01 Sep 2008

Utilization and Effect of Plug-In Hybrid Electric Vehicles in the United States Power Grid

Steven D. Jenkins

John R. Rossmaier

Mehdi Ferdowsi
Missouri University of Science and Technology, ferdowsi@mst.edu

Utilization and Effect of Plug-In Hybrid Electric Vehicles in the United States Power Grid

Steven D. Jenkins, John R. Rossmaier, *Member*, *IEEE*, and Mehdi Ferdowsi, *Member*, *IEEE*
Power Electronics and Motor Drives Laboratory
Missouri University of Science and Technology
Rolla, MO 65409, USA
Email: sdjt2d@mst.edu, jrrvgf@mst.edu, and ferdowsi@mst.edu

***Abstract*—Plug-in hybrid electric vehicles (PHEVs) are uniquely capable of providing both transportation and battery storage interconnection to the electric power grid. This ability allows PHEVs the possibility of serving the power grid in the capacity of a mobile energy storage unit, providing the grid with additional stability, reliability, cost-effectiveness, and efficiency. Additionally, with the higher fuel efficiency of PHEVs, the transportation and power generation sectors can collectively reduce their ecologically harmful emissions and increase their reliance on environmentally friendly energy sources. These concepts are still new and under development; in this paper, the viability of the PHEV as a mobile energy storage unit connected to the power grid is examined from a power system perspective, involving an examination of practicality, reliability, short- and long-term economics, and alternative energy storage units.**

***Keywords*—Energy Storage Unit; Plug-in Hybrid Electric Vehicle; Power Systems; Vehicle-to-grid**

I. Introduction

The United States electric power grid is beginning to show signs of its age. In an ever modernizing world, the stress and strain of unique and increasingly nonlinear operating loads on a 50 year old electrical system built to deliver constant power to linear devices is beginning to take its toll. The rising demand of total power is also taxing current transmission and distribution systems, increasing the number of cascading failures, rolling blackouts, and other large-scale problems in the grid. These increasing system failures are having a rather pointed impact on the national economy, costing US electric power consumers at least $79 billion per year [1]. Rolling blackouts and power outages can cost credit card businesses upwards of $2.5 million dollars per hour of down time, and an hour-long loss of power at the Chicago Board of Trade in 2000 prevented over $20 trillion in trades from being executed [2]. These problems will only become more prevalent and costly if they are not addressed in the near future. Electricity demand is expected to increase well into the future as the American economy continues to expand and grow (see Figure 1) [3], and the present-day power grid is not equipped to handle such a continuous rate of development. There are good reasons to adopt vehicle-to-grid (V2G) technology as electric grid improvements are desired along with better reliability but accompanied by the desire to avoid building more power plants and transmission lines [4].

There has been movement in recent years to modernize the aging US power grid and bring the 20th century infrastructure up to date with a 21st century economy [3, 5, 6]. Most of the investigations associated with this movement tend to reach some of the same conclusions. The electric power grid of the future needs to be reliable, providing dependable power and swift correction. It must be secure, capable of withstanding natural disasters and both physical and digital attacks to the system. It must be economical, able to provide power at appropriate cost as determined by supply and demand. It must be efficient, with emphasis placed on measures which help mitigate cost. And finally, of particular interest to certain groups [6], the future power grid must be environmentally friendly. Improvements in the interaction of electric utilities and the transportation industry could result in significantly improved air quality [7]. Although this may be an idealized view of the future of the power grid, researchers and developers are still dedicated to determining the most feasible solutions to the power problems of today.

