Smart Home Energy Management Considering Real-Time Energy Pricing of Plug-in Electric Vehicles

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Abstract— **This paper presents a new energy management algorithm for a smart home with a Plug-in Electric Vehicle (PEV), home energy storage, and photovoltaics (PV), which is based on grid and PEV energy cost minimization. To achieve this, a new term that represents the exact price of stored energy for PEV is presented and referred to as the Energy Price Tag (EPT). The algorithm establishes a priority order between the PEV, battery, and imported power from the grid with the goal of minimizing the overall cost of imported grid energy and PEV charging cost. Simulation results on a typical smart home over a 24-hour period indicate that considering EPT in energy management calculations not only provides more realistic results but also increases the user benefit, by reducing the PEV's final stored energy cost as well as minimizing the total cost of consumed energy from the grid.**

Keywords— Energy Price Tag (EPT), Photovoltaics (PV), Plug-in Electric Vehicle (PEV), Smart Home Energy Management, Stochastic Fractal Search.

I. INTRODUCTION

As one of the effective strategies to reduce fossil fuel dependency and gas emissions, Plug-in Electric Vehicles (PEVs) have attracted more attention in recent years. Moreover, the deployment of PEVs as dynamic loads and potential energy storage devices accommodates energy management systems in providing cost effective energy. Smart home infrastructures coupled with PEVs are expected to be widely utilized in future smart cities. Since the majority of PEV charging takes place at home, these vehicles can provide grid support by delivering the ancillary services as well as providing financial benefits for their owners when connected to the grid through Home Energy Management Systems (HEMS).

Several papers have studied PEV charging schedule from different perspectives such as ancillary services [1], reliability [2], and combined utilization with renewable energies [3]. To improve the efficiency and reduce the average cost of electricity purchase, a distributed real-time electricity allocation is proposed in [4] for grid connected residential microgrids with Vehicle to Grid (V2G) capability. The effect of PEVs from a financial viewpoint has also been studied in the literature. Authors in [5] discuss PEV market contribution. The results of 40 market diffusion models for PEV showed that operating costs, energy prices, and charging infrastructures are the most important determining factors. Authors in [6] focus on the minimization of charging costs in the electricity market. The results lead to a valley-filling type of charging. A distributed dynamic pricing policy for optimal charging of PEVs to minimize the supply-demand mismatch is proposed in [7]. In this study, home and roaming prices, are applied for charging and discharging of PEVs in a multi-microgrid scenario. In [8], optimal scheduling offers the charge pattern of PEV in a smart home, while transactions are based on the grid real-time price. In all these studies, the PEV storage is considered as an energy reserve that can be charged and discharged without any cost restrictions. Most importantly, the cost of initial and final energy in the PEV is neglected. Nevertheless, in reality, the cost of energy for charging and discharging a PEV exists and directly affects the charge/discharge pattern. Thus, the exact cost of the stored energy should be monitored when dealing with PEVs in future energy transactions.

In this paper, a new approach for determining the stored energy price of PEVs is introduced. To achieve this, a new term referred to as Energy Price Tag (EPT) is proposed that represents the average price of stored energy. This makes EPT a sensitive factor for the household owners, as energy market players, while interacting with the grid. Although most of the PEV charging is predicted to be carried out at home, the PEV charging can also take place in public, commercial or workplace charging stations [9]. Thus, EPT will also influence decision making and charge scheduling of PEVs outside the household. The rapid advance of wireless communication technologies and their integration into the Internet of Things (IoT) will further facilitate the coordinated management of PEVs outside the smart home system. Internet of Vehicle (IoV) as a global heterogeneous vehicular network is one of the revolutions mobilized by IoT [10]. Vehicles connected through the IoV are capable of sharing information which can enhance their energy management strategies. In [10], Wireless Access Technologies (WAT) for various vehicular communication modes have been introduced. These technologies enable the PEV to store the EPT and use it in different transactions in the energy market. Therefore, EPT will play a key role in energy transactions in public places by providing an accurate stored energy cost for each vehicle.

