Day-Ahead Optimal Management of Plug-in Hybrid Electric Vehicles in Smart Homes Considering Uncertainties

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***Abstract*—The plug-in hybrid electric vehicles (PHEVs) integration into the electrical network introduces new challenges and opportunities for operators and PHEV owners. On the one hand, PHEVs can decrease environmental pollution. On the other hand, the high penetration of PHEVs in the network without charging management causes harmonics, voltage instability, and increased network problems. In this study, a charging management algorithm is presented to minimize the total cost and flatten the demand curve. The behavior of the PHEV owner in terms of arrival time and leaving time is modeled with a stochastic distribution function. The battery model and hourly power consumption of PHEV are modeled, and the obtained models are applied to determine the battery's state of charge. The proposed method is tested on a sample demand curve with and without a charging management algorithm to verify the efficiency. The results verify the efficiency of the proposed method in decreasing the total cost using the management algorithm for PHEVs, especially when the PHEVs sell the electricity to the network.**

***Keywords*—Energy management, Plug-in hybrid electric vehicle, Smart home, Stochastic model, Uncertainty.**

I. INTRODUCTION

Electric vehicles (EVs) have globally been developed, and they have been highly penetrated in the electrical network. Increased penetration of the plug-in hybrid electric vehicles (PHEVs) can affect the electrical network, and its integration into the network should be carefully investigated.

The uncontrolled integration of PHEVs leads to power quality problems (voltage instability and harmonics), peak demand growth, and increased electricity demand, resulting in an increase in the total production of fossil fuel power plants. However, the controlled penetration of PHEVs can help the electrical network to manage the demand curve and decrease environmental pollution. Specifically, the controlled charging may improve the peak shaving and demand profile.

The effects of EVs on the power consumption and demand curve have been investigated, and their drawbacks and opportunities have been recognized in various studies. In [1], the integration of EVs and photovoltaic (PV) units have been studied, and the required changes in terms of electricity production have been introduced to realize the high uncertainties of renewable energy systems. The impact of programmed energy management of renewable energy resources and EV is evaluated in [2].

In [3], the drawbacks and benefits of EVs integration to the network have been studied, and its effect on the electricity market, demand curve, and possible changes have been introduced. The impact of PHEV charging on the power transfer system and demand profile has been studied in [4]. The impact of high penetration of renewable energy systems and PHEVs on optimal size and place of resources considering the operating constraints have been investigated [5]. However, the abovementioned studies have not considered the uncertainties in PHEV.

The stochastic behavior of EV and renewable energy resources has been investigated to address an optimal energy management algorithm. In [6], the impact of PHEV integration on peak shaving and valley filling of the demand curve has been studied, and the optimal charging algorithm has been proposed to address the uncertainties in PHEVs.

The effects of the stochastic behavior of EVs and residential load on the distribution network have been investigated, and the predictive algorithm has been proposed to address both uncertainties [7]. In [8], a new energy management algorithm has been proposed for smart grids to address the uncertainties in PV units, wind turbines, and EVs in a day-ahead market. The optimal charging of PHEVs has been found, where the uncertainties of PHEVs and renewable resources have been considered [9].

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It should be noted that the abovementioned studies have been mostly devoted to the uncertainties in renewable resources, and a limited number of resources have investigated the stochastic behavior of the EVs according to the real data.

The charging of EVs has been managed through different methods to address the high penetration of EVs into electrical networks. In [10], the energy management of PHEVs has been studied considering the prediction of velocity changes and the behavior of PHEV owners. In [11], the PHEV charging platform has been proposed to address both network operator and PHEV owner. The operation of electric vehicles has been determined considering the reliability constraints and high penetration of renewable resources [12].

The energy management of the smart grid has been addressed in the presence of renewable energy systems and electric vehicles to minimize the total cost in the electricity market [13]. The EV demand has been managed to minimize the total cost of a residential MG, where renewable resources and storage have been modeled [14]. In [15], the EV charging has been managed in the presence of PV units using a deep reinforcement learning algorithm. The energy management in the residential smart grid has been studied in the presence of PHEVs [16].

