Beyond Batteries: An Examination of the Benefits and Barriers to Plug-in Hybrid Electric Vehicles (PHEVs) and a Vehicle-to-Grid (V2G) Transition

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Abstract: This paper explores both the promise and the possible pitfalls of the PHEV and V2G concept, focusing first on its definition and then on its technical state-of-the-art. More originally, the paper assesses significant, though often overlooked, social barriers to the wider use of PHEVs (a likely precursor to V2G) and implementation of a V2G transition. The article disputes the idea that the only important barriers facing the greater use of PHEVs and V2G systems are technical. Instead, it provides a broader assessment situating such "technical" barriers alongside more subtle impediments relating to social and cultural values, business practices, and political interests. The history of other energy transitions, and more specifically the history of renewable-energy technologies, implies that these "socio-technical" obstacles may be just as important to any V2G transition—and perhaps even more difficult to overcome. Analogously, the article illuminates the policy implications of such barriers, emphasizing what policymakers need to achieve a transition to a V2G and PHEV world.

Keywords: Plug-in Hybrid Electric Vehicle; Vehicle-to-Grid; Transportation policy

1. Introduction

The vehicle-to-grid (V2G) concept links two critically important technological systems—the electric power system and the petroleum-based transportation system—in ways that may address significant problems in both. By drawing on and supplying power to the power grid, electric vehicles could displace the use of petroleum and mitigate pollution and security issues related to oil extraction, importation, and combustion. It could also improve the economics and technical performance of the electric utility industry and generate revenue to owners of plug-in hybrid electric vehicles (PHEVs). Of course, a host of technical and social impediments exists that forestalls the immediate realization of these potential benefits.

In this paper, we explore both the promise and the possible pitfalls of a transition to PHEVs and the V2G concept, focusing first on its definition and then on its technical state-of-the-art. More originally, we assess significant, though often overlooked, socio-technical barriers to implementation of a V2G transition, concentrating primarily on the first link of that transition: PHEVs. The term "socio-technical" encompasses not just technological and engineering obstacles, but also cultural, social, political, and economic impediments.

This article acknowledges that many important barriers facing a transition to a V2G system are technical, but it emphasizes that several remain social as well. It provides a broad assessment situating such "technical" barriers alongside more subtle impediments relating to customer behavior in light of economic uncertainties, cultural and social values, business practices, and resistance to infrastructural changes. The history of other energy transitions implies that these "socio-technical" obstacles may be just as important to any V2G transition—and, perhaps because they are often harder to identify, more difficult to overcome.

Because no commercially viable PHEVs currently exist on the market, our assessment has the benefit of informing policymakers *before* they commit to a predetermined technological pathway (Letendre, Denholm, and Lilienthal 2006). Given that energy technologies such as refineries and power stations require extremely large capital expenditures, the infrastructure built today will remain in operation for 30 to 40 years. By identifying a range of barriers to PHEVs and an eventual V2G transition now, we can help inform policymakers early in the process and perhaps avoid spending huge amounts of money on a promising technological pathway that fails to deliver results.

2. Conceptualizing V2G and PHEVs and the Technical Challenges Ahead

Most modern automobiles employ internal combustion (IC) engines, which start quickly and provide power as soon as drivers need it. But they operate inefficiently and waste energy when idling (Sanna 2005). By contrast, hybrid electric vehicles, which have seen commercial success as the Toyota Prius, Honda Insight, the Honda Civic Hybrid, and others, add a battery and electric motor to a car that uses an IC engine. By marrying advanced power electronics and computer controls with conventional and electric drive trains, hybrid electric vehicles operate more efficiently than those that run on IC engines alone and reduce emissions. They lessen fuel usage because they employ the electric motor frequently (especially in slow traffic), because they shut down the IC engine when the vehicle has stopped for a predetermined amount of time, and because they recapture otherwise discarded kinetic energy during braking (Denholm and Short, 2006; Romm and Frank, 2006). (Insert Table 1).

A "plug-in" or "pluggable" hybrid (PHEV) uses hybrid electric vehicle technology, but it features a larger battery and a plug-in charger. Most PHEV prototypes contain a battery capable of powering the vehicle for between 20 and 60 miles (30 to 100 km) on electricity alone (Denholm and Short, 2006). In 2008, General Motors (2008), for example, began advertising the Chevrolet Volt, an all-electric vehicle that can operate up to 40 miles without recharging on household current. The company targets 2010 as the novel car's launch date.

Finally, an automobile capable of "vehicle-to-grid" (V2G) interaction, sometimes referred to as "mobile energy" or "smart charging," mates an automobile with the existing electric utility system (Williams and Kurani, 2006; Williams and Kurani, 2007). Vehicles must possess three elements to operate in V2G configuration: a power connection to the electricity grid, a control and/or communication device that allows the grid operators access to the battery, and precision metering on board the vehicle to track energy flows (Tomic and Kempton, 2007). This intelligent, two-way communication between the electricity grid and the vehicle enables utilities to manage electricity resources better, and it empowers vehicle owners to earn money by selling power back to the grid.

PHEVs and V2G systems are thus intimately interconnected. PHEVs have the opportunity to become not only vehicles, but mobile, self-contained resources that can manage power flow and displace the need for electric utility infrastructure (McNamara, 2008). V2G vehicles can reduce the lifetime cost of PHEVs, thereby making them more attractive, and if V2G increases the market share of PHEVs, the benefits of PHEV use increase. In this context, the benefits and barriers facing PHEVs remain interconnected with those facing V2G, which explains our discussion of both of them. Since average vehicles in the United States travel on the road only 4 to 5 percent of the day, and at least 90 percent of personal vehicles sit unused (in parking lots or garages) even during peak traffic hours (Tomic and Kempton, 2007), the size of a possible PHEV V2G resource can be quite large: placing just a 15 kW battery in each of the existing 191 million automobiles in the country would create 2,865 GW of equivalent electricity capacity if all the vehicles supplied power simultaneously to the grid—an unlikely occurrence (Kempton, 2005). (This amount is more than twice the total nameplate capacity of all the electric generators in the United States in 2006).