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II. Energy Price Tag and Real-Time Pricing

In the deregulated power market, knowledge of the real-time pricing for all energy storage devices is inevitable. Similarly, the HEMS requires knowledge of the momentary cost for recharging each energy storage device in order to minimize the operating cost as well as to reduce the overall utility cost. On the other hand, cost of providing V2G services should be instantaneously known and this is only possible if the total cost of all energy storage devices including PEV's available energy is known. Depending on the time and place of charging, the PEV owner pays different rates for energy. PEV charge/discharge management requires an intermediate tariff that will function as a bridge between electricity market and the PEV owner. Therefore, in this paper a new term referred to as EPT is presented that indicates the average price of stored energy in (¢/kWh) for each storage device. EPT is defined as the tariff that allows more realistic exchange of energy among storage devices. It is also useful when considering the smart home system. By knowing the price of stored energy, HEMS can optimize the flow of energy between different components to better achieve cost minimization for the user and at the same time, minimize the final cost of stored energy in the PEV. The EPT for each energy storage device at each time step (h) can be calculated by knowing the EPT and the total available energy in the previous time step (h-1), and the price and amount of energy exchanged during that time step:

$$EPT(h) = \begin{cases} \dfrac{[\,EPT(h-1) * Energy(h-1) + \Delta Energy * C(h)]}{Energy(h-1) + \Delta Energy}, & Charging \\ EPT(h-1), & Discharging \end{cases} \tag{1}$$

where $EPT(h-1)$ is the average energy price for time step $(h-1)$, $Energy(h-1)$ is the total available energy in time step $(h-1)$, $\Delta Energy$ is the net change in energy during time step (h), and $C(h)$ is the price of energy that was exchanged during time step (h). Since EPT represents the cost of total available energy, it does not change during discharging and it only changes when energy is received.

III. Proposed Energy Management System

Fig. 1(a) shows the different components of the smart home under study. The smart home consists of a PEV, photovoltaics (PV) array, household battery storage, and home appliances. The HEMS is responsible for the control of energy exchange between the smart home components and the utility grid.

At each instant, the HEMS decides on tasks such as storing the energy for future use and supplying the momentary demand from the available resources. These decisions are based on minimizing the overall operating cost of the system. Usually, there is no need to keep track of the flow of energy between the components, as long as the optimization constraints are met and the objective function is minimized. However, in this paper the proposed energy management algorithm considers the average energy price of stored energy as the main factor in determining the flow of energy within the household components. Therefore, it is of utmost importance to distinguish sources of energy and prioritize the flow of energy. Fig.1(b) shows the different energy exchange paths between all smart home components. During operation, different sources of energy such as the discharged energy from the PEV and storage devices as well as the energy from the grid and PV may exist. On the other hand, the household load and the required charging energy for the household battery storage and the PEV should be supplied at different instants. A prioritization strategy is applied by HEMS in this paper to determine the energy exchange paths between all system components.

In the proposed prioritization algorithm, as the cheapest available energy, the PV energy first goes to the household load. This for sure, reduces the cost of providing energy to the