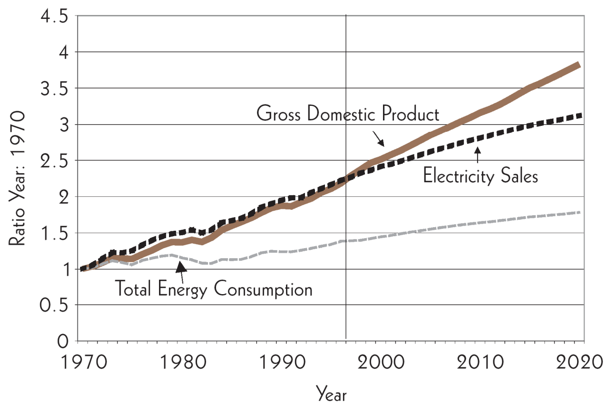

Fig. 1. Projected growth of the electricity market [3]

A portion of the problem comes from the daily behavior of the power grid itself. Electricity demand is not constant over a 24-hour timeframe, tending to rise sharply during the midday hours in comparison to the few hours after midnight. This drastic shift in hourly power demand requires the repeated start-up and shut-down of faster-operating, higher-cost energy sources, such as natural gas plants. The off-and-on operation of these more expensive plants causes the energy prices to fluctuate hour to hour, with low power generation rates around 5 ¢/kWh up to high rates around 30 ¢/kWh [8]. Ideally, the overall power generation for the electric power grid should be uniform; a constant state of operation would allow generators to maximize energy production efficiency while minimizing the necessary start-up and shut-down costs associated with discontinuous power scheduling.

978-1-4244-1849-7/08/$25.00

Additionally, a number of power sources, including wind and solar power generation, cannot be scheduled or regulated like standard coal or nuclear power plants. Wind and solar generation always operate at maximum output, and their operation schedules are determined by the nature of the weather, so the power generated by them cannot always be applied during peak demand hours.

Figure 2 shows what a typical load curve might look like over a 24-hour period. Note the peak around 6 pm and the deep trough at night.

One method of mitigating both problems is with the utilization of energy storage units (ESUs) connected to the power grid. This allows generators to operate at a consistent power delivery schedule, producing additional power during off-peak hours to be stored for later usage. This helps improve the reliability of the power grid while reducing the use of spinning reserves in the power system and stabilizing the power generation rate at a more cost-effective value [8]. Additionally, ESUs can be employed to store energy produced by intermittent sources to be used during peak demand hours. A light plug-in hybrid eclectic vehicle (PHEV) fleet has enormous energy storage capacity [10].

Most ESUs connected to the power grid have been small or medium scale stationary units such as batteries, flywheels, ultracapacitors and others [11]. Recently however, attention has been drawn to an emerging technology as another possibility for an ESU, PHEV. The PHEV utilizes the same technology as a hybrid electric vehicle (HEV) but includes a larger battery accompanied with the ability to connect to the power grid [12]. Battery technology is already undergoing constant development and research in order to improve the storage capacity and driving range of PHEVs. Additionally, the nature of the vehicle itself suggests regular connection to the power grid to maintain a fully charged battery. It would seem like a logical extension for these mobile ESUs, connected in significant numbers, to serve as energy storage for the power grid. With the crude oil market trend, mobile ESUs are becoming a more viable option [13].

There are many concerns involving the use of PHEVs as ESUs connected to the power grid. This paper is primarily concerned with how the PHEV fits into the vision for the future power grid as described previously and whether or not more acceptable alternatives exist. Research concerning power delivery, scheduling, response time, and cost for PHEVs connecting to a power system have been investigated and the results summarized. The results are then compared with conventional power system solutions.

II. Feasibility Studies

There are a number of factors involved in determining whether or not a fleet of PHEVs will be capable of supplementing the power grid as an energy storage unit. These factors include but are not limited to: 1) market penetration of the PHEVs, 2) battery storage capacity, 3) battery charging/discharging speed, 4) cost and complexity of V2G communications network, 5) cost of residential and commercial charging/discharging stations for PHEVs, 6) consumer driving habits, 7) local power demand curves, 8) charging/discharging stations for PHEVs, 8) consumer driving habits, 9) local power demand curves, 10) environmental effect, and 11) overall difference in cost for the shift in transportation fuel consumption to power generation fuel consumption. Additionally, many of these factors are difficult to significantly analyze and discuss since fields such as battery capacity are undergoing constant research and breakthroughs. The electric utilities grid and a fleet of PHEVs are very complementary in energy and power management [14]. It is believed that consumers would be more likely to buy PHEVs even though they are more costly because there are tax incentives, reduced gasoline costs, less maintenance, and a convenience of being able to charge the vehicle at home [15].