The federal government has begun supporting research on the PHEV and V2G concept partly because of these potential benefits that can accrue to a society more dependent on electricity than petroleum. At the U.S. Department of Energy (DOE) and U.S. Department of Transportation (DOT), promotion of research, sometimes known as "R&D pathways," has focused on improving the range, refueling capability, and cost of V2G PHEVs (Romm 2007). Based on a consensus of technical experts, the pathways have deliberately concentrated on mostly technical and economic issues, which have been seen as the primary impediments to widespread use of PHEVs. Researchers at the utility-sponsored Electric Power Research Institute (EPRI) have argued, for example, that "there are no major automaker initiatives to develop and introduce PHEVs, presumably because of battery technology readiness and vehicle cost concerns" (Duvall 2002). Experts convened at DOE conferences have identified a broad range of barriers facing V2G systems, but have also stated that "cost is the primary impediment to producing PHEVs" (Wellinghoff and Kempton, 2007). Reiterating this commonly held view, President

George W. Bush, in his 2007 State of the Union Address, commented on the economic and technical impediments of PHEVs and urged engineers "to press on with battery research for plug-in and hybrid vehicles" (Bush 2007). Finally, the DOE's Energy Efficiency and Renewable Energy Program managers (2007) have succinctly emphasized the point, by noting that "cost is the primary impediment and battery technology is a potential show stopper for production."

This understandable logic leads R&D managers (in government and in corporations) to pursue activities in materials and processing, power electronics, low-cost and lightweight materials, and grid interaction. They have laid out an extensive R&D program aimed at improving batteries' conductivity and mechanical strength. Batteries, notes an EPRI report, remain the "chief concern" of current research (Sanna 2005). Indeed, we certainly agree that the technical and economic barriers facing PHEVs and V2G technologies remain important. However, as we will see after exploring the benefits of a V2G transition, such barriers are not the only significant ones.

3. The Potential Benefits of a V2G Transition to the Petroleum-based Transportation System

The V2G concept excites advocates because it offers mutual benefits to the transportation and the electric power systems. It could assist the former by reducing petroleum use, strengthening the economy, enhancing national security, reducing strain on petroleum infrastructure, and improving the natural environment. It could help the latter by providing a new demand for electricity, ideally during the parts of the day when demand remains low. Moreover, it could add capacity to the electric grid during peak times without the need for the utility industry to build new power plants.

Focusing on the transportation sector, the U.S. DOT (2003) estimates that about 60 percent of vehicles travel fewer than 30 miles per day. A PHEV with a battery capable of a 30-mile range could therefore eliminate petroleum use for these short trips and cut overall liquid fuel use by as much as this amount (Romm and Frank, 2006). The numbers quickly add up: a transition to a V2G strategy has the potential to displace 6.5 million barrels of oil equivalent per day, or more than 50 percent of the nation's entire oil imports (Kintner-Meyer, Schneider, and Pratt 2007).

The immediate effect of widespread use of PHEVs could be lower gasoline prices. Increases in gasoline prices in 2007 and 2008 occurred not only because of crude oil price hikes, but due to refining capacity shortages. No new refinery has been built in the United States in the past twenty years, and refinery closings have taken nearly 830,000 barrels of oil per day *off* the domestic market, dropping national refining capacity from 18.6 million barrels of oil a day in 1976 to 16.8 million barrels a day in 2005 (Wyden, 2001; Hamilton 2006; Hargreaves 2007). Economists have even mused that crude oil could be free, but high prices for fuel would still exist because refineries cannot make enough gasoline (Herman, 2007). In the short term, greater market penetration of PHEVs would immediately curtail gasoline usage, easing refinery shortages, and likely depress prices.

In the long term, reduced oil imports through greater PHEV penetration brings a host of additional benefits. The most significant include savings, due to the avoidance of wealth transfers from oil consumers to producers (especially foreign producers in a way that aggravates the national trade deficit), and the reduced risk of shocks (or macroeconomic dislocations) caused by wars, hurricanes, or accidents that spur huge fluctuations in the price of oil. The savings could reach as high as $13 trillion over a period of about 25 years (Green and Ahmad, 2005; National Defense Council Federation, 2003; Woolsey 2007). Beyond economic advantages, reduced petroleum use would bring immense political and economic advantages, including less American dependence on unstable and unfriendly nations that produce the bulk of the world's oil (EIA 2007a; EIA 2008; Woodward 2007).

A transition to the PHEV/V2G concept may also offer major environmental benefits. Under business-as-usual projections, David Friedman (2003) of the Union of Concerned Scientists expects emissions from greenhouse gases among the American passenger vehicle fleet to grow from 358 million metric tons of carbon dioxide equivalent (MMTCE) in 2000 to 559 MMTCE in 2020. Despite all of the improvements in automobile design, Friedman projects that smog-forming pollution will grow from 847,966 tons of NO_x to 1,322,853 tons, while emissions of benzene will increase from 392,328 tons to 612,044 tons. Obviously, less use of internal combustion engines and greater use of PHEVs or HEVs would drastically (and directly) mitigate greenhouse gas emissions.

