1. Introduction

Plug-in hybrid electric vehicles (PHEVs) have received a great deal of attention due to their potential to reduce the use of petroleum in the transportation sector. PHEVs are similar to hybrid electric vehicles now being sold, but feature a larger battery and plug-in charger that allows electricity from the grid to replace a portion of the petroleum-fueled drive energy.

The PHEV electric performance is designated by the nomenclature “PHEV-XX”, with XX representing the vehicle’s battery storage capacity in miles, such as PHEV-20. It should be noted that a PHEV-20 will not necessarily be able to travel 20 miles on pure electric drive. An “optimized” power train configuration may require blended mode (electric and IC engine) travel at high speeds, during heavy acceleration, or while traveling at grade. Much of the ongoing research and analysis has focused on vehicles with about 20 miles of electric range, which appears to be a reasonably optimal combination of battery size and vehicle performance. The 20 mile range also approximately matches typical daily driving habits. Simulations of a PHEV-20 with average driving patterns and a single charge per day estimate that the vehicle would derive about 40 percent of its miles from electricity [1].

The per mile cost of a vehicle operating on grid electricity is significantly less than when operating on gasoline; electricity at 10 cent per kWh is the equivalent to gasoline at about $1.50 per gallon. When charging with low-cost off-peak electricity, the difference between electric operation and gasoline operating can be even greater. Despite the substantially reduced operating costs, there is considerable uncertainty as to whether consumers will be willing to pay the substantial up front premium for a plug-in hybrid, given demonstrated sensitivity to “first costs” and very high consumer discount rates.

2. Limits to Consumer Adoption of PHEVs

Consumer attitudes towards current hybrids may provide some lessons as to the possible adoption of PHEVs. Sales of hybrid electric vehicles are dominated by the Toyota Prius, with sales of hybrid versions of other popular vehicles such as the Honda Accord and Ford Escape less than predicted. At least two reasons have been given for this disparity. Most dominant is probably the Prius’ image. It has a unique shape and is instantly recognizable as a hybrid, advertising its owner’s desire to reduce emissions, environmental impact, or reliance on foreign oil. Also, the Prius is also only available as a hybrid; there is no non-hybrid version to provide consumers a side-by-side comparison of initial purchase price and operating costs. There is anecdotal evidence that when consumers are given the choice between a conventional and hybrid version of the same vehicle, first costs dominate the decision making process. This should not be a surprise, since high sensitivity to first costs has been consistently demonstrated in consumer adoption behavior of appliances and other energy consuming products.

This sensitivity to first costs could have important implications for the large-scale adoption of plug-in hybrid electric vehicles. There is a significant cost “adder” associated with a PHEV’s larger battery, charger, and drivetrain components. This cost adder is dominated by the battery, and there is considerable uncertainty as to the future price of safe, reliable batteries produced in large volumes. Estimates of future costs under large scale manufacturing are in the range of $2500-$5500 [1,2].

This cost adder must be paid for by the gasoline savings over time; this “payback time” can be considerable depending on the anticipated cost of gasoline. Figures 1 and 2 illustrate several scenarios of cumulative non-discounted costs for a PHEV-20, deriving 40% of its miles from electricity, driving 13,000 miles per year. Costs include only purchase and fuel costs, and do not consider other operation and maintenance. Charging electricity is assumed to be 8 cents/kWh, and two PHEV cost “adders” are assumed: $3000 and $4500. Figure 1 assumes gasoline at $3/gal, while Figure 2 assumes gasoline at $4/gal. In all cases, the payback times for PHEVs exceed 6 years. Nearer term scenarios of higher battery prices and lower gasoline costs have payback times that can exceed 10 years. This payback time approaches the average
lifetime of the vehicle, and market studies of efficient appliance adoption indicates that this payback time is far too long to be adopted by more than a small minority of consumers.

Figure 1: Cumulative non-discounted cost of four vehicle options with gasoline at $3/gallon.

Figure 2: Cumulative non-discounted cost of four vehicle options with gasoline at $4/gallon.

3. Increasing PHEV Acceptance Via Vehicle to Grid Technology

It has been noted that by selling grid services via “vehicle to grid” (V2G) technology, the electrical energy storage capability of PHEVs may add additional value to the vehicle owner and increase economic viability. Bulk energy storage services such as load shifting would require greater battery capacity than PHEVs are likely to offer, and also require frequent cycling of the batteries, reducing battery life. Most of the focus of V2G has been on services that require relatively high power capacity, but with little actual energy delivery.
Possible examples include peak reserve capacity and certain ancillary services such as frequency regulation and spinning reserve.

