On the Choice Between Uncontrolled and Controlled Charging by Owners of PHEVs

Di Wu, *Student Member, IEEE*, Dionysios C. Aliprantis, *Senior Member, IEEE*, and Lei Ying, *Member, IEEE*

***Abstract*—This letter analyzes the decision-making process of owners of plug-in hybrid electric vehicles (PHEVs), when choosing between uncontrolled and controlled charging programs. The minimization of energy cost leads to a set of outcomes determined by electricity and gasoline prices, and impacts the electricity rates of PHEV aggregators.**

***Index Terms*—Aggregators, plug-in hybrid electric vehicles (PHEVs).**

I. Introduction

Owners of plug-in hybrid electric vehicles (PHEVs) will have the option to choose between two different charging programs: 1) uncontrolled charging (i.e., completely unrestricted, similar to any other appliance) with a regular retail electricity price and 2) controlled off-peak charging with a reduced price, offered by PHEV aggregators [1], [2]. Aggregators will coordinate PHEV charging so that it does not occur during peak power system load hours, or so that it does not overload distribution transformers, and will provide ancillary services to the power system and, thus, are expected to play a central role in tomorrow's smart grid. Arguably the most significant factor affecting this decision will be the total energy cost, consisting of expenses for electricity and gasoline.

In this letter, the decision-making process of a cost-conscious PHEV owner, who is trying to minimize his/her transportation energy cost, is studied. The analysis leads to a set of outcomes determined by the prices of electricity and gasoline, and yields certain interesting insights pertaining to the pricing of electricity by PHEV aggregators. It is shown that under certain conditions, some PHEV owners might prefer uncontrolled charging, thus reducing the market share of aggregators and the benefits of coordinated PHEV charging to the electric power system. It should be emphasized that this letter does *not* delve into the factors that affect the decision of whether to purchase a PHEV or not; rather, it is assumed that this decision has already been made.

II. Decision-Making Process of PHEV Owners

The operation of PHEVs can be classified into the charge-depleting (CD) and the charge-sustaining (CS) modes [3], [4]. Therefore, the daily vehicle-miles-traveled (VMT) m can be split into miles in CD and CS modes $m = m_{\rm cd} + m_{\rm cs}$. In the CD mode, the vehicle gradually consumes the energy stored in the batteries, with either a fraction of or the entire tractive energy coming from the battery pack. When a minimum state of charge is reached, the CS mode is activated, and PHEVs operate similarly to conventional hybrid electric vehicles, with all tractive energy coming from the gasoline in the tank.

Therefore, the daily electric energy consumption at the wall outlet can be estimated by

$$\epsilon_e = \frac{\xi h_{\rm tr} m_{\rm cd}}{\eta_e} \tag{1}$$

where $\xi \leq 1$ is the fraction of tractive energy from electricity in the CD mode, $h_{\rm tr}$ is the required tractive energy per mile at the wheels, and η_e is the wall-to-wheels efficiency. A method to estimate ϵ_e has been presented in [5].

On the other hand, gasoline can be consumed during the CD mode (under blended operation) and the CS mode. If the tank-to-wheels efficiency (η_g) is assumed to be the same for both modes,[1] the daily gasoline energy consumption is

$$\begin{aligned}\epsilon_g &= \frac{(1-\xi)h_{\rm tr} m_{\rm cd} + h_{\rm tr} m_{\rm cs}}{\eta_g} \\ &= \frac{h_{\rm tr}(m - \xi m_{\rm cd})}{\eta_g}.\end{aligned} \tag{2}$$

The residential retail electricity price for uncontrolled charging is r_e, the energy content of gasoline is e_g, and the retail price of regular gasoline is r_g. A PHEV's daily energy cost in the uncontrolled charging program is expressed

$$C = \frac{r_g h_{\rm tr} m}{e_g \eta_g} + \xi h_{\rm tr}\left(\frac{r_e}{\eta_e} - \frac{r_g}{e_g \eta_g}\right) m_{\rm cd}. \tag{3}$$

Here, r_e/η_e and $r_g/(e_g\eta_g)$ have the physical significance of *price of tractive energy* (at the wheels) for electricity and gasoline, respectively. A cost-conscious PHEV owner will try to minimize C, and it is obvious from (3) that—all other things being held constant—this decision will be based on the relation between electricity and gasoline prices.

When $r_e/\eta_e > r_g/(e_g\eta_g)$, it is cheaper to drive PHEVs with gasoline instead of electricity. The PHEV owner would decide to make $m_{\rm cd} = 0$ by never charging the vehicle, thus avoiding consuming any electricity from the grid, and would just keep driving in the CS mode. Conversely, when $r_e/\eta_e < r_g/(e_g\eta_g)$, the PHEV owner would take advantage of all opportunities to charge the vehicle (wherever a charging infrastructure is in place: at home, at work, at the shopping mall, etc.), in order to maximize electricity usage and $m_{\rm cd}$.

In the U.S., the average residential retail electricity price in 2010 was ca. 0.12 \$/kWh, and is expected to remain at similar levels over the next 25 years [6]. The annual average re-

[1]PHEVs may have different tank-to-wheels efficiencies in CD versus CS mode [3] but this (small) difference is ignored herein.

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The authors are with the Department of Electrical and Computer Engineering, Iowa State University, Ames, IA 50011 USA (e-mail: dwu@iastate.edu; dali@iastate.edu; leiying@iastate.edu).