The PHEV penetration in networks has been managed in a day-ahead market to minimize the total cost of EV aggregators [17]. The optimization of fuel consumption in PHEVs, considering the trajectory of PHEVs, has been predicted in [18]. An optimal planning algorithm has been proposed in [19] to find the optimal operation of EV, where the Monte Carlo method has been used to model its uncertainties. Ref. [20] has proposed collaborative energy management among PEVs, smart homes, and neighbors' interaction. Ref. [21] has comprehensively discussed three necessary infrastructures by which charging of PHEVs can be done.

In [22], a coordinated scheduling algorithm has been proposed for charge/discharge of aggregated EV fleets to maximize the integration of wind generation and minimize the charging cost for EV owners in a vehicle-to-grid setup. A multi-objective management algorithm has been proposed to schedule the EVs, considering the operational and customer constraints [23]. The abovementioned studies have been focused on improving the financial aspects of EV integration into the grid; however, the financial aspect and improving the demand profile are addressed in this current work.

In [24], the charging of EVs has been managed to modify the demand curve. Ref. [25] has defined both the existing system, where the flexibility has been viewed from the standpoint of charging stations, and the proposed one, where the flexibility has been viewed from the vehicle's perspective. In [26], two-stage stochastic programming has been implemented in a smart home application to reduce an ordinary household's electricity procurement cost.

A novel bi-functional charging management strategy using the mobile edge computation-based framework has been proposed in [27] to book the charging piles with less waiting time effectively and achieve better energy efficiency during charging booking. In [28], a heuristic algorithm has been designed to optimize regional PHEV charging schedules to minimize greenhouse gas emissions from electricity generation.

Charging management of EVs has been proposed to address the optimal operation of EVs in smart buildings [29]. All in all, none of the work in the literature has proposed an optimal charging management algorithm to address the high penetration of PHEVs, where its uncertainties are modeled through the real data. Furthermore, the impact of both uncontrolled and controlled charging on the demand profile is investigated due to the advantages of vehicle-to-grid structure. Therefore, the main contributions of this paper are as follows:

- Proposing optimal charging management of PHEVs to improve demand profile and minimize cost.
- Modeling uncertain parameters of PHEVs (arrival time, leaving time, and the initial state of charge PHEV battery) due to real data.

The rest of this paper is organized as follows. The PHEV model and demand curve are presented in Section II. The methodology for charging management is proposed in Section III. The simulation results and further discussion are addressed in Section IV. Finally, the conclusion is presented and summarized in Section V.

II. Modeling the Plug-in hybrid electric vehicle and demand curve

In this section, the PHEV is modeled considering the battery and stochastic behavior in terms of arrival/leaving time and traveled distance. In addition, the demand curve of residential loads is presented in this section.

A. Plug-in hybrid electric vehicle(PHEV)

The studied PHEVs are modeled in this section in terms of battery, power consumption, stochastic behavior, and PHEV charging model. The PHEV penetration has been highly increased, and it is crucial to assess their network effects. If PHEVs are not managed, it has destructive effects on load curve and power quality constraints. Further, PHEVs are mostly charged at peak hours, which increases the peak demand.

Hence, proposing a methodology for setting charge time is necessary. It is too important to study the model of PHEVs in terms of the battery and stochastic behavior of PHEV owners. The PHEVs uncertainties can be investigated in both arrival time and leaving time to/from smart homes. In this study, Nissan Altra is chosen as a sample PHEV, equipped with a lithium-ion battery [30]; the stochastic behavior of PHEV owners is studied simultaneously.

1) Stochastic study on PHEV

The stochastic study on PHEV is necessary to model its intermittent nature. It should be noted that vehicle owners have various departure time due to their habits and works. They also come back home at various time due to their working hours. Further, the power and fuel consumption of PHEVs are related to traffic and their job location.

In [24], the stochastic behavior of PHEV owners has been modeled in terms of three variables, including leaving time, arrival time, and traveled distance. Analyzing the stochastic nature of PHEVs can be useful for calculating the PHEV power and fuel consumption. Further, the PHEV owner can manage his driving habits; this data can be utilized by network operators. Hence, the traveled distance is:

$$f_d = \frac{1}{\sigma_d}\left(1 + k_d\frac{(d-\mu_d)}{\sigma_d}\right)^{-(1+\frac{1}{k_d})} e^{-(1+k_d\frac{d-\mu_d}{\sigma_d})^{-\frac{1}{k_d}}} \quad (1)$$

where k_d, μ_d and σ_d are the probability distribution function parameters; in this study, these parameters are equal to –0 .05, 17.66, and 7.12, respectively.