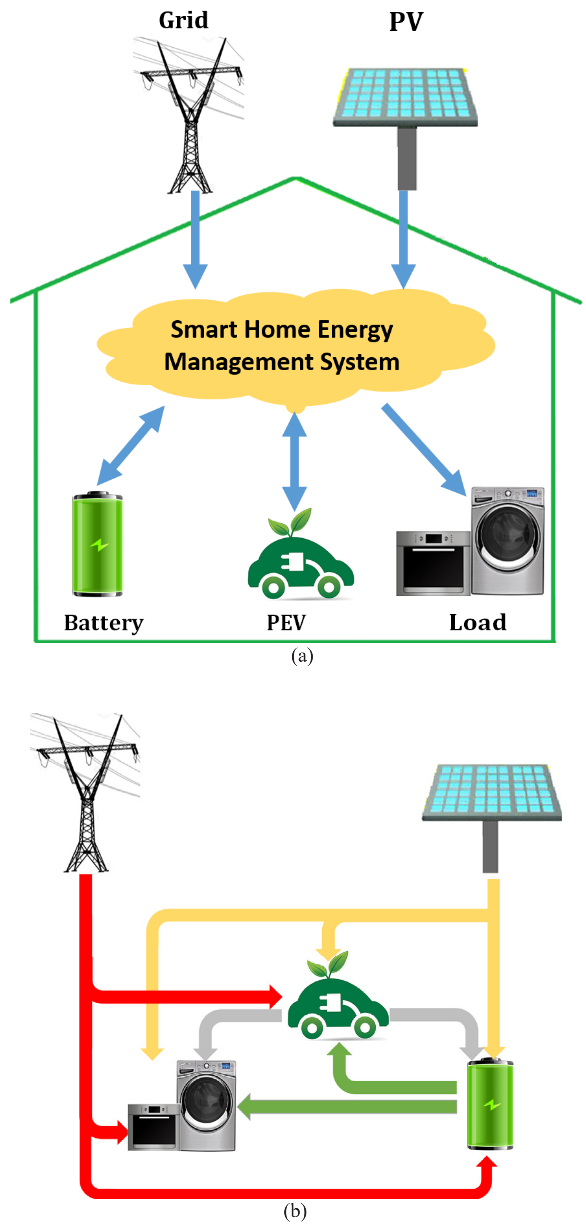

Fig. 1. (a) Smart home components and energy exchange directions, (b) Energy paths between different components

household load. Moreover, it is desired for the household battery to store any cheap energy and provide the load in the absence of PV energy. Thus, the PV excess energy that is not absorbed by the load is saved in the battery for future consumption. This strategy reduces the cost of providing the daily energy for the household load.

On the other hand, since the PV energy is dependent on the availability of sunlight and the household battery energy storage capacity is limited, under certain circumstances, the HEMS will need to import energy from the grid to supply the household demand. Moreover, the PEV battery energy can also take part in energy transactions as a source of energy. In the proposed energy management strategy, the HEMS decides on the PEV energy scheduling based on its EPT during its presence at home. In other words, when the PV and battery energy are not sufficient to meet the load demand, the required energy is supplied from the cheapest available source by comparing the EPT of the PEV and the grid hourly price. Thus, at instants that the EPT of the PEV is less than the grid price, it is more cost effective to supply the energy from the PEV. According to this strategy, in the next step, the HEMS chooses the most cost effective operating point for the household through an optimization process. The EPT of the PEV is also considered in the optimization problem to ensure that the final cost of the stored energy in the PEV is minimized.

IV. Formulation of the Optimization Problem

A. Objective Function

The objective function is defined such that the total buying cost from the grid is minimized, while at the same time the PEV is charged with the cheapest available energy. The total cost would be the sum of hourly cost of buying energy from the grid over a 24-hour period and the cost/revenue of charging/discharging the PEV during this period as defined below:

$$Objective\ function = \sum_{h} [E_{grid}(h) C_{grid}(h) + \frac{|C_{grid}(h) - EPT_{PEV}(h-1)|}{C_{grid}(h) - EPT_{PEV}(h-1)} * E_{PEV}(h) * EPT_{PEV}(h-1)] \quad (2)$$

where $C_{grid}(h)$ is the forecasted price of the grid in ($\frac{¢}{\text{kWh}}$) for hour (h). $E_{PEV}(h)$ is the energy used to charge or discharge the PEV during hour (h) in kWh and is considered positive when charging and negative during discharging of the PEV. $E_{grid}(h)$ is the absorbed energy from the grid in kWh at hour (h).

The first part of the objective function minimizes the sum of the cost of buying energy from the grid. The second term is the sum of PEV charge/discharge costs. The EPT_{PEV} is considered as the tariff for the transactions of PEV. In case of $C_{grid}(h) < EPT_{PEV}(h-1)$, when the grid price is lower than the EPT of the PEV, we have $\frac{|C_{grid}(h)-EPT_{PEV}(h-1)|}{C_{grid}(h)-EPT_{PEV}(h-1)} < 0$. Since $EPT_{PEV} > 0$, positive values of E_{PEV} will reduce the objective function which relates to PEV being charged. Hence, by charging with cheap energy from the gird, the EPT_{PEV} is reduced. On the other hand when $C_{grid}(h) > EPT_{PEV}(h-1)$, negative values of E_{PEV} will result in further reduction of the total cost. In other words, the PEV discharges during these hours in order to minimize the objective function.