Confirming this point, one study (from the Pacific Northwest National Laboratory) estimates that for the nation as a whole, shifting roughly half the vehicles on the road in 2007 to PHEVs would have reduced total greenhouse gas emissions by 27 percent (Kintner-Meyer, Schneider, and Pratt, 2007). PNNL projected that pollution from volatile organic compounds and carbon monoxide emissions would decrease by 93 percent and 98 percent (respectively) under a PHEV transition. Total nitrogen oxides emissions would also be reduced (by 31 percent) as internal combustion engines are displaced along with the corresponding refining processes needed to fuel them. Using a "well-to-wheels" metric, which includes the energy and greenhouse gases used in the manufacturing of the vehicle as well as its fuel cycle and operation, an EPRI study projected that the average HEV emits 22 percent less carbon dioxide than what a conventional vehicle emits (Duvall, 2002). EPRI noted that when gasoline vehicles met California's Super Ultra Low Emission Vehicle standards, an average conventional vehicle would emit 320 g/mi of CO_2 over the course of its lifetime. An HEV with no all-electric range and charged only at night, in contrast, would emit 250 g/mi.

In another study, the Minnesota Pollution Control Agency (2007) calculated that per-mile emissions of particulate matter and CO_2 in projected PHEVs would drop around 60 to 70 percent when compared to conventional vehicles. The study documented that PHEVs reduce emissions of carbon dioxide by 59 to 66 percent, nitrogen oxides from 48 to 80 percent, and particulate matter from 66 to 76 percent. These figures depend on the assumption that the PHEVs had an all-electric range between 20 to 60 miles, were phased in for light-duty vehicles (compact cars, sedans, and station wagons) only, and were powered with electricity from a portfolio of 60 percent coal and 40 percent wind.

The Carnegie Mellon Electricity Industry Center looked at the environmental impact of V2G cars differently, but it found that even when powered entirely by coal-fired electricity, PHEVs still produce around 25 percent fewer greenhouse-gas emissions per mile than do conventional vehicles (Jaramillo and Samaras 2007). The study underscored that the assessment greatly *underestimates* the greenhouse-gas-reducing potential for PHEVs. Emissions would be lower because utility portfolios would include some low-carbon generators, such as renewables and cogeneration units, and would not consist of 100 percent coal-fired generators, as the study assumed. Further studies, performed by Stephen and Sullivan (2008), Samaras and Meisterling (2008), and Bradley and Frank (2008), reiterate the same general conclusion: PHEVs can reduce greenhouse gases significantly, even when operating in a wide variety of conditions.

4. The Potential Benefits of a V2G Transition to Consumers and the Electric Power System

Simply put, consumers may profit from the use of plug-in vehicles because electricity is cheaper than gasoline for equivalent distances traveled. Using 2006 average residential electricity rates (of 7.6 cents per kWh—actually lower than the national average residential price of 10.4 cents per kWh [EIA, 2007b]), it would cost about $1 for a PHEV to travel the same distance as a conventional car would travel using a gallon of gasoline (Letendre, 2006). EPRI estimated that if a PHEV sedan needs around three to four hours to charge per night (and a commercial delivery van around four to five hours), the electricity will cost around $170 to $215 annually (Sanna, 2005). By contrast, the gasoline needed for a car to drive the same distance as the PHEV would cost more than four times as much (assuming a gasoline price of $3 per gallon). EPRI concludes that PHEVs would save about $600 per year for the average American driver.

In addition, PHEVs in a V2G configuration could provide additional revenue to owners that wish to sell power back to the grid. V2G concept pioneer Willett Kempton and postdoctoral scholar Jasna Tomic (2005) estimated that PHEVs could provide much needed assistance to transmission operators as they maintain reliability and operating standards (known as “ancillary services). They estimated the value of those electric services at up to $12 billion per year, some of which would flow to V2G owners. Follow up business studies have projected additional annual revenue for V2G ancillary services at between $3,777 and $4,000 per vehicle (Kempton, 2005; Tomic and Kempton, 2007).

The electric utility system may also benefit from implementing the V2G concept, not only by supplying electricity to the new vehicles, but by drawing power from them. The first benefit derives from the fact that many utility resources go underutilitized, an implication of the way utility managers have traditionally (and logically) designed the electricity infrastructure to meet the highest expected demand for power. Except for these periods of peak use, the power system could generate and deliver a substantial amount of energy needed to fuel the nation's vehicles at only the marginal cost of fuel. A recent study, for instance, suggested that 8 to 12 percent of peak demand occurs within just 80 to 100 hours during the year (Faruqui et al., 2007). Because much of the generating capacity remains unused, 84 percent of electrically powered cars, light trucks, and sport utility vehicles in the United States could be supported by the existing electric infrastructure if they drew power from the grid at off-peak times. Consequently, utility companies would earn extra revenues during these periods (Kintner-Meyer, Schneider, and Pratt, 2007).

But the use of the cars as a supplier of power to the grid offers V2G advocates a more tantalizing benefit (Letendre and Kempton, 2002). Put differently, the V2G cars can serve as distributed generators—supplements to utility power plants—that provide valuable generation capacity at peak times (i.e., during the parts of the day when electricity is most expensive) along with important ancillary services (Tomic and Kempton, 2007; Turton and Moura, 2008; Sedano and Brown, 2004). While the specifics would differ according to local electricity markets, V2G PHEVs could become more like "cash cows" that produce income from existing equipment and less like vehicles that merely consume energy.