Spinning reserve may provide one of the best applications of V2G from PHEVs. Spinning reserve represents the ability of the electric power system to rapidly respond to system contingencies such as the failure of a large power plant or transmission line. In order to provide spinning reserve, a power plant must be running and synchronized to the grid and ready to provide energy rapidly, ramping in a few minutes. Spinning reserves are called upon infrequently; in the PJM market in 2006, spinning reserves were called upon only 39 times, for an average of 9 minutes per event.

A power plant providing spinning reserves is not being optimally utilized – this can result in a less than optimal heat rate, lost opportunity costs, and overall market inefficiencies associated with non-optimal unit commitment and dispatch of the entire power plant fleet. It is difficult to estimate these costs in regulated utility regions, but some market data is available to estimate the “marginal” cost of spinning reserve. Table 1 provides several examples of spinning reserve prices in U.S. markets, with an overall range of $8 - $17 / MW-hr. (A MW-hr is a unit of capacity available over time, not energy.)

<table>
<thead>
<tr>
<th>Market / Year</th>
<th>Spinning Reserve Value ($ / MW-hr)</th>
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<tbody>
<tr>
<td>PJM 2004</td>
<td>15</td>
</tr>
<tr>
<td>PJM 2005</td>
<td>17</td>
</tr>
<tr>
<td>NY-ISO 2005</td>
<td>7.5</td>
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<tr>
<td>ERCOT 2005</td>
<td>8</td>
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<tr>
<td>ISO NE 2004</td>
<td>15</td>
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<tr>
<td>ISO NE 2005</td>
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A PHEV (or stationary battery) represents an almost ideal source of spinning reserves. It is always “synchronized” with the grid without actually operating under part load conditions, and can ramp almost instantaneously, unlike thermal power stations. The capacity actually offered by a PHEV would be limited by the plug circuit. A typical low voltage household appliance circuit (120V @ 20 Amp derated to 85% continuous) would provide a continuous rating of about 2 kW, while an appliance circuit (240V @ 40 Amps) would provide just over 8 kW continuous. Dedicated charging stations could provide even higher current levels and corresponding capacity.

Assuming the use of only household-type circuits, Figure 3 illustrates the potential annual revenue from a PHEV providing spinning reserves. A total of 4 cases are shown considering circuits rated at 2.0 and 8.1 kW, and reserve values of $7/MW-hr (low) and $15/MW-hr (high).
The potential revenue offered by V2G could reduce payback times and increase customer adoption of PHEVs. Figures 4 and 5 illustrate the simple payback times associated with a PHEV-20 under the same conditions as Figures 1 and 2, but with the additional benefits of the provision of spinning reserves providing benefits equal to $600/year. (This value is in the higher range of values in Figure 3, but could also consider a transaction penalty cost.) An additional initial cost of $300 has also been added to the PHEV to enable V2G.

Figure 4: Reduction in PHEV-20 payback time when introducing spinning reserve benefits, with gasoline at $3/gallon and V2G benefits of $600/year.
Figure 5: Reduction in PHEV-20 payback time when introducing spinning reserve benefits, with gasoline at $4/gallon and V2G benefits of $600/year.

At $3/gallon, the addition of V2G has reduced the payback time to about 6.5 years for the more expensive battery case, and just under 5.5 years for the lower cost battery case. The higher gasoline scenario reduces payback times by about a year.

Figure 6 illustrates the relationship between decreasing battery costs and reduced incentives needed to achieve a five year payback. Early PHEV adopters could benefit from the high value V2G services to create a market that drives down the cost of batteries. There are limits to the size of the spinning reserve market, as well as all capacity services that PHEVs could provide. As PHEVs penetrate the market, the various capacity markets will be saturated, and there will be a decrease in per vehicle benefit.

Figure 6: Annual Owner Incentive Required to Achieve a 5-Year Payback
As battery prices fall, or as the price of gasoline increases, alternative, potentially lower value V2G options could be deployed. In addition to other ancillary services, with both controlled charging and V2G capability, PHEVs may also further enable the use of intermittent renewable energy sources such as solar and wind. The arrow in figure 6 represents one of a large family of trajectories that could ultimately lead to a self-sustaining PHEV market with minimal incentives.

4. Conclusions

While PHEVs will provide consumer benefits of reduced gasoline and operating costs, the higher first cost of PHEVs may provide a significant barrier to large-scale adoption. Vehicle-to-grid technology offers a possible solution by providing high-value grid services from the vehicle’s batteries. The highest value services could help create a market for early, higher-cost PHEVs, allowing for continued reduction in battery costs and a sustainable PHEV market.

There are a number of barriers to implementing V2G from PHEVs. There are no provisions for non-utility provision of ancillary services in much of the U.S. In places where markets do exist, rules generally do no allow small loads and generators to participate in ancillary service markets. In addition to changes in market rules, new business models need to be created to aggregate the large number of individual vehicles, and systems must be developed to ensure vehicles can be remotely controlled safely and reliably.

5. References