B. Operational Constraints

In the energy scheduling of all stages of HEMS, system power balance as well as the operating constraints of the PEV and the energy storage should be considered. At every instant, (h), the generated energy must equal the amount of consumed energy

$$P_{PV}(h) + P_{grid}(h) = P_b(h) + P_l(h) + P_{PEV}(h) \quad (3)$$

where $P_{PV}(h)$ is the generated power by the PV modules, $P_{grid}(h)$ is the imported power from the grid, $P_b(h)$ is the household battery power, $P_l(h)$ is the household load demand and $P_{PEV}(h)$ is the PEV power in kW.

The battery and PEV power limits can be described by (4) and (5), respectively:

$$P_{b\_min} \le P_b(h) \le P_{b\_max} \quad (4)$$

$$P_{PEV\_min} \le P_{PEV}(h) \le P_{PEV\_max} \quad (5)$$

where P_{b_min} and P_{b_max} are the minimum and maximum limits of the household battery power, and P_{PEV_min} and P_{PEV_max} are the minimum and maximum limits of the PEV power, respectively.

Equations (6) and (7) show the calculations for updating the state of charge (SOC) of the household and PEV battery. Furthermore, due to lifetime considerations, the SOC for both PEV and household battery is limited between SOC_{min} and SOC_{max}. These constraints are given in (8) and (9):

$$SOC_b(h) = SOC_b(h-1) + \frac{[P_b(h) * (\Delta t)]}{Bat_{cap}} \quad (6)$$

$$SOC_{PEV}(h) = SOC_{PEV}(h-1) + \frac{[P_{PEV}(h) * (\Delta t)]}{PEV_{cap}} \quad (7)$$

$$SOC_{b\_min} \le SOC_b(h) \le SOC_{b\_max} \quad (8)$$

$$SOC_{PEV\_min} \le SOC_{PEV}(h) \le SOC_{PEV\_max} \quad (9)$$

where Bat_{cap} and PEV_{cap} are the household battery storage and PEV battery capacity in kWh.

V. Simulation Results and Discussion

To analyze the effect of EPT with the proposed algorithm, two scenarios were taken into account. In the first scenario, only the price of the electricity purchased from the grid was considered as the cost function to be minimized. In the second scenario, the price of electricity from the grid as well as the EPT of the PEV were considered in the cost function as formulated in (2). The utility grid price and load data were extracted from ComEd's for March 31st, 2017 and shown in Figs. 2-4. For a working day, it was assumed that the PEV arrives home at time

