Plug-In Hybrid Electric Vehicles: Assessing Readiness for the Electrification of Personal Vehicle Transportation

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ABSTRACT

This paper presents an analysis of plug-in hybrid electric vehicle (PHEV) readiness at the community level using parcel level, Tax Assessment data for the City of Madison, WI. Based on results of the readiness analysis, a scenario analysis of electrical grid impact due to varying levels of PHEV adoption is also described.

Key words: plug-in hybrid electric vehicles—infrastructure readiness—electricity accessibility—grid impact
INTRODUCTION

Plug-in hybrid electric vehicles (PHEVs) extend the vehicle technology of hybrid cars to replace a portion of petroleum-powered personal vehicle travel with electric power. What are currently known as hybrid cars or conventional hybrid vehicles are technically named hybrid electric vehicles (HEVs). As the word “plug-in” and the letter “P” is included in its names, plug-in hybrid electric vehicles are designed for external electrical recharge, while HEVs are not. PHEVs render the energy of electricity, which while ubiquitous, an alternative fuel for personal transportation.

Both HEV and PHEV technologies focus on hybridizing the energies of petroleum fuel and electricity to deliver power to vehicle drive trains. The technological extension to PHEV begins with the propulsion and drive power designs of HEV. HEV designs differ among manufacturers and models, but they are alike in that they use petroleum fuel and internal combustion engines to generate electricity, which in turn sustains the power of electric drive systems. Note then, that electric vehicles (EVs), also known as battery electric vehicles (BEVs), have no such hybridization with petroleum energy and would always rely on electricity and, subsequently, recharge connections for it. When HEVs are operated at higher loads, the internal combustion engine power systems supplement the electric drive power. When HEVs are not commanded to be propelled, i.e., during coasting and braking, kinetic energy regenerates electricity for battery storage. While the charge of the HEV battery packs may fluctuate slightly, the HEV power control systems ensure that the internal combustion engines sustain relatively constant battery charges. The current HEV battery packs require stable charges because cyclic and deep depletions and recharges jeopardize their performances and life cycles.

Designs of PHEV propulsion and drive trains also differ among each other. PHEV hybridization of petroleum and electricity functions similar to HEVs. However, the ability to plug these vehicles into external sources of electricity indicates that the battery packs of PHEVs are rechargeable and more able to be depleted with greater fluctuations than the HEV battery packs.

PHEVs are typically classified among themselves according to the distance in miles a fully charged battery can propel the vehicle under standard conditions while operating completely with electricity, or in 100% charge depleting mode. For instance, when fully charged, a PHEV-40 will travel about 40 miles on level terrain with mild acceleration without needing petroleum fuel and the internal combustion engine. When in charge sustaining mode, PHEVs operate much like HEVs—nearly exclusively with the internal combustion engine sustaining the non-depleting battery portion and supplemented only by regenerated electricity. A blend of the two energies propels a PHEV that has a fully charged battery greater distances or with harsher operation by depleting the battery more slowly while the internal combustion engine is selected to co-operate with the battery pack. Particularly, a PHEV-0 operates like this all of the time. It is not an HEV since its battery pack can be recharged, but it also will not travel exclusively electrically with its fully charged battery pack. Once the rechargeable portion of a PHEV battery back is depleted, the internal combustion engine alone energizes the drive system much like an HEV.

While PHEVs are recognized as a promising technology for reducing some of the economic, environmental, geo-political, and energy disadvantages associated with the conventional internal combustion engine (ICE) automobile, the adoption of PHEVs into our communities is not without challenges. The net societal benefit of PHEVs over the ICE vehicles also depends on an array of factors such as recharging infrastructure, energy production life cycle, and vehicle and energy costs.

One particular challenge associated with PHEV adoption is the infrastructure that distributes electrical energy and the necessary connections to that infrastructure for charging PHEV battery packs as more PHEVs penetrate that national personal vehicle fleet. Currently, only a fractional percentage of the current
U.S. personal automobile fleet consists of PHEVs in forms of manufacturer prototypes, eager early-adopter personal vehicles, and retrofitted conventional hybrid vehicles. The future market penetration of PHEVs in the United States is predicted to range from 100,000 vehicles by 2011 (1) to 25% of the light-duty vehicle fleet by 2050 (2). Policy makers’ desire to encourage PHEV adoption and the present uncertainty of PHEVs’ eventual level of market penetration raise the question of whether, and to what extent, our current infrastructure is ready to support communities’ adoption of PHEV.

This study sets out to evaluate communities’ PHEV readiness, defined here as the ability of the current electricity infrastructure to meet the demand of additional new “fuel” utilized by PHEV. In particular, we consider a household as being “PHEV ready” if it has the ability of at-home charging. PHEV readiness is also considered as the base criterion for a household to qualify as part of the market pool for early PHEV adoption.