Some of these potential benefits have already been carefully studied. The PNNL, for example, has assessed the impacts of a V2G transition on the revenue and cost streams of two sample utilities, Cincinnati Gas & Electric (CGE) and San Diego Gas & Electric (SDG&E) (Scott et al., 2007). (The first company primarily generates its own power, while the second utility mostly serves as a power marketer.) Researchers concluded that with 60 percent penetration, PHEVs would generate income during off-peak hours and help the companies recover their fixed costs and borrowing expenses more quickly than if they did not sell power to vehicles. By doing so, the utilities could reduce overall rates by as much as 0.4 cents per kWh for CGE and 5.0 cents per kWh for SDG&E. CGE could boost profits in the short term, enabling it to invest more in infrastructure; SDG&E could use its transmission and distribution capital more effectively in off-peak periods, meaning that its cost of power would decline. In other words, sales of power to V2G cars could improve the companies' load factors (i.e., allow the companies to use their equipment more effectively) and reduce the overall cost of service on a per kilowatt-hour basis. As the cost of service declines, so could prices to customers.

NREL also studied the hypothetical addition of PHEVs to actual recorded utility loads and considered their impact for peaking generation and reserve capacity (Denholm and Short, 2006). Assuming a PHEV penetration of 50 percent, the study found that utilities could utilize large amounts of existing capacity to power PHEVs as long as they retained some control over when charging occurs. Put differently, the company could increase revenues if they could restrict charging of the vehicles to off-peak times.

Indirectly, V2G PHEVs can further reduce emissions and air pollution in the electricity sector by providing storage support for intermittent renewable-energy generators. In other words, the batteries in the vehicles could store electricity produced by wind turbines, for example, and provide the power back to the grid when needed. The power produced from the turbines fluctuates greatly due to wind gusts, cloud cover, thermal cycles, the movement of weather fronts, and seasonal changes. Given that they produce most of their electricity at night, just when PHEVs would need recharged, a V2G strategy could greatly help level daily fluctuations in wind power. V2G PHEVs could also offset the need for spinning reserves and load management necessary to integrate these intermittent resources (and others, such as solar photovoltaics) into the grid (Kempton and Tomic, 2005). The cars would replace (or more likely, supplement) large-scale pumped hydroelectric and compressed air energy storage systems, which have already proven effective for enhancing the value of renewable-energy technologies (Denholm et al., 2005).

5. Social and Cultural Barriers to a V2G Transition

These potential benefits obviously tantalize advocates of the V2G concept, spurring them to continue work on what they see as the biggest obstacles, namely problems with battery technology and high costs compared to conventional internal-combustion vehicles (Romm, 2006). While technical obstacles to a PHEV transition obviously exist, the rest of this article argues that researchers and policy makers need to recognize other impediments. Most importantly, they need to consider the impact of a host of socio-technical considerations, such as those that may arise among consumers, those relating to business practices and regulatory regimes, and those dealing with social conflict. It may turn out that, even with technical problems resolved, the V2G concept may not gain widespread acceptance. To help understand the problems, we compare V2G concerns to those experienced in the introduction of other nontraditional energy technologies.

As researchers from the DOE and EPRI have already noted, V2G PHEVs face a significant first-cost hurdle, which serves as an economic disincentive. One survey among California households, for example, found that not one of them had estimated the present value of fuel savings as part of a decision to purchase a new vehicle (Greene, German, and Delucchi, 2007). For those consumers who do consider fuel economy when purchasing a vehicle, surveys conducted by the Geller and Attali (2005) and Steiner (2003) found that buyers expect vehicle efficiency improvements to pay for themselves in the first three years or less, even though they typically take 10 to 14 years for average vehicles and four to five years for a HEV (Allen 2008).

The International Energy Agency (IEA) further noted that implicit discount rates—the rate at which consumers want to recover their investment—are often 20 to 35 percent for home air conditioners and home insulation, greater than 80 percent for water heaters, and furnaces, and 500 to 800 percent for gas water heaters. Using this last discount rate, investments in energy-efficient products would require a payback period of fewer than five months. Thus, how consumers improperly assess future savings and discount rates can serve as a powerful impediment to investing in new technologies, one proven through many studies of consumer behavior (Meier and Whittier, 1983; Koomey, 1990; Hassett and Metcalf, 1993; Soft, 1995; Levine et al. 1995; Koomey et al. 1996; DeCanio 1998).

Such high discounting may explain why hardly anyone purchased prototype electric automobiles in the late 1980s and early 1990s even though they demonstrated fuel economy as high as 71 equivalent miles per gallon (Howarth and Sanstad 1995). It also explains the lack of market pressure for improved fuel economy standards throughout the 1980s (Von Hippel and Levi, 1983). Indeed, when researchers quantified things such as comfort, freedom, flexibility, and mobility into monetary terms and then surveyed drivers about their vehicle preferences, they found that owners believed electric vehicles had a disutility of between $10,000 and $16,250 (Morton et al. 1978; Beggs and Cardell, 1980; Bunch et al. 1991). In other words, consumers felt they would need compensation exceeding $10,000 to deal with the inconvenience of owning an EV compared to a conventional vehicle.

To be sure, the return to higher oil prices in 2008—with the resource hovering at more than $140 per barrel for a short time—has convinced some consumers to switch permanently from gas-guzzling behemoths to more energy-efficient automobiles. But it also appears that the motivations for this switch were not detailed economic analyses, but simple reactions to sharp increases in the price of fuel. Most people apparently remain unable or perhaps unwilling to conduct careful economic calculations of the cars they buy, a trend that will take more than higher oil prices to change. Recall, too, how consumers initially bought fuel-efficient cars in the 1970s after the initial energy crisis pushed up gasoline prices, only to return to previous levels of consumption (from use of inefficient SUVs, minivans, and gas hogs) when prices declined in the 1980s (Pitts et al.

1981). The historical record suggests that consumers may no longer like PHEVs if gasoline prices collapse, as they did in late 2008.