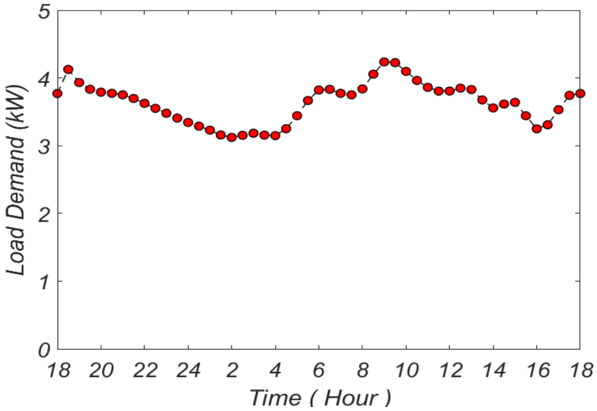

Fig.2. Load demand for both scenarios

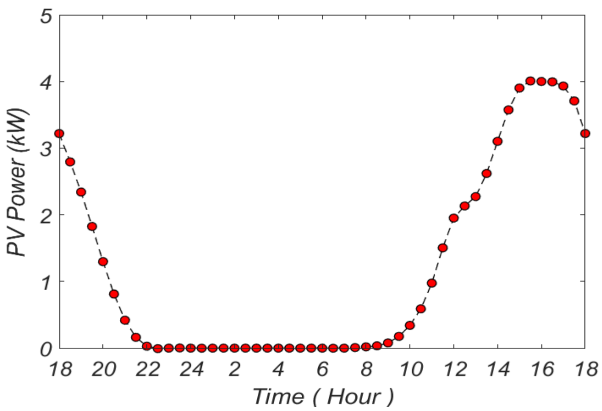

Fig.3. PV generation for both scenarios

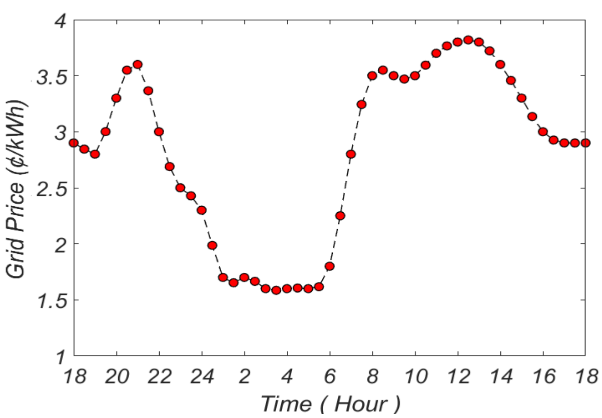

Fig. 4. Daily grid price for both scenarios

18:00 and leaves at 8:00 the next morning. The final desired SOC of the PEV is also set to 70% to guarantee sufficient energy for the next trip. To provide a fair comparison of the results for both scenarios, the final SOC of the household battery is constrained to be the same as its initial value. The system parameters used for this simulation are listed in Table I and the results of both scenarios are shown in Figs. 5-12. In this paper, Stochastic Fractal Search (SFS) is utilized as the optimization algorithm. SFS is capable of solving both constrained and unconstrained global single objective and multiobjective optimization problems [11].

TABLE I. SYSTEM PARAMETERS USED FOR SIMULATION

Parameter	Value	Parameter	Value
Initial SOC of PEV	40%	SOC_{PEV_min}	30%
Initial SOC of home battery storage	50%	SOC_{PEV_max}	90%
Final SOC of home battery storage	$50 \pm 2\%$	SOC_{b_min}	20%
Initial EPT of PEV	3 ¢/kWh	SOC_{b_max}	80%
Bat_{cap}	14 kWh	PEV_{cap}	30 kWh