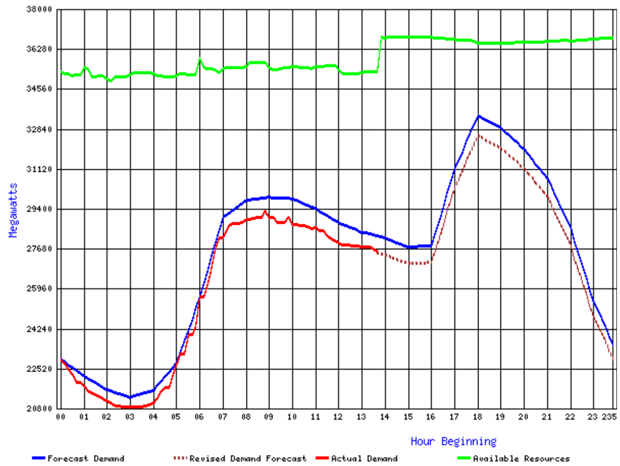

Fig. 2. Load curve [9]

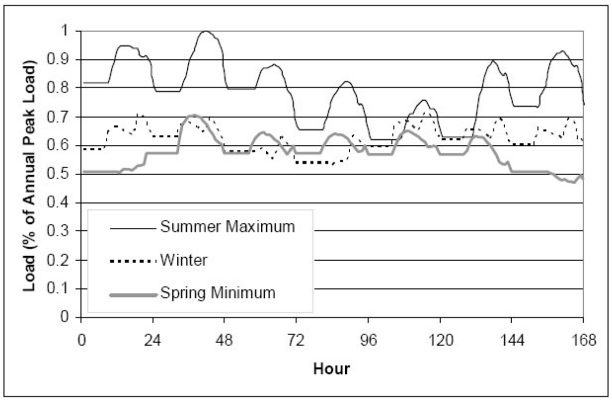

Fig. 3. Daily demand load with PHEVs at 50% market penetration (Midwestern Region) [16]

One feasibility study has focused primarily on whether or not a large market penetration of PHEVs drawing power from the electrical power grid would require greater amounts of connected generation in order to supply the loads [16]. In order to simplify this preliminary study, certain assumptions were made as to the nature of the vehicles and the amount of control the utilities had over the times that the vehicles connected to the system would charge and discharge. The battery capacity of the average fleet vehicle was estimated to be 10.2 kWh given current battery technology. Since full control of the dispatch of PHEVs was assumed for the utilities, a simple dispatch routine was run to schedule the charging of PHEVs during off-peak hours of power demand. A reproduction of the dispatch is shown in Figure 3.

According to the study, and backed by Figure 3, a 50% market penetration of PHEVs all charging under optimal dispatch conditions would not necessitate the installment of new generation for the Midwest. The study also examines the discharge capability of these same PHEVs during peak daily power loads, effectively replacing "super-peak" capacity – generation which provides a significant fraction of installed capacity but is only used during peak demand hours. The results from the study show that the capacity of just a 10% market penetration of PHEVs could replace 25% of the installed generation capacity in most regions of the United States, assuming that the PHEVs are delivering roughly 7 kW per vehicle.

Though the results speak rather favorably on the use of PHEVs in conjunction with the electric power grid, there are a few items that need to be taken into consideration. First of all, a 50% market penetration of PHEVs may take some amount of time to accomplish, even given the current US economy. Many of the findings from this test may only be applicable after a couple of decades have passed, assuming that PHEVs gain market favor. In addition, this study also assumes the absolute management of resources by the utilities, allowing them the ability to dispatch the charging and discharging of PHEVs as needed. Realistically, this would require some form of communication between the vehicles and a centralized controller, as well as some agreement between businesses and utilities as to the timing and management of PHEV charging and discharging.