For the earlier part of this decade, HEVs suffered from the problem of costing significantly more than corresponding conventional vehicles, often as much as $2,500 to $14,500 extra (Duvall 2002). Another 2005 survey found that the premium for existing hybrids averaged $4,000. For the typical vehicle traveling 15,000 miles a year, burning gasoline priced at $2.50 per gallon, hybrid technology would require a payback period of between seven and fifteen years (although higher gasoline prices would have reduced this payback period). Since the average American owns a car for only six years, the long payback period might make little economic sense (Romm and Frank, 2006). As one columnist for *Car & Driver* jokingly put it, many drivers believe that “you have to drive [a hybrid electric vehicle] till it’s as used as Willie Nelson to save gas enough to get your cost back” (Bedard, 2005). Of course, federal tax credits for some owners of HEVs and PHEVs help mitigate the high first costs, but this tax policy would need to be expanded to all owners and perhaps with higher incentives to ensure more widespread acceptance. (We also recognize that if component costs decrease, pushing lower the price of cars, this element of resistance would diminish.)

Furthermore, sociological research of American driving habits suggests that many still do not properly evaluate the savings from more fuel-efficient vehicles. A 2007 study of drivers conducted by the Institute of Transportation Studies at the University of California concluded that no single respondent analyzed vehicle fuel costs in a systematic way, almost none tracked gasoline costs over time, and few considered transportation fuel costs in household budgets (Turrentine and Kurani, 2007). The study found that drivers rapidly forgot the price they paid for gasoline on a particular day, and that drivers "lack the basic building blocks of knowledge" needed to make intelligent decisions about fuel economy. Finally, the study discovered a negative social stigma against more fuel-efficient vehicles. Respondents indicated that automobiles with good fuel economy were often associated with being "cheap," "light," and "small," and were consequently resisted by middle and upper class purchases that wanted to avoid any association with "econo-boxes."But more uncertainties exist, further complicating the payback calculation. For example, the owner loses money if her car's battery must be replaced over the life of the vehicle, a likely event for PHEVs with a 20 mile all-electric range since they depend on batteries exclusively for the full extent of their range (Duvall 2002). When commonly used batteries discharge to nearly 20 percent state of charge, they perform poorly, and their lifetime can be significantly shortened. While Toyota and other companies are improving their warranties (Toyota warrants batteries on the Prius for 8 years or more), the cost of a new battery can mitigate the savings from driving this novel vehicle. Researchers from Cornell University and the Department of Citywide Administrative Services in Queens, New York, surveyed the managers of 68 taxi fleet companies employing more than 13,000 taxi drivers in New York City about their preferences for PHEVs (Gao and Kitirattragarn, 2008). The study group found that the managers believed the average lifetime for their fleet vehicles was a mere 3.7 years and that concerns about battery replacement expenses for PHEVs were "pervasive." As a result, the authors concluded that without government intervention, PHEV penetration in the New York City market will remain limited. Given that people must make decisions about a relatively new consumer technology—one that hasn't yet provided much experience concerning battery life and replacement periods—purchases of hybrid vehicles may lag for many drivers.

Drivers of electric vehicles of all kinds must also become aware of how their driving habits can affect energy efficiency and the ultimate payback period. While the existence of vehicle consoles that tell drivers their current fuel economy helps mitigate some of this uncertainty, most of the hybrid cars can only achieve maximum fuel economy when their owners drive conservatively and draw on the vehicles' regenerative braking systems. But aggressive driving, which often requires extra power consumption and inefficient use of the novel braking system, can cause fuel efficiency to decrease by more than 30 percent. In conventional vehicles (those that do not convert kinetic energy into useful electrical energy), such aggressive driving behavior diminishes fuel economy by only 5 to 10 percent (Romm and Frank, 2006). Customer surveys and automotive industry testing programs have revealed that most people need to be taught, either through courses or advanced instrumentation, to drive well (Kurani, 2007). Left to their own intuitions and vices, most drivers prefer higher top speeds, more aggressive acceleration, and less coasting—actions that reduce fuel economy. In short, customers sensitive to the economic value of electric vehicles may be discouraged by the number of variables and the difficult-to-make assumptions they need to consider. Such difficulties serve as an important disincentive to the acceptance of PHEVs.

Conversely, other drivers appear to be purchasing alternative vehicles such as EVs, HEVs, and PHEVs as quickly as they can—and may desire to own them regardless of their performance. Sherman (1980) surveyed household travel behavior in the 1970s, and found that consumer choice was not determined by purely "rational" components such as cost or range. Instead, he found that product styling (such as color or shape) and deeper attitudes and values (such as mobility or comfort) played an equally significant role. Similarly, surveys of early adopters of EVs in the late 1990s found that drivers purchased them not only to save money on fuel, but also in an attempt to establish an alternative “traffic culture” based on slower speeds, more careful driving, and fewer accidents (Gjoen and Hard, 2002). Brown (2001) found that the motivation for California’s approach to promoting zero emissions vehicles consisted of seeking improved environmental performance *as well as* implementing an idyllic vision of civic and urban renewal based on community integration and public participation. In interviews of early purchasers of PHEVs in California, Heffner et al. (2007) found savings from fuel efficiency constituted only a small part of the reason they adopted PHEVs. Other justifications included a strong ethnical belief to protect the environment or oppose war, a desire to reduce dependence on foreign oil to improve national strength and vitality, and an assertion of individualism and embracing of new technology. Thus, some drivers of EVs and PHEVs believe that they can gain social standing through their choice of transport, since they obviously feel (and act) committed to improving the environment.

However, this initial phase of excitement could dissipate and turn into disappointment as people gain real and extended experience with PHEVs and V2G technologies. For example, current U.S. Environmental Protection Agency determinations of fuel economy for electric vehicles may skew results in actual driving experiences, since they assume straight roads, a top highway speed of 60 mph, ideal weather, and temperatures of between only 20 and 30 degrees Celsius (Romm and Frank, 2006). Owners of hybrids in cold northern climates will likely obtain lower fuel economy than implied by the government rating. Advanced testing of PHEV prototypes conducted by the U.S. Department of Energy in 2007 has also shown that seasonal variations in fuel economy range from 10 to 11.5 percent (Karner and Francfort, 2007).