The PHEV time to reach home can be described as follows, where the parameters of this function are investigated according to the historical data and fitting the probability distribution function using the machine learning toolbox of MATLAB.

$$\tau_a = \frac{1}{\sigma_a}\left(1 + k_a\frac{(t-\mu_a)}{\sigma_a}\right)^{-(1+\frac{1}{k_a})} e^{-(1+k_a\frac{t-\mu_a}{\sigma_a})^{-\frac{1}{k_a}}} \quad (2)$$

where k_a, μ_a and σ_a are equal to –0.06, 17.27, and 0.85, respectively. The leaving time of PHEV owners can be similarly modeled according to the recorded data of PHEVs. The leaving time is also fitted as follows.

$$\tau_l = \frac{\beta}{\alpha}(\frac{l}{\alpha})^{(\beta-1)}e^{-(\frac{l}{\alpha})^{\beta}} \quad (3)$$

where α and β denote the probability distribution function parameters and are equal to 7.67 and 21.38, respectively, the leaving time of PHEV owners is similarly modeled with the machine learning toolbox of MATLAB using the recorded data of PHEVs.

2) Modeling power consumption of PHEV

The PHEVs can be charged or discharged when they are at home, assuming that the PHEV charge is started at $\tau_a$and will be finished at τ_l. Power consumption of the vehicle is shown by P_t^{EV} [31]. Constraints on PHEVs charge/discharge power and state of charge are as below. The operating power of the vehicle's charger should be within a predefined range. P_{max}^{EV} and P_{min}^{EV} are the maximum and minimum operating power of the charger at t^{th} period.

$$P_{min}^{EV} \le P_t^{EV} \le P_{max}^{EV} \qquad (t = 1 \sim T) \quad (4)$$

The state of charge for the battery of the vehicle at t^{th} period, SOC_t, should stay within the maximum and minimum limits that are represented by SOC_{max} and SOC_{min}.

$$SOC_{min} \le SOC_t \le SOC_{max} \qquad (t = \tau_a \sim \tau_l) \quad (5)$$

Sign function of P_t^{EV} represented by sgn_t, representing the state of charging/discharging of vehicle's battery when it is plugged in (i.e., $t = \tau_a \sim \tau_l$); during this period, SOC_t is defined as (7).

$$sgn_t = \begin{cases} -1 & P_t^{EV} < 0 \\ 1 & P_t^{EV} \ge 0 \end{cases} \quad (6)$$

$$SOC_t = \begin{cases} \dfrac{SOC^a + P_t^{EV}(\eta)^{sgn_t}\Delta t}{Q} & (t = \tau_a) \\ SOC_{t-1} - \dfrac{SOC^a + P_t^{EV}(\eta)^{sgn_t}\Delta t}{Q} & (t = \tau_a + 1 \dots \tau_l) \end{cases} \quad (7)$$

where the length of each period is shown by Δt, and η is the efficiency of the charger that can be between 0 and 1. Q is the capacity of the onboard vehicle battery.

The initial charge of each EV after arriving home is shown by SOC^a; SOC^l denotes the SOC of EV after leaving home, so ΔSOC is the net charging of the vehicle, and it should be satisfied during the scheduling.

$$\sum_{\tau_a}^{\tau_l}[P_t^{EV}(\eta)^{sgn_t}\Delta t] = \Delta SOC = SOC^l - SOC^a \quad (8)$$

Since the traveled distance of the vehicle is stochastic (defined in (1)), the SOC after arriving home should be a function of distance traveled and greater than SOC_{min}.

$$SOC^a = (1 - \frac{f_d}{d_{max}})SOC^l \quad (9)$$

$$SOC^a \ge SOC_{min} \quad (10)$$

B. Demand Curve

The demand curve can be determined through the measurement or studying habits of residential users [32]. It is crucial to identify the load curve to control power consumption and costs. It is also important from the operator side to supply enough power for residential sectors.

The peak demand is at $t = 16$, equal to 840 kW, and the minimum amount occurs at $t = 5$. The demand curve increases from morning to afternoon due to high temperatures during this period. The demand curve stays at high value during nights in hot seasons because people prefer to sleep later, and it decreases between $t = 2$ to $t = 6$ when people usually sleep; during this period, only some residential appliances like refrigerators, heating/cooling systems consume power.