A second more recent feasibility study performed a similar analysis using the energy consumption of the VACAR (South and North Carolina and much of Virginia) energy supply region [17]. One test performed under this study compared the effects of time of charging on the power demand for the system. In this instance, rather than having all vehicles scheduled to charge in a manner to "fill in the valleys" like the previous test, the charging times were instead scheduled at a distribution of times either during night (Figure 4a) or during the evening (Figure 4b).

The results from this test verify that nighttime charging is much more beneficial to the current power system, as it would not require additional generation capacity to be developed. However, as shown in Figure 4b, if the fleet of PHEVs were allowed to charge merely a few hours earlier, at least 2 GW of additional generation would have to be met to meet this demand. Electric utility rates will be driven higher if introducing PHEVs requires adding generation, transmission, and distribution [18].

An additional test performed by the same group also calculated the change in peak power demand if the amount of charging for each vehicle were varied. Demand curves were plotted for a July power curve in which the fleet of PHEVs in the VACAR energy supply region was charged during the evening hours. The curves were plotted for three different levels of power draw by the PHEVs – 1.4, 2, and 6 kW. The results showed that, as with the results shown in Figure 4b, additional generation capacity was required in every instance, varying from an additional 1 GW required for the 1.4 and 2 kW charging cases, and as much as 4 or 5 additional GW of generation required for the 6 kW charging case [17].

These tests show some of the problematic aspects involved in using PHEVs as V2G technology. If charging

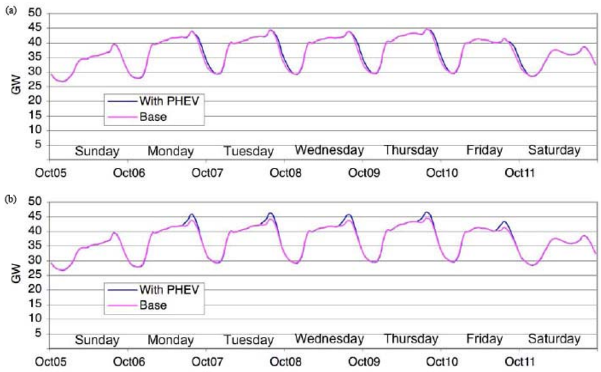

Fig. 4. VACAR projected 2018 system demand for night and evening charging of PHEVs [17]

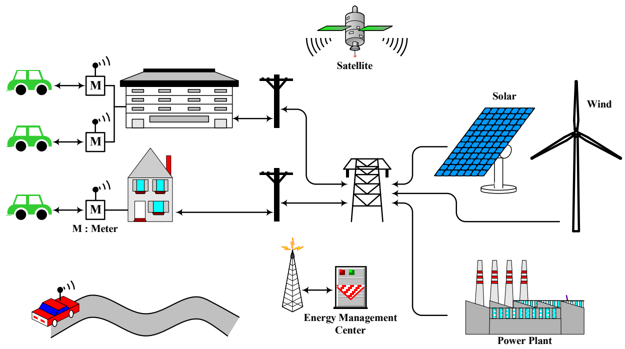

Fig. 5. Interconnected energy system

times and charge amounts for PHEVs are not properly regulated, the effect of V2G interconnections could do the power industry much more harm than good. Furthermore, the energy management system required to allow the system to perform optimally can be very complex, costly, and time consuming to implement (see Figure 5).

Another important aspect pertaining to feasibility has to do with vehicle availability, which is directly related to consumer driving habits. Although it is important that vehicles charge during appropriate hours that limits the need for new generation and development, it is equally important that a sufficient amount of vehicles are available during peak power draw hours in order to provide the additional power demanded. To that end, research must also be done on the driving habits of consumers and how this might effect the ability of V2G interconnect to cover peak power use.