Such a disparity in hopes and realities could alienate customers, and it already appears to be influencing early public perception of some PHEV owners. Researchers at the Plug-In Hybrid Electric Vehicle Research Center in California interviewed early adopters of PHEVs in California and found that most of those interviewed wished that their vehicle performed better (Kurani et al., 2007). Participants commonly hoped PHEVs could attain higher top speeds; several felt that displays and interfaces were too complex, in some cases causing drivers to ignore fuel economy displays; and many owners attempted to drive PHEVs “like a normal vehicle[s]” instead of employing techniques that would maximize fuel efficiency. The study also found that a majority of owners preferred to recharge their cars during the day rather than at night (some owners reported keeping their vehicles continually plugged in whenever possible); that most drivers did not calculate cost savings from operating their PHEVs; that many drivers found it embarrassing to ask hotel clerks, parking attendants, and property managers for permission to recharge when needed; and that most were unconcerned with the prospect of operating their PHEV in a V2G configuration.

The history and sociology of energy consumption suggests that while a few early adopters may assert their individualism, most consumers often remain impatient and close-minded about new energy technologies (Kirsch, 2000). Instead of embracing new energy technologies, some rely on notions of tradition and familiarity when they make consumer choices, especially when dealing with hardware that requires huge capital costs (and often the acquisition of sizeable debt).

To convince the public of the durable reliability of their products, manufacturers of novel hardware often portrayed them as neither unfamiliar nor sensational, but as safe, familiar, and comfortable. From the 1890s to the 1910s, for example, product styling of new electric appliances imitated those being replaced. General Electric designed its first electric lights to look like gas-fired streetlights. The company produced early electric stoves to look like the earlier gas ranges and coal stoves. Marketers for utilities and manufacturers learned that people tend to resist technologies they perceive as untested, radical, or different (Nye 1998).

Many of those promoting V2G PHEVs, nonetheless, present them as novel and revolutionary technologies. Though this approach may appeal to early adopters of technologically sophisticated devices and to people who wish to make a statement, historical analogy suggests that they may not win the huge market share that advocates of the technologies seek, even if cheaper battery hardware emerges quickly. Tradition will always play a significant role in shaping cultural attitudes and decisions regarding technology. For this reason, V2G PHEVs may face significant resistance, despite winning a good reception from the relatively few who have spurred demand for hybrid cars.

While the potential benefits of a V2G transition remain significant, they may not accrue without social conflict. Moving the pollution from automobiles to distant power plants, which produce power to the electric vehicles, may ensure that the negative externalities from energy production do not affect city dwellers, but such a move could have serious consequences. It could polarize relationships between rural and urban communities or different economic classes of people. Opposition to wind turbines located in rural areas in the United States, for example, have been deeply varied and frequently have little to do with the technology itself, but more with how wind projects inflame preexisting social conflicts. Sociologists and geographers conducting interviews of wind farm opponents in the Midwest and Pacific Northwest have found that rural residents often resent urban developers who wish to build energy projects in their midst (Pasqualetti, Gipe, and Righter, 2002). The researchers have also found, paradoxically, that some people oppose the new generators because they feel that they have been excluded from the policymaking, permitting, or siting process. In other cases, those interviewed reported that rural residents want renewable-energy projects for their own use—as a vehicle for economic development—and resented what seems like meddling by urban residents intent on preserving the countryside for its scenic and recreational value. In this way, wind turbines become more than simply an electrical generation technology: they simultaneously symbolize a way of generating electricity, a way of organizing the landscape, a system of ownership and control, and a personal ethic or a reflection of attitudes (Pasqualetti, Gipe, and Righter, 2002).

6. Business and Institutional Barriers to a V2G Transition

Before Americans accepted new energy technologies in the past, policymakers and business people first needed to erect significant amounts of infrastructure. Each system required huge financial (and associated legislative and policy) investments: the growing use of coal in the nineteenth century required mines, railways, and novel distribution pathways; rising natural gas use in the twentieth century created demand for wells, pipelines, liquefied natural gas (LNG) tankers, and storage facilities. The increasing popularity of electricity necessitated huge capital investments in power plants, transmission lines, and distribution facilities. As important (or more so in some cases), the electric utility infrastructure expanded because of supportive legislation, allowing power companies to be considered regulated natural monopolies, for example. Utility firms also gained control over the technological, financial, political, and educational institutions relating to the power network (Hirsh, 1999).

As controllers of an existing infrastructure, incumbent automobile manufacturers and petroleum companies may try to block a transition to V2G PHEVs. After all, they already blocked development of competing ways to produce fuel: as early as 1947, several of President Truman's advisors realized that the end of the war had not guaranteed adequate fuel supplies and that peacetime energy demand would shortly outstrip domestic supplies. The Truman Administration developed a plan for producing 1,000,000 barrels a day of synthetic oil from oil shale, and liquefied coal and gas (Vietor, 1980). Before announcement of this public initiative, the petroleum industry had maintained a studied ambivalence toward commercial synfuel development.

After its announcement, however, Standard Oil and the Military Petroleum Advisory Committee opened a fierce campaign against federal synfuel programs, arguing that it would drain scarce steel and investment capital needed for the exploration and development of petroleum. The industry also fought synthetic fuels because it threatened almost all aspects of the petroleum fuel chain. Of all the segments of the industry, only independent gasoline marketers stood to gain from the production of alternative transportation fuels. The huge integrated oil companies with foreign concessions would gain nothing. The oil industry pressured the National Petroleum Council in 1953 to claim that all methods of producing synthetic fuels were uneconomical, and President Eisenhower cancelled the program in 1954. When ruminating on the demise of the synfuels program, Democratic Senator Estes Kefauver (Tennessee) proclaimed that "the oil companies tried for a long time to close down synthetic fuel plants because they do not want the competition of oil from coal … It now appears that the big interests have prevailed" (Vietor, 1980, 29).