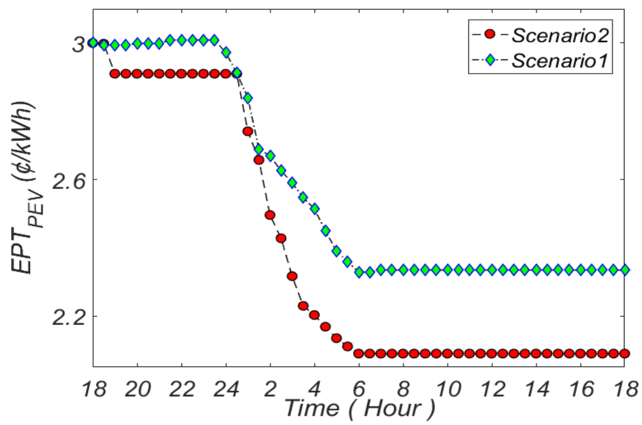

Fig. 5. EPT of PEV

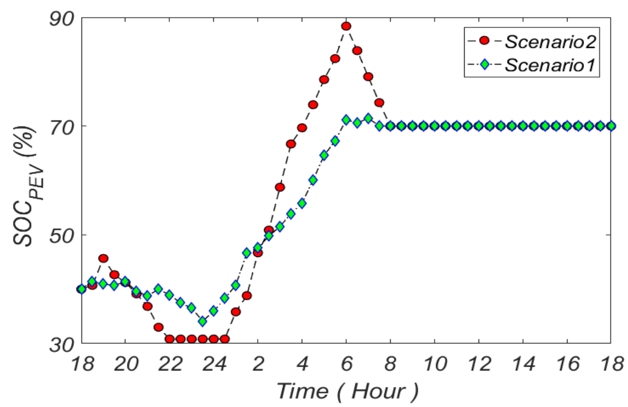

Fig. 6. State of charge variation of PEV battery for both scenarios

The simulation results indicate that the total daily cost of purchasing energy from the grid is 157.46 ¢ and 156.68 ¢ for scenario 1 and scenario 2, respectively. However, according to Fig. 5, the final EPT_{PEV} for scenario 2 is 2.09 ¢/kWh whereas for scenario 1 it is calculated to be 2.33 ¢/kWh. In comparison, EPT_{PEV} for scenario 2 is lower by 0.24 ¢/kWh. This difference in EPT_{PEV} translates to 5¢ cost difference in the overall cost of stored energy when considering the PEV battery capacity and its final SOC value. Therefore, while the daily electricity bill remains almost constant for both scenarios, by intelligent charging management of PEV in the second scenario, its charging/discharging is distributed over the 24-hour period such that the required energy is stored with a lower price.

From the results of Fig. 6, it is observed that in scenario 2, the PEV discharges during the expensive hours of the grid while fully charges to its maximum limit in the less expensive hours. Whereas, in scenario 1, the PEV has less contribution compared to scenario 2. This behavior results in a lower EPT_{PEV} for scenario 2. Furthermore, during 1:00-6:00 when the grid price is at its minimum value, in both scenarios the PEV stores the cheapest energy. The PEV is charged with lower energy prices than its initial EPT and therefore its EPT decreases over time. However, it can be seen from Fig. 6 that during this time interval, only in scenario 2 the PEV is charged to its maximum capacity and thus makes full use of all its capacity to store the cheap energy. As a result, the EPT_{PEV} in scenario 2 significantly decreases compared to that of in scenario 1. Figs. 7-12 show the power contribution of each component during a 24-hour period for both scenarios. The difference between the grid price and EPT_{PEV} is shown in Figs. 9 and 12 and indicates when the grid price is higher or lower than the calculated EPT