One group studying the use of different HEVs in California performed some interesting analysis in this regard [20]. Their studies began with the information shown in Figure 6. The object of this portion of their study was to determine the amount of PHEVs available to the electric power grid during the heaviest traffic loads during the day. Three estimation methods were used in this determination, each having varying sensitivity levels and presumed styles of driving behavior. The first method simply estimated the number of vehicle-hours available for grid connection assuming that each vehicle only spent 30 minutes of a 3-hour rush hour time frame in order to commute from work to home or vice versa. The method was further refined by presuming that some people spent the time shopping or running errands, which would

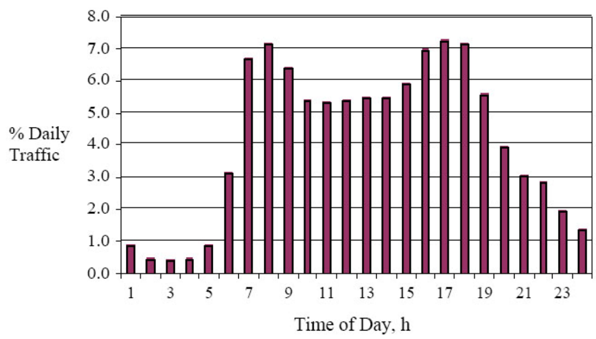

Fig. 6. Hourly distribution of daily traffic in San Diego, CA during a summer weekday (July 21, 1999) [20]

decrease the time spent on the road to about 15 minutes. This method resulted in an estimated percentage for vehicle availability equal to 92%.

The second method was based off the data from Figure 6, rather than simply assuming that all cars are in use at some point during the 3-hour rush hour time frame, and resulted in an estimated percentage equal to 96.3%. The third method refined the second method by including some driver behaviors such as additional stops either to or from work, which could provide additional time spent at a facility not equipped with V2G plug-in technology. This would reduce the available time for connecting cars to the network, and the estimated percentage of 94.5% for vehicle availability reflects this.

The conclusion this group reached was that, even at the highest amount of vehicle unavailability for V2G connections, a percentage of cars somewhere between 92% and 95% were always available for vehicle to grid interconnect. Data such as this is important for determining the amount of power available to the grid from PHEVs during the peak power demand hours of the day.

A study by Argonne National Laboratory suggests that the purchase of a PHEV for a user driving less than 22 miles per day, or about 50 minutes, would not be justified by the benefits of saving money on gas [21].

It may also be noted that in a study by the National Renewable Energy Laboratory that an electric motor will cost three cents per mile to operate as compared to a vehicle with an internal combustion engine which has a cost of thirteen cents per mile [22].

III. Marketability Studies

The practicality of vehicle-to-grid power transfer is not solely dependant upon whether or not PHEVs are capable of bolstering the capability of the electric power grid without putting undue demand on preexisting generation, despite the fundamental importance of feasibility itself. In order to support the power grid in the capacity of spinning reserve, a large number of PHEVs must be connected to the network, and this amount of market penetration can only be achieved if the vehicle is marketable as a profitable option in comparison to a standard vehicle. This profit can come into play in a number of different ways, though some will only be remotely felt by the consumer.

For example, research by the Pacific Northwest National Laboratory investigated the effect of a very large market penetration of PHEVs on the cost of generation and power [23]. According to their investigations, if the current-day fleet of light-duty vehicles across the United States were PHEVs, and if the generation, transmission, and dispatch capacity of the current power grid remained unchanged, then the idle capacity of today's grid could supply power to 73% of those PHEVs. Although an impressive figure, the significant fact is that this would translate into increased power sales for an unchanged infrastructure and the same capital investment. This would drive down the average cost of electricity, and depending on the amount of change, this could translate into savings both in terms of vehicle fuel costs and home electricity bills.

