ending values from the previous day's run. Moreover, each day's unit commitment is solved in two steps. The first is a unit commitment with a two-day planning horizon and a four-hour timestep for the commitment variables (the dispatch variables still have an hourly timestep in this first commitment problem), which is used to determine and fix the ending commitment and dispatch of each generator and charge level of each PHEV battery. After these variables are fixed, the one-day problem is solved with hourly timesteps for all variables. Appendix A gives a detailed mathematical formulation of the model used.

2.1. Power System Data

Conventional generators consist of all the thermal, hydroelectric, and wind generators that were in operation in ERCOT in 2005. Conventional generation 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 generating cost function. Generation costs were estimated based on heat rate values, fuel and emission permit prices, and variable operation and maintenance costs obtained from Global Energy Decisions (GED) and Platts Energy.[4] Typical conventional generation constraints are modeled, including: minimum and maximum operating points when a generator is online, minimum up and down times when a generator is started up or shutdown, and ramping limits; all of which were also obtained from GED and Platts Energy. Ancillary service qualifications, which indicate whether a unit is able to provide spinning or non-spinning reserves, were also obtained from GED, and the actual MW limit were computed from the ramp limits by assuming a 15-minute response time. We further assume that a conventional generator must be online in order to provide spinning reserves in a given hour, but can provide non-spinning reserves in either an on- or off-line state. Wind availability data was taken from a mesoscale model conducted by AWS Truewind for the Public Utility Commission of Texas.

The model includes hourly load-based ancillary service requirements consisting of a 4.5% spinning reserve requirement and a 9% total reserve requirement, which could be met by either spinning or non-spinning reserves. The model does not represent regulation procurements, since we assume PHEVs do not participate in the regulation service market. Although Kempton and Tomić (2005) note that PHEVs have extremely fast response times that would allow them to participate in the regulation market, we do not consider this application for several reasons. First, frequency regulation from a distributed PHEV fleet represents a number of technical challenges, both in modeling and in actual deployment, requiring tracking the state of a large PHEV fleet and the resulting availability for both up and down regulation. Second, current market rules may result in uneconomic dispatch of PHEVs that participate in the regulation market. This is because many SOs settle regulation calls at the prevailing real-time price of energy, which is set in the real-time spot market, but dispatch regulation resources without regard to generation costs—which could potentially result in a high-cost generator being dispatched at a net loss. As discussed below, because PHEVs incur a relatively high expected battery replacement cost when discharged, regulation sales may prove uneconomic—especially in off-peak periods when the real-time energy price tends to be low. Spinning and non-spinning reserves, by contrast, do not pose this problem since spinning and non-spinning reserves are deployed in real-time based on an economic dispatch model and are used in determining the real-time price of energy.[5] For these reasons, and the challenges of accurately modeling the frequent calls for regulation in the distributed PHEV fleet, we consider only spinning and non-spinning reserves in this work. We further assume that generators that provide spinning or non-spinning reserves must be capable of maintaining a full deployment of reserved capacity in real-time for two hours, which is a requirement of some SOs. As discussed below, this implies a PHEV must be connected to the grid for two consecutive hours and have sufficient energy stored to maintain a two hour-long deployment. Clearly, these assumptions regarding the ancillary service market will understate the potential value of V2G services. In peak periods in which the

---

[4]Nuclear generators are assumed to be non-dispatchable and run at full capacity and as such their generating costs are not modeled. Wind generation is assumed to be costless. Hydroelectric generation is assumed to have a fixed marginal cost based on an assumed water value obtained from GED, but no startup or no-load costs.

[5]Moreover, spinning and non-spinning reserves are called relatively infrequently, as discussed in Kempton and Tomić (2005).

real-time price of energy is expected to be high, participating in the regulation market would likely result in higher value with a low risk of an uneconomic regulation call. Moreover, some markets differentiate regulation down from regulation up, and a PHEV could offer regulation down service by increasing its charging load if it is deployed in real-time, which would not result in battery degradation. Similarly, given the high potential value of V2G services, SOs may be willing to relax some ancillary service qualification rules, such as maintaining a two-hour deployment, for PHEVs.

2.2. 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, of which we assume 85% to be driven within and interconnect with the ERCOT control area.[6] We conducted a series of runs with PHEV penetration levels between 1% and 15% of the total vehicle fleet.

Vehicle driving patterns are based upon 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 EWGCC (2003a,b). 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 is evenly divided into the 227 driving profiles corresponding to the driving pattern data. Furthermore, we assume that all vehicles of each PHEV type are dispatched identically—thus we model 227 different 'PHEV types' corresponding to the driving profiles. The total contribution to the objective function, and ancillary service and load balance constraints from each PHEV type is determined by multiplying the variables associated with each PHEV type by the number of PHEVs of that type.

The driving data was used to determine the hours in which the PHEVs are driven, the total distance traveled in that hour, and those in which they are grid-connected and could be dispatched to charge or discharge their batteries or provide ancillary services. In doing so, we assume that for a PHEV to be considered 'grid-connected' during an hour, it must not be driving for the entire hour. Depending on the state of charge (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. Using the Advanced Vehicle Simulator, described in Markel et al. (2002), the driving pattern data was used to simulate the average gasoline and battery energy usage for each PHEV driving profile (in gallons per mile and Wh per mile, respectively) 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 further assume that PHEVs always have sufficient gasoline to operate in either CS or CD mode.