A more recent example of resistance to infrastructural changes comes about four decades later and concerns electric vehicles, rather than PHEVs. During the early 1990s, California policymakers decided to require automakers to sell electric vehicles within their state (Sperling, 1994). The original mandate set by the California Air Resources Board (CARB) called for a zero-emissions-vehicle sales quota of 2 percent of the fleet imposed on dealers by 1998, 5 percent by 2001, and 10 percent by 2003. Any manufacturer failing to meet CARB requirements would be fined up to $5,000 for each vehicle falling short of the quota. New York and Massachusetts quickly followed with similar mandates (Sperling, 1994).

General Motors and Honda responded by initiating research aimed at mainstreaming electric vehicle production. GM worked on the EV1 vehicle, and Honda started developing the EV Plus. Other automobile companies and the American Automobile Manufacturers Association (AAMA), however, mounted a two-pronged attack on the CARB mandate. First, the AAMA claimed that alternative vehicles would be too costly for consumers, adding $2,823 to the price of each vehicle complying with the Northeast mandates, for example (National Petroleum News, 1994). Chrysler pointed out that its 1995 TEVan would require 35 nickel-cadmium batteries that cost $38,000 alone (Peak, 2002).

Automobile companies also claimed that EVs provided no significant environmental benefits. They alleged that EVs would have a net negative effect on the environment because of discharges of lead from battery manufacturing facilities and from the necessary disposal process for lead-acid batteries. The automobile industry argued that both factors offset any savings from tailpipe emissions, in some cases overestimating the manufacturing costs of alternative vehicles by a factor of ten (Stewart, 2001; Flower, 1997).

In concert with these moves, a consortium of major oil companies (including Exxon, Shell, and Texaco) contributed in 1994 and 1995 more than $1.1 million to legislative candidates in California in an attempt to weaken the state's push towards electric vehicles; the Mobil Oil Corporation spent an additional $3.5 million in advertisements aimed at discrediting potential alternative fuel vehicles (Calef and Goble, 2007). The oil industry did not limit itself to mere advertising, however; it also resorted to "greenwashing" and "Astroturf lobbying" (a strategy by which corporations attempt to conceal their involvement in lobbying behind the façade of faux grassroots groups) by establishing three organizations designed to influence public opinion against alternative vehicles (Calef and Goble, 2007).

These efforts apparently convinced CARB to capitulate, and in 1996 it rolled back the electric vehicle mandate by five years. Further reviews by CARB have delayed introduction of electric vehicles, with emphasis on development of hydrogen fuel-cell cars instead. But even the promise of such vehicles has recently faded, as Ballard, a major fuel-cell manufacturing company has withdrawn from pursuing more research on the technology. Recognizing that earning profits from large-scale production of fuel cells remains a distant prospect, the company sold 80% of its stake to auto companies Ford and Daimler in late 2007 (Boschert, 2007; Malloy 2007).

Why, then, did the automobile companies resist EVs? The reason may stem from the differences between electric vehicles and conventional vehicles—a lesson that has direct relevance for PHEVs and V2G systems, since they also differ from conventional vehicles. The heart of an electric vehicle is electronic, rather than mechanical. Electric vehicles do away with gasoline engines, with their thousands of precisely engineered and moving parts operating at high temperatures, and replace them with motors having one major moving part and a controller with no moving parts. Electric vehicles thus require an entirely new set of suppliers, assembly processes, and technicians than exists to service the more than 135 million cars on the road in 2005 (U.S. DOT 2007). The alteration of manufacturing processes and creation of new production lines would therefore require considerable intellectual and human capital along with huge financial expenditures in the hundreds of billions of dollars (Worden, 1994).

Indeed, PHEVs and V2G technology seem destined to threaten and alter the structure of the car business in a similar fashion. Conventional automotive industry logic sees vehicles as merely the receivers of petroleum, isolated from other energy systems; the engine is viewed as the primary commodity; expertise is rooted in combustion, mechanical engineering, and low-cost production; and consumers are seen as preferring performance and comfort to fuel economy (Kempton, 2005). The V2G strategy turns each of these tenets on their head: automobiles become valuable resources; the energy they produce is a valuable commodity; expertise is centered on electrochemistry and power electronics; and consumers are seen as valuing fuel economy and the additional revenue to come from V2G operations (Kempton, 2005; Lund and Kempton, 2008).

Moreover, a transition to EVs would likely induce a significant loss of business for repair and maintenance companies. The cost of EV maintenance should be minimal, since the vehicles have fewer moving parts and need no lubricating oils, filters, coolants, clutches, spark plugs, wires, oxygen sensors, timing belts, fan belts, water pumps, catalytic converters, or mufflers (Fontaine, 2008). Unlike IC vehicles, EVs do not require oil changes, tune-ups, smog checks, or mandatory annual emission inspections. Considering that automotive service technicians held 818,000 jobs in 2002, it becomes understandable why the industry may not want to move quickly away from conventional vehicles. The automotive industry may therefore resist a transition to V2G systems (at least privately), especially since they have the potential to disrupt the core business as much as EVs did. (Fontaine, 2008).

Similar opposition could come from petroleum companies, especially vertically integrated firms such as ExxonMobil, which face lost revenues from extraction of oil, refining, and sales of gasoline to ultimate customers if electric cars become popular. Such companies remain extremely profitable within the current industry infrastructure and therefore have an extraordinary incentive to resist V2G PHEVs.