Another investigation by Public Utilities Fortnightly determined the annual potential revenue of a PHEV owner selling energy to the power grid for regulatory and spinning reserve purposes [24]. A standard residential connection to the power grid has two options for reverse power flow – 2kW on a 120 V, 20 A circuit, and 10 kW on a 240 V, 50 A circuit. Through their investigations concerning modern battery technology, they determined that the current limitation for vehicle-to-grid power transfer capacity lies with the power connections rather than with the battery or any of the other vehicle power components themselves, especially if the battery is fully charged and the duration of dispatch is short. They then proceeded to calculate, using market-clearing prices and an assumed battery state of charge of 50%, the amount of annual revenue a PHEV owner could expect given certain discharging conditions and choice of connection for power flow. Their results suggest that the PHEVs could generate significant annual revenue for the owner, from as low as $184 per year to as much as $3,285 per year, depending on the local price of energy and the demand. In some cases the profitability of owning a PHEV is affected by ancillary services in the area [25].

An additional study by Kempton [20] reached similar conclusions. Different tests were run which would calculate the consumer revenue and costs associated with using their PHEV as spinning reserves. Historical data on the market-clearing price in the day-ahead market for spinning reserves was used in the calculation of the information, and three different types of PHEVs were tested to determine their possible revenue and cost. The data obtained from the analysis showed that while PHEVs simply containing an enlarged battery did not stand to earn much of anything, in terms of profit, both gasoline/motor-generator and natural gas/motor-generator hybrid vehicles could earn anywhere between $19 and $1,886 per year by supplying power as spinning reserves. This depended primarily on the market-clearing price used to calculate revenue. Increased use of PHEVs in the grid may affect wholesale electricity markets as their suppliers' resources are limited for long periods of time [26].

The range of amounts for possible profit is varied and shows some of the inherent risk involved with selling energy on the electric market using V2G technology. Given appreciable market-clearing prices, selling energy to the power grid can become a profitable benefit to owning a PHEV. However, if the market-clearing prices on average fall, as would be expected over time and given a large number of vehicles connecting to the grid to sell power, consumers stand to earn a lot less as profit. Thus, selling energy for spinning reserves would seem to be a more lucrative option for PHEV owners before PHEV market saturation becomes great.

A study by AC Propulsion Inc. suggests that consumers would be more likely to purchase a HEV over a PHEV simply because it deviates the least from what the consumer is used to. This leads the auto industry to take a more conservative approach when deciding to design HEVs or PHEVs [27].

IV. CONCLUSIONS

At this stage in time, it is still difficult to determine whether or not PHEVs and V2G technology will become lucrative and feasible in the future. PHEV technology such as battery capacity and drive train design is constantly undergoing research and testing, and new results and models are produced that affect the dynamic and direction of the industry. Though more tests are being performed in order to determine the future of the industry, there is still much that must be examined and analyzed. Much of this also relies on an available network for properly dispatching power and managing charging and discharging times. Overall, however, it seems that PHEVs as an alternate energy storage system for electric power dispatch is a viable and marketable option for mitigating some of the problems plaguing the current United States power grid.

REFERENCES

[1] LaCommare, K. H., and Eto, J. "Cost of Power Interruptions to Electricity Consumers in the United States (U.S.)," *(to be printed in)* Energy: The International Journal, February 2006.

[2] "The Value of Electricity When It's Not Available," National Renewable Energy Laboratory Phamplet, NREL/BR-200-34231, May 2003.

[3] "Grid 2030: A National Vision for Electricity's Second 100 Years," US Department of Energy Initiative, July 2003.

[4] Kempton, W., Tomic, J., "Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy," Journal of Power Sources, 2005.

[5] "A Vision for a Modern Grid," National Energy Technology Laboratory Initiative, March 2007.

[6] "Energy and Economic Impacts of Implementing a 25-Percent Renewable Portfolio Standard and a 25-Percent Renewable Fuel Standard by 2025," Energy Information Administration Report, August 2007.

[7] Kempton, W., Murley, C., "Modeling V2G for a Utility with a High Wind Generation Portfolio," University of Delaware, September 2006.