We assume that hours in which a PHEV is not driven it has access to a charging station, at which it can be charged, discharged, or have its capacity reserved for ancillary services. As Kempton and Tomić (2005) describe, PHEVs have two constraints on their dispatch as V2G resources: the energy storage limit of the battery and the lesser of the power capacity of the on-board electronics and of the plug used in the charging station. We assume each PHEV battery has an energy storage capacity of 9.4 kWh, which corresponds to an electric-only driving range of between 20 and 40 miles, depending on the vehicle class,[7] and that the battery can only be discharged to a 30% SOC.[8] We assume the plug in the charging station has a power

---

[6]We assume 85% of Texas's motor vehicles are within ERCOT based on ERCOT serving approximately 85% of Texas's retail electric customers.

[7]See EPRI (2001, 2002, 2005) for estimates of energy storage needs for different PHEV classes with different electric-only driving ranges.

[8]We do allow a PHEV, however, to provide spinning or non-spinning reserves which would take the SOC below 30% if deployed, since spinning and non-spinning reserves are called sufficiently infrequently that this would be unlikely to occur. As described above, because of the requirement that a reserve deployment be sustained for two hours, we do require there be sufficient energy stored in the battery so the PHEV could maintain an ancillary service deployment for two consecutive hours without depleting the battery's storage level.

capacity of 5 kW, making it an average of a standard 120 V home circuit and a 240 V appliance circuit. The internal circuitry of a PHEV, by contrast, has a much higher capacity of at least 50 kW, and as such we limit the power of the circuit to the 5 kW capacity imposed by the plug. We assume that recharging a PHEV battery results in 10% energy losses and 7% losses when discharging it for grid services.

Discharging a PHEV battery results in three costs: recharging the energy drawn from the battery, any increase in gasoline costs due to the PHEV being driven in CS as opposed to CD mode on subsequent trips, and a reduction in the usable cycle life of the PHEV battery. The cost of recharging the battery is modeled by enforcing a constraint that each PHEV's battery must be fully recharged at 4am.[9] [10] In this way the energy replacement cost is captured by requiring any energy discharged be replaced. The additional gasoline cost incurred as a result of discharging a PHEV battery and increasing the number of CS miles driven is captured by including the total gasoline costs of driving in the objective 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. Finally, the lithium-ion batteries that are proposed to be used in PHEVs have a usable cycle life that is a decreasing nonlinear function of the change in depth of discharge (DOD), which is the percentage of total energy storage capacity at which the battery's SOC is left after being 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. EPRI (2005) estimates the cycling performance of PHEV batteries, giving the number of times a PHEV battery can be cycled as a function of the DOD. In order for this cost to fit within our MILP framework, we approximate this relationship using the four-segment piecewise-linear function shown in figure 1. We then impose a cost on each battery discharging based on the reduction in the number of usable battery cycles and a battery replacement cost—which we assume to be $3572, based on estimates in EPRI (2001, 2002, 2005). For example, since a PHEV battery can be cycled 12,000 times to 40% DOD, discharging a PHEV battery to that level would incur an expected battery replacement cost of:

$$\frac{1}{12000} \cdot \$3572 = \$0.2977.$$

Figure 2 plots the expected battery life lost and cost as a function of DOD, corresponding to the piecewise-linear approximation shown in figure 1. Ancillary service procurements, by contrast, do not incur any cost on PHEVs and are modeled as such.[11]

3. Simulation Results

3.1. System Costs of PHEV Charging and V2G Services

In order to measure the value of V2G services we simulate and compare the commitment, dispatch, and cost of conventional generator and PHEV fleet operations—both with and without PHEVs providing V2G services. In simulations with V2G services the model dispatches the PHEV fleet by determining MWh of

---

[9]Based on the PHEVs' assumed energy storage and power limits, it could take up to two hours to recharge a PHEV battery. Some vehicle types are being driven at 3 am or 4 am, and as such this constraint would be infeasible. In these instances, we enforce the 'battery recharged' constraint in the closest hour to 4 am in which the vehicle is not driving for two consecutive hours.

[10]As discussed above, the unit commitment model has a single-day planning horizon, which would normally not impose a requirement that energy discharged from a PHEV battery after 4am be replaced. We overcome this issue by imposing the 'battery recharged' constraint on each of the two days in the initialization unit commitment and fix the starting and ending SOC of each PHEV type's battery in the subsequent one-day unit commitment.

[11]Obviously if an ancillary service award is subsequently deployed in the hour-ahead or real-time market, that would incur a cost. Those deployments would, however, be made in a separate economic dispatch with an energy cost (based on the same components used to compute the cost of battery discharges for energy) represented in the model. For the purposes of reserving capacity in a day-ahead unit commitment, however, there is no cost incurred.
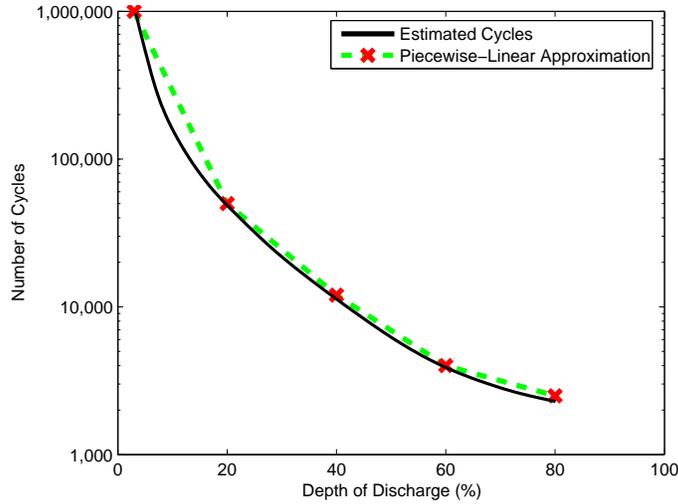
Figure 1: Estimated cycle life of PHEV batteries as a function of DOD and piecewise-linear approximation used in model.
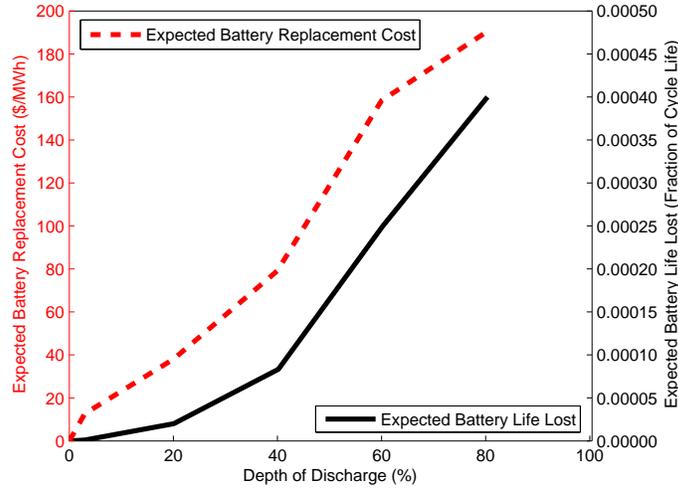