Even electric utilities, which have the arguably the most to gain from a V2G transition, could become opponents. Researchers at the Paul Scherrer Institute and the Technical University of Lisbon have cautioned that if a V2G transition achieves high levels of customer engagement, it may alter the conventional role that utilities play as the primary sources of power (Turton and Moura, 2008). The researchers noted that widespread use of V2G cars could shift investment away from centralized plants and be seen as a competitor to traditional forms of electricity supply, in turn motivating electric utilities to persuade network regulators to impose onerous requirements on interconnecting and operating V2G technology. Such resistance has already been seen with regard to distributed generation and renewable energy in the United States (Sovacool, 2008; Hirsh and Sovacool, 2006; Sovacool, 2006). To be sure, the automobile manufacturers appear to be developing electric cars, but their motives and commitment must be viewed as suspect given their past experiences.

People and businesses, moreover, seem reluctant to fully embrace the opportunity to generate their own electricity, regardless of whether it comes from a vehicle, a solar panel, a small-scale wind turbine, or their own conventional generator. The cookie baker is concerned with making better chocolate chips, the restaurateur with perfecting a crispy batter, the homeowner with mowing the lawn and perhaps watching television (Sovacool, 2006). Most Americans do not want to be in the "business of making energy," and would rather use their resources—financial and otherwise—promoting core business activities or doing other things. To win the cooperation (and acceptance) of people, PHEVs truly need to be designed so lifestyles and behaviors are not altered. The hardware must be designed so vehicle owners do not need to expend effort to figure out optimal times to recharge their vehicles or sell power back to the grid. All aspects of their operation must be transparent and simple—a goal that requires not only good engineering, but good knowledge of customer behavior and psychology.

In short, many of the most significant participants in the existing transportation infrastructure have huge stakes in maintaining the status quo. Opposition, of course, does not always prevent technologies from emerging into the market. Nonetheless, in the case of automotive manufacturing, the relatively limited number of major firms, fierce competition, and well developed brands may limit the ability for new firms and competitors to enter the market (Svensson and Malmqvist, 2002). Today's situation parallels the one early in the twentieth century, when stakeholders in electric vehicles fought against a rapidly developing (though much smaller) infrastructure built around the internal combustion engine. To be sure, today's manufacturers of hybrid electric vehicles, such as Toyota, are bigger and better organized than the myriad of small electric car manufacturers of a century ago. But today's industries built around petroleum-based fuels also have greater resources and clout as well. Automobile manufacturers express concern that they cannot quickly or profitably make a transition to electric vehicles—which, they contend, customers may not really desire. Moreover, other stakeholders in the existing infrastructure, from the people who repair internal combustion engines to owners of gas stations, would face near-extinction if V2G PHEVs or other forms of electric vehicles became popular.

7. Conclusion

A transition to V2G technology has much to offer. Reducing petroleum use would help insulate the American economy from oil price spikes and shocks on the global market, enhancing national security and mitigating the transfer of wealth to oil-producing countries. It would also greatly improve the quality of the nation's environment, displacing noxious emissions and the human health, ecological, and climate-changed damages they bring with them. Moreover, PHEVs, the necessary precursor to V2G technology, offer motorists potential cost savings and from their use of electricity as a fuel instead of gasoline, and they could greatly improve the economic performance of electric utility companies, especially those that use renewable-energy generators such as wind turbines and solar panels.

While the benefits of such a transition have been widely recognized, they have not yet been achieved, perhaps because the impediments facing such technologies remain simultaneously technical and sociall, especially for the PHEV, the first link in a V2G transition. Impediments relating to customer acceptance, the historical aversion to new technologies, and hearty resistance from stakeholders in the existing infrastructure may be significant impediments. V2G technologies and PHEVs may experience rejection from consumers because of their high initial cost, a serious impediment considering that most people do not discount the savings from energy efficient technologies as do financial experts. Motorists will likely be unaware of how their driving patterns and habits negatively affect V2G PHEV performance, exhibiting impatience and frustration if technologies do not perform precisely as anticipated, especially given the high expectations they developed during the years in which the vehicles have been developed. More serious resistance may come from automobile manufacturers, oil companies, and repair businesses that have sunk billions of dollars into supply and production infrastructure for conventional vehicles. One would expect these powerful industries to exert immense influence with policy makers and the public to maintain the status quo.

If one accepts that PHEVs and V2G technologies have significant advantages, but remain impeded by socio-technical obstacles, then R&D pathways need to change. We certainly endorse continued research efforts to improve battery and associated control technologies. Indeed, we think that improved batteries, for example, can help mitigate some of the impediments we describe. However, we simply note that work to improve the technical performance of hardware must be coupled with attempts to overcome economic, behavioral, cultural, and infrastructural obstacles. These latter types of barriers do not fit neatly into traditional R&D categories and remain deeply embedded in the social and institutional fabric. Overcoming them may require a substantial effort that currently eludes much discussion.

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Tables:

Table 1: Conventional and Unconventional Vehicle Classifications

Vehicle Type	**Engine**	**Advantages**
Conventional	Internal combustion engine	Rapid starting, relatively quick acceleration and power
Hybrid Electric Vehicle (HEV)	Internal combustion engine with separate electric motor	Regenerative braking, fuel savings
Plug-In Hybrid Electric Vehicle (PHEV)	Larger electric motor and battery with smaller internal combustion engine	Can recharge at night to capture HEV benefits plus an all-electric range varying from 20 to 60 miles
Vehicle-to-Grid (V2G) PHEV	Larger electric motor and battery with smaller or eventually no internal combustion engine	Captures PHEV benefits and can send power back to the grid