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tail gasoline price in the U.S. has been higher than 2 \$/gallon since 2005, and is expected to increase to 4–6 \$/gallon in the next 25 years (in today's dollars) [6]. Since $\eta_e \approx 0.65$–0.70 [5] and $\eta_g \approx 0.25$–0.3, it can be readily verified that using electricity rather than gasoline to power PHEVs makes financial sense in most of the U.S. today. For example, in Iowa during 2009, the average $r_e \approx 0.10$ \$/kWh, while the average $r_g \approx 2.3$ \$/gallon, making the tractive energy price of electricity about 60% that of gasoline. Nevertheless, there are some states where the retail electricity price is quite high. One example is Hawaii where, in 2009, the two rates were $r_e \approx 0.24$ \$/kWh and $r_g \approx 3.0$ \$/gallon, so the cost of moving PHEVs with electricity would have been about 9% higher.

In the controlled off-peak charging scenario, a PHEV owner relinquishes control of the battery's state of charge, in exchange for a reduced electricity rate ($r'_e < r_e$). In this case, some charging that normally would have occurred during on-peak hours may not be allowed by the aggregator, and so, a fraction α of the daily VMT may shift from the CD to the CS mode; hence, a greater portion of the tractive energy would be derived from gasoline. Using the simulation method and parameters of [5], based on the 2009 National Household Travel Survey, a statistical analysis on α has been performed, revealing that $\alpha = 0$ for a significant portion of PHEVs, but reaching values as high as $\alpha = 0.5$ (or more) for the remaining PHEVs. The energy cost for controlled charging is (cf. (3))

$$C' = \frac{r_g h_{\mathrm{tr}} m}{e_g \eta_g} + \xi h_{\mathrm{tr}} \left(\frac{r'_e}{\eta_e} - \frac{r_g}{e_g \eta_g} \right) (1-\alpha) m_{\mathrm{cd}}. \quad (4)$$

The choice of charging program depends on the cost difference

$$C' - C = \xi h_{\mathrm{tr}} m_{\mathrm{cd}} \left[\frac{(1-\alpha) r'_e - r_e}{\eta_e} + \frac{\alpha r_g}{e_g \eta_g} \right]. \quad (5)$$

The owner will benefit from joining the controlled charging program only if $C' < C$, which requires

$$r'_e < r_e + \frac{\alpha \eta_e}{1-\alpha} \left(\frac{r_e}{\eta_e} - \frac{r_g}{e_g \eta_g} \right) = r_e + R. \quad (6)$$

It is interesting to note that the condition above is independent of 1) ξ, or drivetrain design; 2) the tractive energy, related to the PHEV weight/type; and 3) m_{cd}, related to the battery size.

In summary, the following four cases are identified:

1) If

$$\frac{r_e}{\eta_e} > \frac{r'_e}{\eta_e} > \frac{r_g}{e_g \eta_g} \quad (7)$$

then the PHEV owner will prefer driving solely on gasoline, and will never charge the vehicle's battery. All of the miles traveled will be driven in the CS mode.

2) If

$$\frac{r_e}{\eta_e} > \frac{r_g}{e_g \eta_g} > \frac{r'_e}{\eta_e} \quad (8)$$

then the inequality (6) is satisfied. Therefore, the PHEV owner will prefer the controlled charging program.

3) If

$$\frac{r_g}{e_g \eta_g} > \frac{r_e}{\eta_e} > \frac{r'_e}{\eta_e} \quad (9)$$

and (6) is satisfied, then the PHEV owner will subscribe to the controlled charging program.

4) If

$$\frac{r_g}{e_g \eta_g} > \frac{r_e}{\eta_e} > \frac{r'_e}{\eta_e} \quad (10)$$

and (6) is not satisfied, then the PHEV owner will join the uncontrolled charging program.

III. Concluding Remarks

Based on today's and forecast energy prices, the most probable situation will be either case 3 or 4 (otherwise, with gasoline prices lower than electricity, it is unlikely that PHEVs will become popular), where the owner's decision depends on (6). A key observation is that setting r'_e slightly below r_e will not suffice to attract every owner; the two rates must differ by at least $|R|$ (an owner-specific parameter), which could be substantial. For example, assuming typical values $\eta_e = 0.7$, $\eta_g = 0.25$, and $\alpha = 0.2$ for a certain driver, and prices $r_e = 0.12$ \$/kWh and $r_g = 3.5$ \$/gallon, then an aggregator should set its rate $r'_e < 0.083$ \$/kWh to attract this owner. If r_e represents a discounted overnight rate of a time-of-use program, then the aggregator would have to reduce its rates further (e.g., $r_e = 0.08$ \$/kWh leads to $r'_e < 0.033$ \$/kWh). On the other hand, aggregators would be able to increase rates when the price differential between electricity and gasoline is smaller. Alternatively, (6) implies that the aggregator should carefully design its control algorithms in order to minimize the "leakage" factor α, while avoiding expensive on-peak charging or overloading distribution circuits.

The average excise tax on gasoline today in the U.S. is 0.48 \$/gallon, of which 0.184 \$/gallon is a federal tax that feeds the Highway Trust Fund (HTF), which has not been adjusted for inflation since 1993. These monies are used to maintain the Interstate Highway System and state/local roads. Due to the higher fuel efficiency of modern automobiles, the HTF has been recently plagued by a severe capital shortage, which will certainly become worse with the advent of PHEVs, unless this tax is extended to the PHEV owners (as users of the same transportation infrastructure). If such a tax (on the order of a few cents per kilowatt-hour) were to be imposed equally on uncontrollable and controllable PHEV load, it would not affect the difference between r_e and r'_e, but it would affect R (a convergence of electrical and gasoline tractive energy costs would occur). This would have a positive impact on aggregators' market share and revenue, but a negative impact on the transportation costs of individual PHEV owners.

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