Figure 2: Piecewise-linear approximation of expected battery life as a function of DOD and equivalent expected battery replacement cost.

energy to charge and discharge, and MW-h[12] of ancillary service procurements to take from each PHEV type in each hour in which the vehicle type is not driving. Moreover, vehicle miles driven in CD and CS modes are also tracked in hours in which each PHEV type is driving, both to track the SOC of each PHEV type's battery after a vehicle trip and to account for increased (or decreased) driving costs resulting from a battery discharge (or recharge). Simulations without V2G services restrict PHEV discharges and ancillary service procurements to always be zero, but still allow flexibility in recharging PHEV batteries anytime the vehicle is not being driven—thereby allowing the SO to minimize the cost of recharging PHEV batteries.

Table 1 compares average daily power system operation costs (i.e. the cost of operating conventional generating units only) with and without V2G services provided by the PHEVs over the 365-day sample. The value of V2G services reported is the difference in system costs and shows that V2G services provide some value in reducing conventional generator costs. Indeed, at a 1% PHEV penetration level, the vehicle fleet

---

[12]A MW-h, which is a unit for one MW of ancillary service capacity provided for one hour, should be distinguished from a MWh, which is a unit of energy and is one MW of power provided for one hour.

benefits the electric power system in net, in that the additional generation costs stemming from recharging the fleet is less than the cost savings from V2G services.

Table 1: Average Daily Generation Costs With and Without V2G Services Provided by PHEV Fleet

PHEV Penetration	Generation Costs ($)		Value of V2G ($)
	With V2G	Without V2G	
0%	n/a	34,133,080	n/a
1%	34,117,191	34,153,689	36,498
5%	34,199,011	34,299,564	100,553
10%	34,353,691	34,492,594	138,903
15%	34,534,952	34,690,096	155,144

Table 2 summarizes total annual ancillary service and gross energy sales[13] from the PHEV fleet. The table highlights the fact that most of the value provided by V2G services stems from the provision of costless spinning reserves, since the PHEV fleet provides only a fraction of a percent of the electric load, whereas it provides up to two-thirds of the system's ancillary service requirements. Because conventional generators must be online, incurring a noload cost, to provide spinning reserves, there is an opportunity cost associated with reserving spinning capacity from a conventional generator which would otherwise increase its generating output to serve load. PHEVs, by contrast, do not incur any such costs due to the nearly instantaneous response times of vehicle batteries. The net effect of procuring spinning capacity from the PHEV fleet is that it allows the SO to commit less conventional generator capacity, since less of that capacity is needed to meet the ancillary service requirement.

Table 2: Gross Energy and Ancillary Service Sales of PHEVs

PHEV Penetration	Gross Energy Sales		Ancillary Service Sales	
	Total (MWh)	% of Load	Total (MW-h)	% of Ancillary Service Requirement
1%	21,813	0.01	1,575,298	5.84
5%	32,015	0.01	7,246,475	26.80
10%	86,830	0.29	12,927,893	47.62
15%	158,909	0.53	18,017,823	66.11

It is interesting to note that between the 10% and 15% PHEV penetration level, the PHEV fleet saturates the spinning reserve requirement, with the vehicle fleet providing more than 66% of the total ancillary service requirement at a 15% PHEV penetration level. Since only 50% of the ancillary service requirement must be met by spinning reserves, the additional 16% is displacing non-spinning reserves. Non-spinning reserves, in contrast to spinning reserves, can be served by conventional generators that are not committed, and as such there is no opportunity cost in procuring non-spinning capacity from conventional generation. Thus, the vehicle fleet's ability to reduce the commitment of conventional generation is exhausted at a 15% penetration level. This reduced effect of the PHEV fleet is reflected in the fact that the value of V2G services reported in table 1 grows non-linearly with the PHEV fleet, with a diminishing per-vehicle value of V2G services.