PAST STUDIES OF PHEV READINESS

The use of home charging/refueling ability to define the upper bound of early PHEV market is not new and is drawn from past observations of ICE vehicle adoption. At the advent of the ICE vehicle introduction, gas stations as we know them were not prevalent. Motorists purchased vehicle fuel in bulk for storage at home. Doing so among these early ICE adopters sustained ICE vehicle growth, until stations became profitably operable. The same may be for PHEV. After a period when motorists who elect to own PHEVs do so with the exclusive home charging, a PHEV fleet may grow to demand secure, public recharging or battery swap stations that resemble, replace, or replicate the current gas station infrastructure. Such stations, thereby, may preclude the need or desire for additional home recharge stations and may induce a market to those without home structural capacity for recharge stations.

The correlation between PHEV adoption and home charging is evaluated to some degree by (3) noting that 120 VAC outlet accessibility defines “prospective owners” as what we would call a pool market for potential PHEV adoption (4). This indicates that while garages can define the pool market, they too may need modification before motorists bring PHEVs home intending to recharge at home. In fact (5), in writing about home 120 volt and 240 volt charging only briefly mentions the use of a standard wall outlet for charging a PHEV. It is conjectured in the study that existing circuits currently in garages could be used, but a switch may be required that deactivates the wall socket in favor of PHEV charging socket and vice versa. In such cases, homeowners, electrical codes, and installers will need to assess continuous power to other garage appliances.

Two studies conducted surveys, with which access to home charging locations was quantified. In (6) 2,372 U.S. nationwide household respondents, 52.4% “identified a electrical outlet within 25 feet of their vehicle parking spot at their home location at some time during their 24-hour day.” The precision of that question does account for vehicle owners who may not park in single-home garages yet still have access to an outlet. In (7), 400 consumers in Boston, Atlanta, Phoenix, and Los Angeles were sampled for other PHEV-related items, such as “relatively easy access to a plug, with 120 volt systems being relatively hassle free.” Unfortunately, the phrasing of the question is not evident and with 86% of households reporting such access, which seems intuitively excessive, by no means matches the rate of (6). Nonetheless, the precision of not necessarily relying on single-home garage information is noted.

For a larger sample size, (4) uses the 1% Public Use Microdata Sample (PUMS) of the 2000 Census of the State of California. These data were used for the purpose of analyzing not just capabilities for only electric home refueling but for future hydrogen refueling as well. With it, housing stock built after 1974 was used as a proxy for “home connection hardware.” Buildings built since 1974 have been wired according to the National Electric Code revision of that year, and those authors intimate that code as
sufficient for the purpose of their study. This limits the precision of the PHEV pool market by underestimating older homes and, specifically, their garages that could easily have been wired for PHEV charging and overestimating the number of buildings, which could include apartments and condominiums. The result of that assessment was a pool market of 15% of households. Similarly, the publicly available American Housing Survey is used by (8) to identify the existence of a “garage or carport” amenity at a single-unit house is a proxy for “likely PHEV buyers.” The pool market assessment in this case yields 38.7% of households. Extending electricity to carports may be more code cost prohibitive than even doing so with detached garages, since electrical raceways exposed to the elements do require additional code adherence. So, assuming that builders included costs to serve carports with electricity may have overestimated the pool market in this case.

The four aforementioned studies have delivered significantly different assessments of pool markets. As described above, pool markets among households are either 52.4%, 86%, 15%, or 38.7%. Intuitively, the values, 86% and 15% seem too large and too small, respectively. The values, 52.4% and 38.7% both seem reasonable, yet where 38.7% of single homes have garages or carports might overestimate the pool market on behalf of carports; that value is still less than the survey respondents’ 52.4% pool market. Perhaps opening the pool market of that survey to include any outlets within 25 feet subsequently overestimated it.

A report on compressed natural gas (CNG) infrastructure of the 1980s shares lessons about alternative fuel transportation (9). That report does call exception to the electricity utility infrastructure, “which is already available in homes, (…and…) can avoid this issue (inadequate infrastructure) through affordable repowering.” The report also stated that “the main barrier was a lack of infrastructure to support the converted vehicles” and “utilities or energy suppliers can be allies, but need to ensure that their actions are strategic in building the market.” These comments are the basis for this paper.