The demand curve is obtained for a smart home community, so different numbers of PHEV can be considered in this residential community. It is important to consider that PHEV penetration increases over time, and this growth should be addressed in planning studies. The high penetration of PHEVs in the network can increase the peak of the demand curve, which is not desirable for the electrical network.

As a result, the gradual increase of PHEVs in the network is studied in this paper, and its effect on peak demand and demand increase is shown. The importance of charging management is highlighted in the high penetration of PHEVs and renewable energy systems when the uncertainties increase in the network.

III. Methodology

The PHEVs charging can be managed through different approaches, as discussed in the introduction section. Two different approaches are addressed in this study. The first approach only considers the arrival time, so the PHEVs are plugged in after arriving home. The second approach considers minimizing the total cost of the PHEV owner.

Smart homes are introduced to simplify energy management, and it is too important to manage the electricity cost in today's network. Managing the cost and charging of PHEVs is valuable for both PHEV owners and network operators. The main objective of the PHEV owner is to minimize his cost, considering the environmental issues. Additionally, the network operator considers the network constraints, where the PHEV integration may not increase the barriers of today's networks. Two approaches are explained as follows:

A. Charging without management

In this case, the PHEVs are plugged into the network after arriving home, and the arrival time must be calculated from (2). In this case, there is no constraint on charging time, so the PHEV owner prefers to plug the PHEVs into the network after arriving home. The arriving time is generally at 18, so it is expected that a high electricity demand occurs at this hour.

In this case, there is no incentive for shifting the charging time, which is only determined by the arriving time. This case may happen in non-smart homes, where shifting the charging time causes dissatisfaction for PHEV owners. As a result, they prefer to charge their vehicles after arriving home instead of shifting it to the early morning.

B. Charging with cost management

The energy management of smart homes can be useful from different aspects, and the charging time of PHEVs can be shifted to any time without unfavorable effects on the owner's relief. The charging time can be determined at any time over day or night to minimize the total cost of PHEV owners. In this case, the charging time is specified on the condition that the total cost is minimized.

The PHEVs are not plugged into the network immediately after arriving home, and charging time is shifted to time that minimizes the total cost. Also, PHEVs can sell a part of their power to the network to increase the revenue of the smart homes. The energy management system of smart homes can receive electrical signals from the network and determine the charging time to minimize the total cost.

The smart home energy management system is programmed to minimize the total cost of PHEV owner, and the charging time of PHEV is determined to reach this objective. There are different methods for electricity pricing, including real-time pricing and time of use (TOU) [33]. In this paper, the TOU pricing is considered during three time periods (i) off-peak hours (9 pm-5 am); (ii) mid-hours (5 am-5 pm); and (iii) peak hours (5 pm- 9 pm).

The objective function of the energy management system at the smart home is defined in (12), which aims to minimize the total cost of PHEV charging. The total cost of PHEV charging must be minimized during the charging period so that the charging time should be chosen considering the SOC and the required period for charging the PHEVs.

$$\begin{aligned} \min_{u} F = \sum_{t=1}^{T} P_{uncontrollable}(t) \times cost(t) \\ + \sum_{t=1}^{T} P_{controllable}(t) \times cost(t) \\ + \sum_{t=\tau_a}^{\tau_l} x_{ch}(t) \times P^{EV}(t) \times cost(t) \\ - \sum_{t=\tau_a}^{\tau_l} x_{dch}(t) \times P^{EV} \times cost(t) \end{aligned} \quad (12)$$

s.t.

$$\{x_{ch}(t), x_{dch}(t)\} \in [0,1] \quad (13)$$

$$max(x_{ch}(t) + x_{dch}(t)) = 1 \quad (14)$$

From (12), $P_{controllable}(t)$ and $P_{uncontrollable}(t)$ are the power consumption of controllable and uncontrollable loads, $T_{charging}$ denotes the charging time, $x_{ch}(t)$ and $x_{dch}(t)$ are binary variables for charge and discharge of PHEVs, and $cost(t)$ is the cost of electricity during the charging period, determined based on TOU.

The objective function defined in (12) is defined to minimize the total cost of charging PHEV over the charging time due to the initial charging time. Hence, the decision variables of this objective function are the initial charging time and shifting time of controllable loads.