Table 2 also shows that PHEVs provide virtually no energy storage (i.e. although they provide ancillary services, very little energy goes through the storage cycle). This is primarily because of the high battery cycling cost associated with discharging the PHEV battery. Based on the battery cycling cost given in figure 2 and the inverter losses, a minimum difference of about $15.13 is needed between the cost of energy that is charged and discharged into the battery for energy storage to be economic. Coupling this large cost difference with the fact that PHEVs may not be available for charging and discharging at the right time explains the fact that very little energy storage is used. These results also tell us that if PHEV

---

[13]Gross energy sales is defined as total energy discharged from PHEV batteries in hours in which the vehicles are not driving. Net energy sales are always negative due to inverter losses and recharging PHEV batteries for vehicle miles driven.

batteries are more expensive or cycle more poorly than the estimates in EPRI (2001, 2002, 2005), which is a concern given uncertainty over batteries, the net effect on the value of V2G services would be marginal. This is because batteries that are more expensive or cycle more poorly would make energy storage more uneconomic, which would have little impact since energy storage is uneconomic with the assumed battery characteristics. Conversely, because the provision of ancillary services does not require energy to go through the storage cycle, the cost and cycling capability of batteries will have no impact on the value of V2G.

Comparing the generation costs reported in table 1 without V2G services across the rows shows that generation costs increase non-linearly with the size of the PHEV fleet. Table 3 shows average daily per vehicle charging costs, which is defined as the incremental generation costs (above the 0% PHEV penetration case) divided by the size of the PHEV fleet, and is considerably higher for a vehicle fleet larger than 1%. The difference in charging costs stems from the efficiency of the generators used to serve the incremental charging load with different-sized vehicle fleets. Table 4 shows the average incremental heat rate of the charging load, which is defined as the incremental heat content of fuel burned divided by incremental generation (above the 0% PHEV penetration case), and shows that generators that serve the charging load become significantly less efficient at a 5% fleet size and higher.

Table 3: Average Daily Per-Vehicle PHEV Charging Costs Without V2G Services Provided by PHEV Fleet

PHEV Penetration	Charging Cost ($)
1%	0.27
5%	0.44
10%	0.47
15%	0.49

Table 4: Average Incremental Heat Rate of Charging Load Without V2G Services Provided by PHEV Fleet

PHEV Penetration	Incremental Heat Rate (BTU/kWh)
1%	5,733
5%	7,795
10%	8,059
15%	8,105

It bears mentioning that the low incremental heat rate associated with a 1% PHEV fleet does not mean the charging load is served by generators with an average heat rate of 5,733 BTU/kWh. Rather, because of the flexibility the SO has in when it chooses to recharge the PHEVs, it is able to time these vehicle charges in such a way that it can commit an efficient generator to serve vehicle loads. This in turn allows the SO to decommit a less efficient generator that would otherwise serve a portion of the fixed customer load (i.e. non PHEV-charging load), and meet this load with the more efficient generator. This results in both the charging load and a portion of the customer load being served by a more efficient generator, which reduces the incremental heat rate. Without the vehicle charging load, unit operating constraints would not allow the more efficient generator to serve this load. In computing the incremental heat rate, efficiency gains in PHEV-charging and fixed customer loads are all allocated to the incremental charging load of the PHEVs, giving the low heat rate.

In addition to determining the value to the system of V2G services, another important consideration is the cost to and profits earned by PHEV owners from the provision of those services. These profits will both determine whether PHEV owners will make their vehicles available to the SO to be used as grid resources, and can affect individuals' decisions of whether to purchase a PHEV as opposed to an HEV or CV, since the revenue stream may reduce a PHEV's lifetime ownership cost in comparison to the other two vehicle types.

Table 5 breaks down average annual PHEV operating costs with and without V2G services provided and shows that in all but the 15% PHEV penetration case, gasoline and battery costs are lower when providing V2G services. This reduction in vehicle operation costs is due to the increased available capacity

of conventional generators that are committed (from which ancillary services are not needed due to the PHEV fleet providing capacity) being used for more midday recharging of PHEVs. This midday recharging increases the number of miles driven in CD mode, thereby reducing gasoline usage, and also helps maintain a higher SOC for PHEV batteries after vehicle trips, which reduces cycle life loss. It is important to note that although there is excess generating capacity available to recharge vehicle batteries, it is generally not economic to commit a unit and incur a startup cost solely for vehicle charging. The higher PHEV operating costs when providing V2G services with the 15% penetration level is due to the cost of battery discharges for V2G services outweighing the reduction in driving costs from midday recharging.

Table 5: Average Annual Per-Vehicle Costs With and Without V2G Services Provided

PHEV Penetration	Gasoline Cost ($)		Battery Cost ($)		Battery Cycle Life Loss	
	With V2G	Without V2G	With V2G	Without V2G	With V2G	Without V2G
1%	305	309	404	439	0.113	0.123
5%	306	309	413	439	0.116	0.123
10%	308	309	429	438	0.120	0.123
15%	311	309	441	437	0.123	0.122

Table 6 summarizes the net effect of V2G services on the power system and PHEV fleet by comparing the average daily cost of operating the electric power system and PHEV fleet with and without V2G services. The costs reported include both the cost of operating conventional generators, as well as the gasoline and expected battery replacement costs associated with driving the PHEV fleet. Thus, the cost savings in table 6 include any added cost of operating the PHEV fleet due to its provision of V2G services, and as such should be considered the total social value of V2G services. The results show that PHEVs can provide system savings of close to half a percent of total power system plus PHEV fleet costs.

Table 6: Average Daily Total System (Generation and PHEV Driving) Costs With and Without V2G Services Provided by PHEV Fleet

PHEV Penetration	System Costs ($)		Value of V2G ($)
	With V2G	Without V2G	
1%	34,264,420	34,308,891	44,471
5%	34,943,790	35,074,968	131,178
10%	35,884,592	36,042,209	157,617
15%	36,875,615	37,012,591	136,976

It is interesting to note in table 6 that the value of V2G decreases between the 10% and 15% PHEV penetration level, despite the fact that generation cost reductions from V2G services (shown in table 2) increase from the 10% to 15% penetration level. This decrease in the total social value of V2G services stems from the increased vehicle operation costs shown in table 5—although providing V2G services reduces daily conventional generator costs by $155,144, the provision of V2G services increases daily PHEV operation costs by $18,168, resulting in a net V2G value of $136,976.