[8] Ferdowsi, M. "Plug-in Hybrid Vehicles – A Vision for the Future," 2007.

[9] Hawkins, D., "Vehicle to Grid-A Control Area Operators Perspective," California Independent Systems, December 2001.

[10] Kempton, W., Dhanju, A., "Electric Vehicles with V2G," University of Delaware, Windtech International, 2006.

[11] http://www.eere.energy.gov/de/energy_storage.html

[12] Denholm, P., Short, W., "An Evaluation of Utility System Impacts and Benefits of Optimally Dispatched Plug-In Hybrid Electric Vehicles," National Renewable Energy Laboratory, October 2006.

[13] Letendre, S., Denholm, P., "Electric and Hybrid Cars-New Load, or New Source," Public Utilities Fortnightly, December 2006.

[14] Kempton, W., Tomic, J., "Vehicle-to-Grid Power Fundamentals: Calculating Capacity and Net Revenue," Journal of Power Sources, 2005.

[15] Markel, T., Brooker, A., Gonder, J., O'Keefe, M., Simpson, A., Thornton, M., "Plug-In Hybrid Vehicle Analysis," National Renewable Energy Laboratory, November 2006.

[16] Denholm, P., and Short, W. "An Evaluation of Utility System Impacts and Benefits of Optimally Dispatched Plug-In Hybrid Electric Vehicles," National Renewable Energy Laboratory Technical Report, NREL/TP-620-40293, October 2006.

[17] Hadley, Stanton. "Impact of Plug-in Hybrid Vehicles on the Electric Grid," Oak Ridge National Laboratory, October 2006.

[18] Pratt, R., Kintner-Meyer, M., Schneider, K., Scott, M., Elliot, D., Warwick, M., "Potential Impacts of High Penetration of Plug-In Hybrid Vehicles on the U.S. Power Grid," Pacific Northwest National Laboratory, June 2007.

[19] Carlisle, N., Elling, J., Penney, T., "A Renewable Energy Community: Key Elements," National Renewable Energy Laboratory, January 2008.

[20] Kempton, Willett et al. "Vehicle-to-Grid Power: Battery, Hybrid, and Fuel Cell Vehicles as Resources for Distributed Electric Power in California," Institute of Transportation Studies, UC Davis, UCD-ITS-RR-01-03, June 2001.

[21] Santini, D.J., "Energy and Petroleum Consumption Attributes of Plug-In Hybrids," Argonne National Laboratory, Undated.

[22] Lilienthal, P., Brown, H., "Tackling Climate Change in the U.S.-Potential Carbon Emissions Reductions from Plug-In Hybrid Electric Vehicles by 2030," National Renewable Energy Laboratory, Undated.

[23] Pratt, Rob et al. "Potential Impacts of High Penetration of Plug-in Hybrid Vehicles on the US Power Grid," Pacific Northwest National Laboratory, DOE/EERE PHEV Stakeholder Workshop, June 2007.

[24] Letendre, S., Denholm, P., and Lilienthal, P. "Electric & Hybrid Cars: New Load, or New Resource?" Public Utilities Fortnightly, December 2006. I. S. Jacobs and C. P. Bean, "Fine particles, thin films and exchange anisotropy," in *Magnetism,* vol. III, G. T. Rado and H. Suhl, Eds. New York: Academic, 1963, pp. 271-350.

[25] Tomic, J., Kempton, W., "Using Fleets of Electric-Drive Vehicles for Grid Support," Journal of Power Sources, Spring 2007.

[26] Kintner-Meyer, M., Schneider, K., Pratt, R., "Impacts Assessment of Plug-In Hybrid Vehicles on Electric Utilities and Regional U.S. Power Grids," Pacific Northwest National Laboratory, November 2007.

[27] Gage, T., "Development and Evaluation of a Plug-In HEV with Vehicle-to-Grid Power Flow," AC Propulsion Inc., December 2003.