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

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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 di erent-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 o 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.

K y wor s Plug-in hybrid electric vehicles, unit commitment, electricity markets

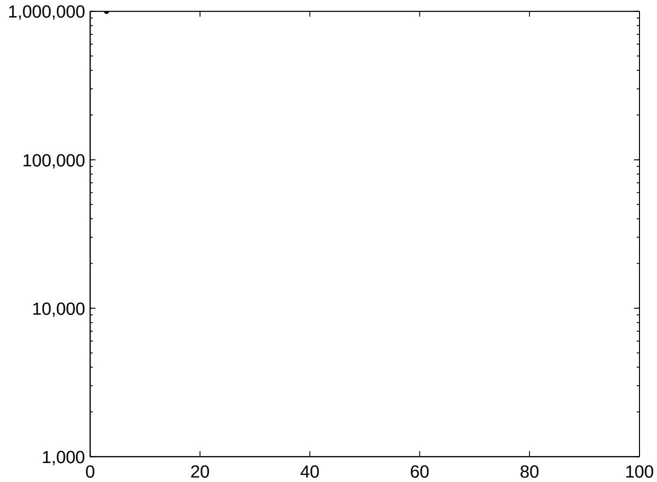
Introduct on

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 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 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.

ow r yst 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 emis

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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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.

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 e ect 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) 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 e ect 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.

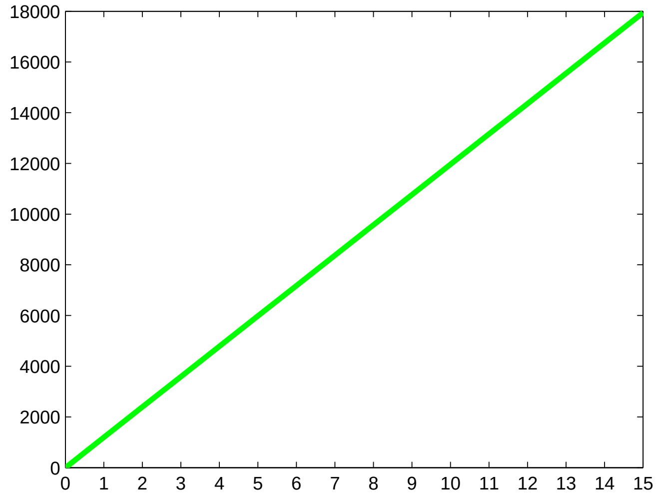
Table 6: Average Daily Total System (Generation and PHEV Driving) Costs With and Without1.22406.00878(V)-322.006(fl)1.4ha6(n)3.08773(a)4

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

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

HEV wn rs p 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



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16000
14000
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8000
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4000
2000
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0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

b Conc us ons

- $_i$: generator i's noload cost
- $_i$: generator i's startup cost
- $_i^-$, $_i^+$: generator i's minimum and maximum operating points, respectively
- $_i^-$, $_i^+$: generator i's rampdown and rampup limits, respectively
- $\overline{}_i$, $\overline{}_i$: generator i's spinning and non-spinning reserve capacities, respectively
- $_i^-$, $_i^+$: generator i's minimum down- and up-time, respectively
- $_v$: number of PHEVs with driving profile
- $\overline{p}$: power limit of PHEV charging station plug
- $\overline{}$, $\underline{}$: maximum and minimum SOC of PHEV battery, respectively
- $b(\ )$: expecte.5.048(S)122632]TJ /R1089.96264Tf -20

$_{v,t}$, $_{v,t}$, $p_{v,t} = 0$, J $_{v,t} >$