Table 7 summarizes the net revenue impact of providing V2G services for PHEV owners, by showing the average annual per vehicle value of V2G services and the net increase in payoffs to a PHEV owner. The values of V2G services with different-sized PHEV fleets are taken from table 6, and divided by the number of PHEVs. The payoff to PHEV owners is computed based on payments received by PHEV owners for net energy sales (i.e. energy sold less vehicle charging) and ancillary services provided, assuming these are priced using the marginal cost of energy and ancillary services. From these payoffs, the net increase in gasoline and battery replacement costs stemming from the provision of V2G services are subtracted to yield the net increase in payoffs to PHEV owners. Our results show that PHEV owners fully recover the cost of providing V2G services and receive a higher payoff than the value they provide to the system.

Table 7: Annual Average Per Vehicle Value of V2G Services and Increase in Net Payoff to PHEV Owner

PHEV Penetration	V2G Value ($)	PHEV Owner Value ($)
1%	214	224
5%	126	137
10%	76	136
15%	44	123

3.2. PHEV Ownership Costs

The reductions in driving costs and energy and ancillary service payments discussed in section 3.1 can help to reduce the lifetime ownership cost of a PHEV, and reduce the amount of time it would take for a PHEV purchase to recover the higher upfront capital cost. Figure 3 shows the total average ownership cost of a CV, HEV, and PHEV (both with and without providing V2G services), for a 1% PHEV penetration level. The ownership cost of the CV includes only the gasoline cost associated with driving, which is based on simulations of gasoline usage for the same 227 driving profiles associated with the PHEV fleet. The simulations were conducted using the Advanced Vehicle Simulator described in Markel et al. (2002). The annual gasoline costs are an average over the set of driving profiles. The HEV costs includes a $4,058 capital cost 'adder,' which is the estimated incremental cost of an HEV (above the cost of a CV) for the battery, powertrain, and on-board electronics used in Denholm and Letendre (2007); as well as gasoline costs from the Advanced Vehicle Simulator using the same 227 driving profiles. The cost of the PHEV without V2G includes a $6,427 capital cost adder (this is an incremental cost of $6,427 above the cost of a CV), based on estimates in EPRI (2002); as well as gasoline and energy purchase costs. The cost of battery replacement is not included, since this cost is assumed to be sunk in the upfront purchase of the vehicle and including it would 'double-count' this cost, although we do note the expected time of battery failure.[14] The cost of the PHEV with V2G includes a $6,727 capital cost adder, with the additional $300 being the added cost of the V2G electronics, as well as gasoline costs and energy and ancillary service payments. Our simulations show that with V2G, a PHEV can recover its additional capital cost in just under seven and a half years, as opposed to just over nine years for a PHEV without V2G.[15]

4. Sensitivity of PHEV Costs to Assumptions

The results of our analysis will clearly be sensitive to a number of model and parameter assumptions made. We explore the sensitivity of the cost of PHEV ownership and battery charging to some assumptions underlying our analysis.

4.1. Cost of Uncontrolled Charging

Our analysis thus far has assumed a controlled charging case, in which the SO can time PHEV charging to minimize total system costs. While such a scheme will minimize the cost of recharging PHEV batteries, it can prove problematic in terms of PHEV integration. For one, sophisticated and distributed control, communications, and sensing systems will be needed for the SO to exercise this level of control over PHEVs, which will add further cost barriers for initial technology adoption. Secondly, consumers may be wary of giving complete control of vehicle charging to the SO. Although development of control technology and customer tariffs may eventually alleviate these issues, an interesting question is what effect an uncontrolled charging scenario, in which PHEV drivers make charging decisions, would have on PHEV costs.

In order to estimate the effect of uncontrolled charging on generation costs we examined an extreme uncontrolled charging case, in which PHEVs are charged whenever they are not driven. We assume that

---

[14]An alternative justification for this assumption is that most HEVs have battery warranties of at least 8 years and PHEVs are expected to have the same.

[15]It bears mentioning that like Denholm and Letendre (2007) these costs are undiscounted, and would underestimate cost recovery times for consumers who would discount future cost savings.
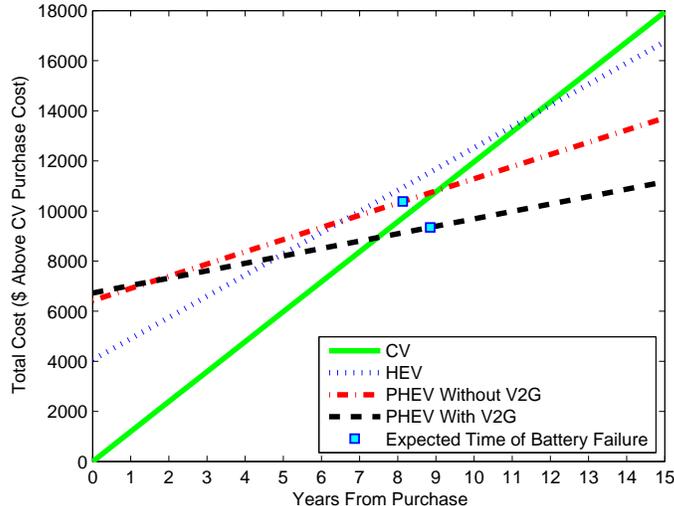
Figure 3: Lifetime ownership cost of a CV, HEV, and PHEV with 1% PHEV penetration.

when a PHEV charges, it will charge to the lesser of its power and battery energy constraints. Table 8 summarizes the average increase in daily generation costs with uncontrolled and controlled charging. The increases are given relative to the case with no vehicle charging. The 10% and 15% fleet size cases are not shown, since the entire charging load could not be served in the uncontrolled charging case. The table also shows the increase in generation costs with uncontrolled charging, as a fraction of the increase in costs with controlled charging. This last column highlights the fact that generation cost increases from uncontrolled charging are most pronounced with the 1% fleet size, since the loss of control by the SO does not allow the efficiency gains seen in tables 3 and 4.