A SPATIAL ASSESSMENT OF PHEV READINESS

In order to accurately assess current and future infrastructure needs, it is imperative that the electrical utility organizations and agencies know both how much PHEV load will be added to their infrastructures and the locations where that PHEV load will be added. For that, local utilities will need quantitative and geospatial insight into assessments of the PHEV pool market. The work described is intended as a tool for this purpose. Specifically, the authors present a method of geospatially determining PHEV electricity demand for distribution planners. This may be one of only a few, if any, methods that will assist the assessment of PHEV Readiness at the community level.

The ability for motorists to refuel their personal vehicles at home with connection to an electric outlet is one of the touted advantages of PHEVs. Focusing on the present for a first assessment of PHEV infrastructure support directs consideration of detached housing units that are known to have the secure and convenient personal-vehicle parking location of a garage. A survey conducted by the research team confirms that of the 267 sampled households residing in single detached houses with attached garages in the City of Madison, WI, 98.5% have access to 120 volts in their garages. Of the 43 sampled households residing in single detached houses with detached garages, 100% have access to 120 volts in their garages. Acknowledged are potential early or present PHEV adopters who have no access to home charging sources yet know they can rely on electrical outlets at their employers’ parking locations or their other activities’ parking locations. Similarly acknowledged are potential PHEV adopters who live in condominiums or apartment complexes yet can still arrange vehicle charging connections. While such dwelling facilities may or may not, and moreover infrequently, have secure charging amenities, the authors are certain that most garages associated with detached homes do.
Based on the above reasoning, the authors’ analysis of PHEV readiness in the City of Madison, WI, is based on the assumption that all single detached houses with garages in the City of Madison, WI, have electric service in their garages for recharging. Differing from previous studies that used the Census data to identify the aggregate distribution of such housing units across census reporting units, the authors opted for the City’s Property Tax Assessment data, which provide housing information at the land parcel level. This allows the authors to pinpoint the exact locations of housing units that are PHEV ready or not.

Specifically, the City of Madison Tax Assessment data were geo-referenced using the Madison Area Transportation Planning Board’s land parcel boundary data in ArcGIS format. As such, each land parcel in the city is characterized by its property class, property use, and garage type, among other attributes. Parcels with the following properties are then classified as PHEV ready:

- Property Class = “residential”
- Property Use Code = “single family”
- Garage Type = “detached” or “attached”

When these parcels are displayed on a map as shown in Figure 1, distinct clusters and sectors of these parcels are evident, thus displaying the PHEV Pool market.

![Figure 1. Distribution of single-family residential units by garage type](image-url)
AN ASSESSMENT OF GRID READINESS

Charging PHEVs in household garages substantiates a notable change in household electricity use, which in turn impacts the temporal and spatial load distribution seen by utilities. For instance, charging a fully depleted PHEV-40 from a standard 120 volt outlet would be on the order of operating a small hair dryer or one-third of a central air conditioning unit (different voltages aside), non-stop for two hours every other day (assuming full depletion of the PHEV-40 is a result of 40 miles all-electric driving; 20 miles/day x 2 days) all year. This could potentially be the second largest energy load in the cooling months and, in the course of a year, perhaps the single largest energy load, at the household level.

Fundamentally, all electrified homes, and subsequently their garages, are connected to electric power utilities and the generators that serve them through a network of transmission equipment and distribution lines. With the aforementioned substantial load of one household’s PHEV in mind, the aggregate load of many households with PHEVs will merit study.

Following from the PHEV readiness analysis, the authors present a preliminary analysis performed to gauge the impact of adding significant PHEV load at the transformer level. According to a study performed by Duke Energy, the most significant impacts of PHEV market penetration will likely be due to geographic clustering of vehicles (1). Such demand clustering suggests the need for analyzing areas with high concentration of PHEV-ready households.

The grid impact analysis is based on data provided by Madison Gas & Electric (MG&E), the local utility serving the City of Madison, WI. MG&E provided a typical peak-day load curve for the daily consumption of eight customers fed from a single 50 kVA transformer. The data obtained are an approximation based on the load curve for a primarily residential feeder within MG&E’s service territory. This approximation was used because MG&E does not record hourly load data at the transformer level.

As a case study, a small neighborhood of eight PHEV-ready households in Madison who share a selected transformer is the focus for the grid impact analysis. The scenarios of one, two, three, …, and up to all eight of these households becoming owners of PHEV are examined. These households are assumed to charge their vehicle from a standard 120 VAC 15 A outlet available in their garage. Although these outlets are rated to provide power up to 1.44 kW, preliminary studies on actual charging patterns from converted Hymotion Prius PHEVs show that the average power drawn by the vehicle when charging is approximately 0.77 kW (1).