IV. SIMULATION AND RESULT DISCUSSION

The presented method is tested on a sample demand curve. Different PHEV penetration levels are considered in this section. It is important to consider both charging with and without a management algorithm to evaluate the efficiency of the presented method.

A. Scenario 1- Charging without management algorithm

In this section, the effect of penetration of PHEVs in an electrical network is studied in case that the charging procedure is not managed. The time to reach home and time to leave home is modeled in Section II. In this case, each EV is plugged into the network after arriving home, which is determined by (2).

There is no constraint on the plug-in time of PHEVs to the network. As discussed in the previous section, the usual time of arriving home for PHEVs is $t = 18$, and the high increase is seen at this hour, which is predictable due to the high plug-in of the PHEVs network at this hour.

Also, it is possible to observe another peak at $t = 16$, which is the peak demand before PHEVs integration. The increase in the demand curve normally occurs between 12 to 24, which is also predictable, considering the arriving time of PHEVs. The serious issue of integrating PHEVs is represented in Figure 1.

Figure 1 shows that the peak demand experiences a sharp increase while the correlation between demand at different hours decreases. The abovementioned case leads to a big problem for network operators since the powerplant production should be highly increased at peak hours while there is low demand between 2 to 6. The integration of PHEVs only increases the network problems in this case, which can be considered as a new challenge for the electrical network. In addition, the PHEV owner should pay a lot of money due to an increase at peak hours.

B. Scenario 2- Charging with a management algorithm

In this case, PHEV integration is addressed through a management algorithm. A probability distribution function is considered for PHEV arriving time, assuming that the uncontrolled charging leads to similar results with scenario 1.

In this scenario, each PHEV is not plugged into the network after reaching home, and the time for plugging the PHEV into the network is chosen in order to minimize the total bill of the PHEV owner. As shown in Figure 2, a high increase occurs between $t = 1$ to $t = 7$, which are considered as low demand hours at the demand curve before PHEV integration.

Therefore, there is no increase at peak hours when several PHEVs arrive home. The results show that PHEV owner prefers to plug their vehicles after 12 pm, which is considered in off-peak hours to minimize their bill. It is useful for network operators, which can be considered as a load shifting, and the demand curve gets smoother in this case.

Another condition is also assumed to charge the PHEVs using the management algorithm, where the PHEVs can also sell power to the grid. PHEV owners can achieve more benefits by shifting the charging to off-peak hours and selling electricity to the network at peak hours. PHEV charging with management and vehicle to grid transactions is shown in Figure 3.

C. Discussions

In this work, it was investigated two different scenarios for managing the PHEVs. In the managed charging, it was considered two cases that PHEVs can sell power to the network. Also, it is shown a comparison between the total cost of different scenarios, including

- scenario 1: PHEV charging without management,
- scenario 2 (a): PHEV charging with management, and,
- scenario 2 (b): PHEV charging with management and vehicle to grid transactions.

The impact of increasing the penetration of PHEVs in the smart grids with and without the management algorithm is studied. If the PHEV penetration increases without considering a suitable charging algorithm, the total cost significantly increases, which needs more power production at peak hours. This situation is not favorable neither for the network operator nor for the PHEV owner.

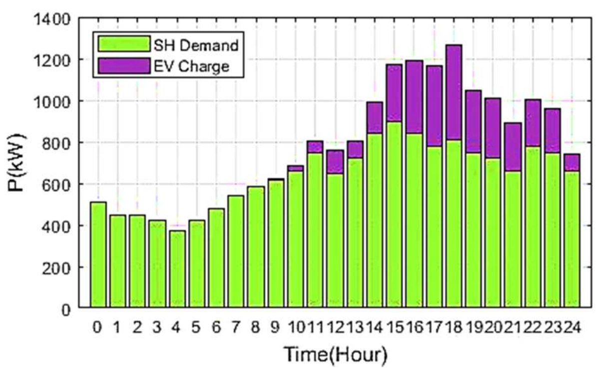

Figure 1. Comparing the demand curve changes with and without PHEV (PHEV charging without management algorithm).