Table 8: Average Daily Increase in Generation Costs (Above No Vehicle Case) with Controlled and Uncontrolled Vehicle Charging

PHEV Penetration	Controlled ($)	Uncontrolled ($)	Cost Increase (%)
1%	20,609	59,862	190
5%	166,484	264,641	59

4.2. Vehicle Capital Costs

Our analysis of PHEV cost recovery times in section 3.2 will clearly be sensitive to the upfront capital cost of purchasing the different vehicle types. The cost adders used in figure 3 were taken from Denholm and Letendre (2007) so that our analysis could be compared to theirs. Because PHEVs are still under development and the cost of battery manufacturing is still unknown, these cost estimates may be incorrect, which would affect the cost recovery time of a PHEV. For instance, Kromer and Heywood (2007) suggests that future HEVs may only cost $1,900 more than a CV. Figure 4 shows the lifetime ownership cost of the three vehicle types assuming HEVs have a cost adder of only $1,900 above a CV, and that PHEVs have a cost adder of $4,527 above HEVs (i.e. that they have the same cost premium above a CV as in figure 3). Figure 4 shows that with these lower costs, HEVs become considerably more attractive compared to other vehicle types, being the least expensive option if the vehicle is owned for between 5.5 and 8.8 years, with a PHEV with V2G services being the most attractive option beyond that. We can also use figures 3 and 4 to determine the impact of PHEV cost reductions (or increases) on PHEV cost recovery times. With the higher HEV cost adder of $2,369 a PHEV cost reduction of $901 would reduce the payback time by a year, whereas with the lower HEV cost adder of $1,900 a PHEV cost reduction of $549 would reduce the payback time by a year.
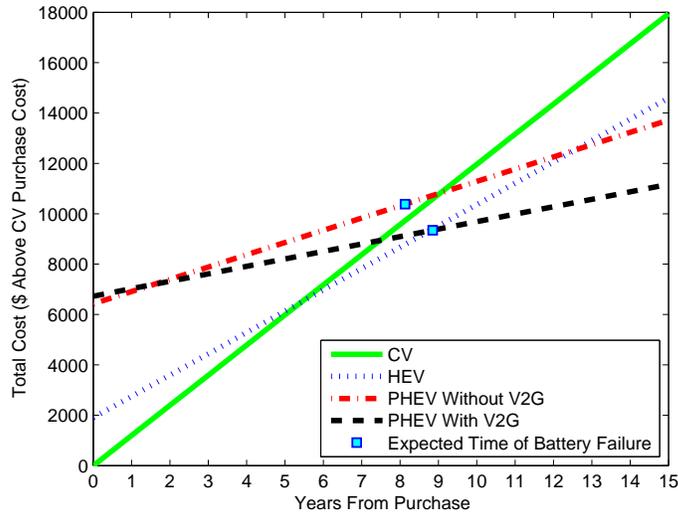
11

Figure 4: Lifetime ownership cost of a CV, HEV, and PHEV with 1% PHEV penetration and a $1,900 cost adder for HEV.

4.3. Gasoline Costs

Another important assumption in our estimates of PHEV cost recovery is the price of gasoline. While 2005 had relatively low retail gasoline prices—averaging about $2.20 per gallon in Texas—more recent years have seen some dramatic increases in gasoline prices. For instance, on 2 June, 2008, the average US retail price of regular-grade gasoline was reported at $3.98 by the Energy Information Administration. Although gasoline prices have dropped from their highs in 2008 (due in part to the current global recession), there are expectations that prices will eventually rise and perhaps surpass the levels seen in 2008. As such, we repeated our simulations, both with and without V2G services, assuming a retail gasoline price of $3.50 per gallon for the entire year. Our simulations result in roughly the same value of V2G services to the system and PHEV owner, averaging $207 and $224 per vehicle on an annual basis, respectively. Figure 5 shows the lifetime ownership costs of the different vehicle types with gasoline costing $3.50 per gallon, showing the cost recovery time of a PHEV is reduced to about four years and nine months.
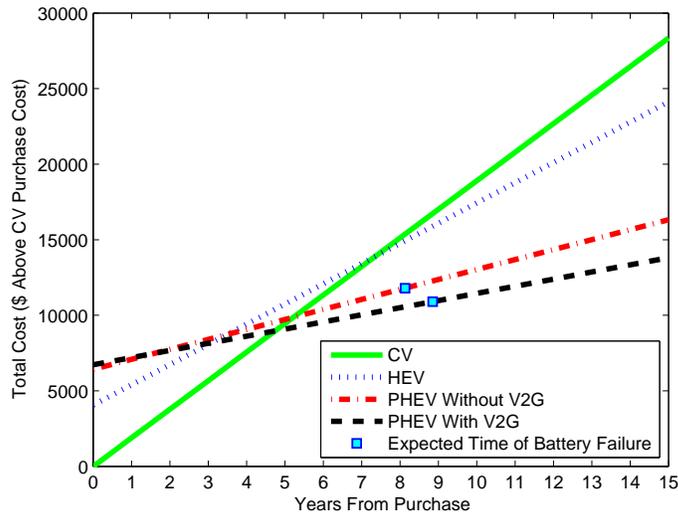

Figure 5: Lifetime ownership cost of a CV, HEV, and PHEV with 1% PHEV penetration and $3.50 per gallon gasoline.