Combining the transformer data and the vehicle data, the authors were able to determine the energy impact of adding discrete PHEV load to the selected transformer. Given that the transformer is rated at 50 kVA and assuming an average residential power factor of 0.8, it is possible to determine how adding PHEV load will impact the percent loading of the transformer. Utilities will likely attempt to minimize PHEV contribution to peak load by implementing certain rate structures. However, as a worst-case scenario, we can assume that customers will elect convenience over cost and charge their vehicles in the late afternoon. This unfortunately coincides with the typical residential peak load. Figure 2 illustrates the impact of adding PHEVs to the selected 50 kVA transformer, assuming each adopter owns a single PHEV.
Figure 2. Transformer load profiles for the base and the eight levels of PHEV adoption scenarios

It should be noted that prior to adding any PHEV load to the system, this selected transformer is already approaching its rated value. Recall that this is not the typical load seen by the transformer, but rather the load seen on a particularly warm day within the last five years. However, adding four PHEVs to this transformer does increase the percent loading to over 107%, and adding eight PHEVs to this transformer increases the percent loading to nearly 115%. It will be important of utility planners to understand when, where, and how much the PHEV load will add to the system in order to adequately plan maintenance, upgrades, and additions to the distribution system.

DISCUSSION

The authors should consider that more than one PHEV could be associated with any parcel, where there may be circuitry in multi-car garages to simultaneously charge multiple PHEVs or where staggered charging times are used. In fact, the City of Madison Tax Assessor data do include variables for multiple garages on parcels and for their quantities of parking stalls. For the demonstration herein, the envelope of demand and pool market was assumed as only one PHEV per single home parcel with garage.

Focusing on just the present did eliminate the future considerations of battery transfer stations for drivers who may have elected to own a PHEV yet have no periodic access to electrical charging sources. Moreover is the potential for retail charging stations that resemble gas stations, where PHEVs can be charged in time frames of minutes instead of hours. Even though most home charging is likely to occur during sleeping hours, which fortunately corresponds to off-peak electricity demand, some charging may necessarily occur during daytime hours. So far in this work, only residential charging durations on the order of two hours have been discussed.
A range of other PHEV topics extends from the vehicle-operator level to the energy policy and national market demand level. At the vehicle-operator level, for instance, fuel-related performances perceived and recognized by PHEV operators and battery size with weight conditions and benefits are analyzed with respect to electric fuel balances, blends, and choices against, with, and over gasoline. At the policy national market level, researchers investigate attributes related to regional and national energy use and the same aspects of fuel types, and as well implore the engagement of electric utilities to utilize rate structures that encourage leveling overall electricity demand with off-peak versus peak charging.

Another analytical complication may arise when electric utilities consider another conjectured attribute of PHEV—that of “plugging out” with “Vehicle-to-Grid” electricity. In that scenario, PHEV motorists elect to charge their vehicles as lower, off-peak cost, then subsequently resell some of the vehicle energy back to the utility for a higher price during higher demand, whether still at home or at a secure municipal/utility station. This aspect of PHEV is not covered herein, but to do so in the future would require an analysis of commercial/industrial geographic areas where such opportunities are more likely to be installed. It is hoped that this method would assist with those expanded efforts.

Policy makers and transportation planners alike may involve themselves with the process of defining other PHEV pool and real markets, since PHEVs and charging them does present one particular equity issue. Notable is the alleged $10,000 premium. If this was simply a premium for a standard ICE car, there would be a set of the motorist population that would not afford it. However, there could be members of that lower income group who may elect to purchase PHEV on the merits of fuel economy. Such instances may require a geographic representation that defines sectors of population with less vehicle purchase power yet perhaps does not include the population with single detached homes. Furthermore, if those with less purchase power could purchase a PHEV, they still may be prohibited from doing so because they still cannot afford to purchase their own secure personal charging station, i.e., a detached dwelling with a garage—their own home. Omitting sectors where the primary charging locations of single detached homes exist may help reveal where municipal, commercial, or dwelling complexes should be encouraged to install charging stations.

Additionally, agencies that wish to adopt policies encouraging denser built environments with goals of fewer road miles may reveal a contradiction with PHEV home charging. If single-unit personal garages remain the universal primary charging locations, the inclusion of those garages will use more land. Furthermore, residents who choose to live in denser urban environments may be served well by PHEV if they must own personal vehicles but may not have adequate access to PHEV charging opportunities. It is anticipated that the availability of a geo-spatial reference would assist in these assessments.
ACKNOWLEDGMENTS

The authors thank the many staff at the City of Madison Assessor’s Office, Madison Area Transportation Planning Board’s GIS unit, and Madison Gas & Electric for providing data for our analysis. This research was funded jointly by the Public Service Commission of Wisconsin’s Environmental and Economic Research and Development (EERD) Program and the Center for Freight Infrastructure Research and Education of University of Wisconsin, Madison. The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein.

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