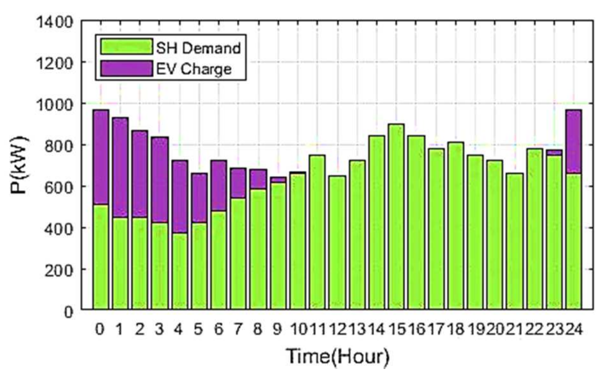

Figure 2. Comparing the demand curve changes with and without PHEV (charging PHEV with management algorithm).

Hence, the network operator should address more power production, resulting in instabilities in electrical networks. On the other hand, PHEV owner should pay more costs due to increased peak demand. In this condition, using conventional vehicles is better for both vehicle owners and network operators. The controlled charging can address these issues for both sides. In the first case of scenario 2, the PHEVs are charged through the management algorithm, but they do not sell any power to the network. However, the total cost significantly decreases compared to scenario 1.

In the second case of scenario 2, the PHEVs are charged through the management algorithm, and they can sell power to the network. As shown in Figure 4, the total cost is reduced compared to the other case, which highlights the importance of managed charging when integrating PHEVs into networks.

The percentage of cost reduction after applying the charging management is presented in Table 1, where the importance of transactions with the grid is highlighted. As a result, the management of PHEV charging can solve the network problem and minimize the total cost of PHEV owners.

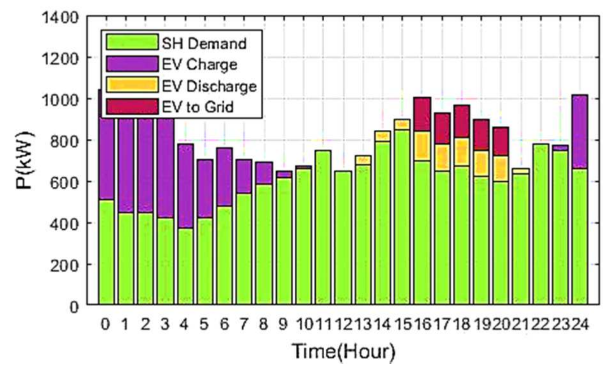

Figure 3. Comparing the demand curve changes with and without PHEV (charging with management algorithm and considering a vehicle to grid transactions).

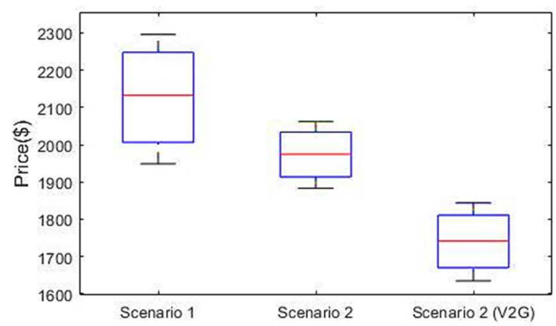

Figure 4. Comparing the total cost of a smart home for (i) scenario 1, and scenarios 2 (a) and 2 (b), respectively.

TABLE 1. COMPARING THE PERCENTAGE OF TOTAL COST REDUCTION FOR A PHEV CHARGING MANAGEMENT WITH SCENARIO AND SCENARIO 2.

PHEV Penetration (%)	Cost Reduction (%)	
	Scenario 2 vs. Scenario 1 [24]	Scenario 2 (V2G) vs. Scenario 1
10	2.54	15.97
20	4.01	17.10
30	7.54	17.92
40	10.27	19.64
50	10.87	21.02

V. Conclusion

In this work, a management algorithm was proposed for charging the PHEVs when integrating into the grid to minimize the total cost considering their uncertainties. The importance of proposing a precise algorithm for PHEV development was highlighted in this study. It was shown that the managed charging reduces the total cost, where the demand curve is also smoothened. The results were improved after considering the vehicle to grid transactions. The presented charging management algorithm was applied to mitigate the possible drawbacks for high integration of PHEV through peak shaving and reduced cost for PHEV owners. Future work is needed to develop a stochastic charging management algorithm, where a day-ahead electricity market [34] will be precisely modeled.

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