12

5. Conclusions

We have estimated system operation cost savings from a PHEV fleet providing V2G services, as well as the value derived by PHEV owners. We have shown that a PHEV fleet can result in substantive cost savings for a power system of up to a more than $200 annual per vehicle savings. Moreover, the value of providing V2G services to PHEV owners, both from energy and ancillary service payments and slightly reduced driving costs, can help reduce the lifetime ownership cost of a PHEV and the time to recover the higher upfront capital cost from over nine years to about seven years. We further demonstrated the sensitivity of PHEV charging costs and ownership costs to uncontrolled charging, the capital cost of vehicles, and increases in gasoline costs.

It is important to stress that the analysis in this paper is illustrative to the extent that we have focused on the ERCOT power system, and excluded some potentially high-value V2G services. While PHEV charging will tend to impose additional costs on power systems, and flexibility in the timing of PHEV charging can provide the SO an opportunity to improve power system efficiency, these costs and efficiency gains will likely differ between power systems. Similarly, the value of V2G services and AS will also vary by power system. For instance, a power system with high penetration of wind may benefit significantly from V2G services and controlled PHEV charging, since the SO can use PHEVs to buffer wind supply variability. Another limitation of our analysis is that it does not consider some high-value V2G services, such as regulation. Assuming that some of the market design issues can be addressed, regulation is an AS that PHEVs can easily provide, given the nearly instantaneous response time of PHEV batteries. As such, the V2G values reported here may be viewed as a lower bound, insomuch as other high-value services were not considered in our analysis.

References

Denholm, P., Letendre, S. E., September 2007. Grid services from plug-in hybrid electric vehicles: A key to economic viability? In: Electrical Energy Storage—Applications and Technology Conference.

EPRI, 2001. Comparing the benefits and impacts of hybrid electric vehicle options. 1000349.

EPRI, 2002. Comparing the benefits and impacts of hybrid electric vehicle options for compact sedans and sport utility vehicles. 1006892.

EPRI, 2005. Batteries for electric drive vehicle—status 2005: Performance, durability, and cost of advanced batteries for electric, hybrid electric, and plug-in hybrid electric vehicles. 1010201.

EWGCC, January 31 2003a. Household travel survey: Final report of survey methodology. East-West Gateway Coordinating Council.

EWGCC, January 31 2003b. Household travel survey: Final report of survey results. East-West Gateway Coordinating Council.

Kempton, W., Letendre, S. E., September 1997. Electric vehicles as a new power source for electric utilities. Transportation Research Part D: Transport and Environment 2, 157–175.

Kempton, W., Tomić, J., June 2005. Vehicle-to-grid power fundamentals: Calculating capacity and net revenue. Journal of Power Sources 144, 268–279.

Kromer, M. A., Heywood, J. B., 2007. Electric powertrains: Opportunities and challenges in the U.S. light-duty vehicle fleet, publication Number LFEE 2007-03 RP.

Markel, T., Brooker, A., Hendricks, T., Johnson, V., Kelly, K., Kramer, B., O'Keefe, M., Sprik, S., Wipke, K., August 22 2002. ADVISOR: a systems analysis tool for advanced vehicle modeling. Journal of Power Sources 110, 255–266.

A. Unit Commitment Model Formulation

The unit commitment model used in our analysis is presented. We first define the following problem parameters:

- T: number of hours

- I: generator index set

- V: driving profile set

- $C_i(q_i)$: generator i's non-decreasing stepped variable generating cost function

13

- N_i: generator i's noload cost

- SU_i: generator i's startup cost

- K_i^-, K_i^+: generator i's minimum and maximum operating points, respectively

- R_i^-, R_i^+: generator i's rampdown and rampup limits, respectively

- $\overline{SP}_i, \overline{NS}_i$: generator i's spinning and non-spinning reserve capacities, respectively

- τ_i^-, τ_i^+: generator i's minimum down- and up-time, respectively

- NV_v: number of PHEVs with driving profile v

- $\overline{p}$: power limit of PHEV charging station plug

- $\overline{e}, \underline{e}$: maximum and minimum SOC of PHEV battery, respectively

- $b(\delta)$: expected battery replacement cost as a function of DOD, δ

- γ: cost of gasoline

- ce, de: charge and discharge efficiencies of PHEV battery, respectively

- $dist_{v,t}$: distance driving profile v drives in hour t

- cd_v^W: average net battery energy usage of driving profile v when in CD mode

- cd_v^G, cs_v^G: average gasoline usage of driving profile v when in CD and CS modes, respectively

- D_t: system load in hour t

- ρ^s, ρ^t: spinning and total reserve requirements (as a fraction of load), respectively

We now define the following decision variables:

- $q_{i,t}$: generation provided by generator i in hour t

- $sp_{i,t}, ns_{i,t}$: spinning and non-spinning reserves provided by generator i in hour t, respectively

- $u_{i,t}, s_{i,t}, h_{i,t}$: binary variables indicating if unit i is up, started-up, and shutdown in hour t, respectively

- $SOC_{v,t}, ch_{v,t}, ds_{v,t}, \delta_{v,t}$: ending SOC, energy charged into and discharged from battery, and DOD of a PHEV with driving profile v in hour t, respectively

- $Vsp_{v,t}$: spinning reserves provided by a PHEV with driving profile v in hour t

- $cd_{v,t}^m, cs_{v,t}^m$: miles driven in CD and CS mode, respectively, by a PHEV with driving profile v in hour t

- $\widetilde{cd}_{v,t}$: binary variable indicating whether a PHEV with driving profile v is in CD mode in hour t

The problem is formulated as minimizing total system costs, which consist of conventional generator costs and PHEV operation costs:

$$\min \sum_{t \in T} \left(\sum_{i \in I} (C_i(q_i) + N_i u_{i,t} + SU_i s_{i,t}) + \sum_{v \in V} NV_v(\gamma \cdot (cd_v^G cd_{v,t}^m + cs_v^G cs_{v,t}^m) + [b(\delta_t) - b(\delta_{t-1})]^+) \right);$$

14

subject to the following constraints:

$$D_t = \sum_i q_{i,t} + \sum_{v \in V} NV_v(de \cdot ds_{v,t} - ch_{v,t}/ce) \quad \forall\, t \in T \qquad \text{// load-balance}$$

$$\sum_{i \in I} sp_{i,t} + \sum_{v \in V} NV_v Vsp_{v,t} \qquad \forall\, t \in T \qquad \text{// spinning reserves}$$

$$\geq \rho^s \left(D_t + \sum_{v \in V} NV_v ch_{v,t}/ce \right)$$

$$\sum_{i \in I} (sp_{i,t} + ns_{i,t}) + \sum_{v \in V} NV_v Vsp_{v,t} \qquad \forall\, t \in T \qquad \text{// total reserves}$$

$$\geq \rho^t \left(D_t + \sum_{v \in V} NV_v ch_{v,t}/ce \right)$$

$$K_i^- u_{i,t} \leq q_{i,t} \qquad \forall\, i \in I, t \in T \quad \text{// minimum generator output}$$

$$q_{i,t} + sp_{i,t} \leq K_i^+ u_{i,t} \qquad \forall\, i \in I, t \in T \quad \text{// maximum generator output}$$

$$q_{i,t} + sp_{i,t} + ns_{i,t} \leq K_i^+ \qquad \forall\, i \in I, t \in T \quad \text{// maximum potential generator output}$$

$$sp_{i,t} \leq \overline{SP}_i \qquad \forall\, i \in I, t \in T \quad \text{// maximum generator spinning reserves}$$

$$ns_{i,t} \leq \overline{NS}_i \qquad \forall\, i \in I, t \in T \quad \text{// maximum generator non-spinning}$$
$$\text{reserves}$$

$$R_i^- \leq q_{i,t} - q_{i,t-1} \qquad \forall\, i \in I, t \in T \quad \text{// generator ramp down}$$

$$q_{i,t} - q_{i,t-1} + sp_{i,t} + ns_{i,t} \leq R_i^+ \qquad \forall\, i \in I, t \in T \quad \text{// generator ramp up}$$

$$\sum_{y=t-\tau_i^+}^{t} s_{i,y} \leq u_{i,t} \qquad \forall\, i \in I, t \in T \quad \text{// generator minimum up time}$$

$$\sum_{y=t-\tau_i^-}^{t} h_{i,y} \leq 1 - u_{i,t} \qquad \forall\, i \in I, t \in T \quad \text{// generator minimum down time}$$

$$s_{i,t} - h_{i,t} = u_{i,t} - u_{i,t-1} \qquad \forall\, i \in I, t \in T \quad \text{// generator state transitions}$$

$$SOC_{v,t} = SOC_{v,t-1} + ch_{v,t} \qquad \forall\, v \in V, t \in T \quad \text{// PHEV battery charge balance}$$
$$- ds_{v,t} - cd_v^W cd_{v,t}^m$$

$$1 - \delta_{v,t} = SOC_{v,t}/\overline{e} \qquad \forall\, v \in V, t \in T \quad \text{// PHEV DOD definition}$$

$$cd_{v,t}^m + cs_{v,t}^m = dist_{v,t} \qquad \forall\, v \in V, t \in T \quad \text{// PHEV driving requirement}$$

$$Vsp_{v,t}/de \leq SOC_{v,t} \qquad \forall\, v \in V, t \in T \quad \text{// PHEV charge spinning reserves bound}$$

$$SOC_{v,t} - (ds_{v,t} + ds_{v,t+1}) + ch_{v,t} \qquad \forall\, v \in V, t \in T \quad \text{// PHEV two-hour sustained discharge}$$
$$\geq 2Vsp_{v,t} \qquad\qquad \text{spinning reserves bound}$$

$$\widetilde{cd}_{v,t} \geq \frac{SOC_{v,t} - \underline{e}}{\overline{e} - \underline{e}} \qquad \forall\, v \in V, t \in T \quad \text{// PHEV CD mode definition}$$

$$cs_{v,t}^m \leq dist_{v,t}(1 - \widetilde{cd}_{v,t}) \qquad \forall\, v \in V, t \in T \quad \text{// PHEV CD to CS mode transition}$$

$ch_{v,t}, ds_{v,t}, Vsp_{v,t} = 0$ $\forall\, v \in V, t \in T \mid dist_{v,t} > 0$ // no PHEV recharging or V2G when driving

$\underline{e} \leq SOC_{v,t} \leq \overline{e}$ $\forall\, v \in V, t \in T$ // variable bounds

$0 \leq ch_{v,t}, ds_{v,t} \leq \overline{p}$

$u_{i,t}, s_{i,t}, h_{i,t} \in \{0,1\}$ $\forall\, i \in I, t \in T$ // integrality of commitment variables

$\widetilde{cd}_{v,t} \in \{0,1\}$ $\forall\, v \in V, t \in T$ // integrality of PHEV variables