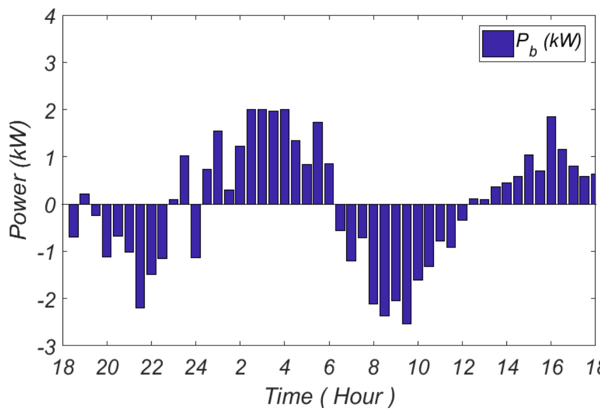

Fig. 7. P_b for scenario 1

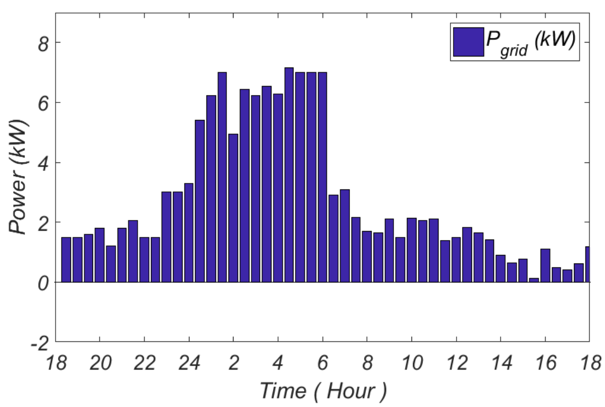

Fig. 8. P_{grid} for scenario 1

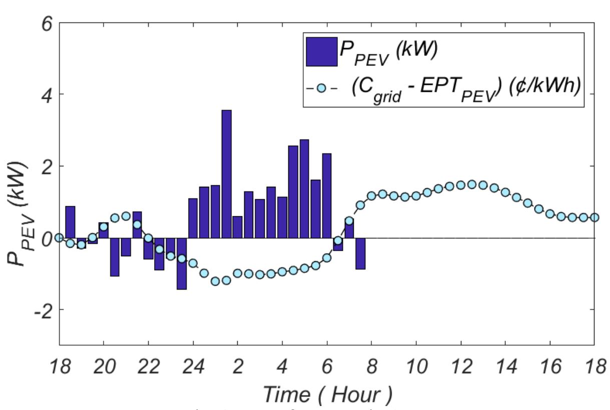

Fig. 9. P_{PEV} for scenario 1

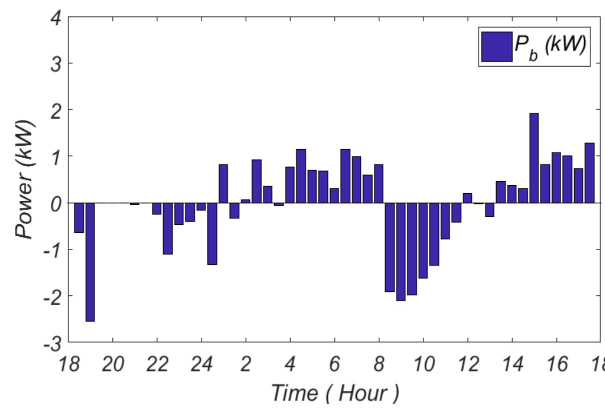

Fig. 10. P_b for scenario 2

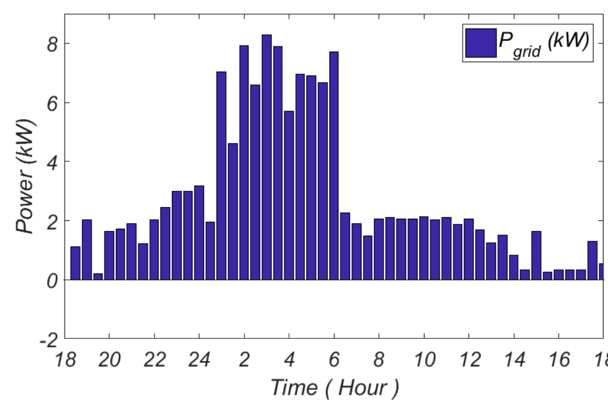

Fig. 11. P_{grid} for scenario 2

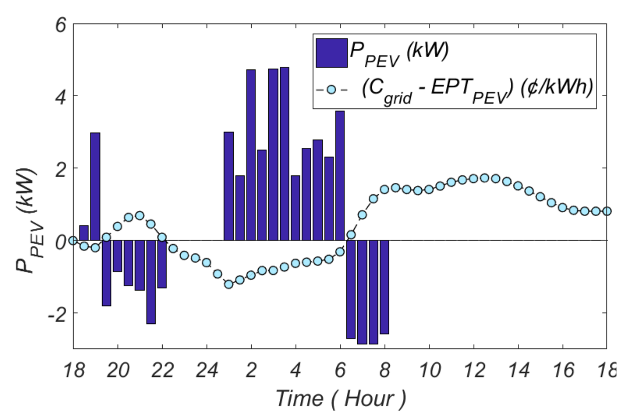

Fig. 12. P_{PEV} for scenario 2

of the PEV. It is worth mentioning that although EPT is not considered in the objective function of scenario 1, it is calculated at each time step in the results of this scenario for comparison purpose.

Comparing the results of Figs. 9 and 12 shows that for scenario 2 during 18:30-19:00, since C_{grid} is less than EPT_{PEV}, the PEV is being charged more than scenario 1. This results in a significant reduction of EPT_{PEV} compared to scenario 1. On the other hand, during 19:30-22:00 when C_{grid} is higher than EPT_{PEV}, in scenario 2, the PEV discharges more compared to scenario 1 which allows the PEV to store significant amount of energy at a lower price for future use. During 22:30-24:30, when grid price gradually decreases and becomes less than EPT_{PEV}, in scenario 1, the PEV is being discharged which is not the most optimized solution. This is due to the fact that since in scenario 1 EPT_{PEV} is not considered in the objective function, PEV energy is considered as a free source of energy and therefore is used to meet the load requirement during this time. During hours 6:30-8:00, when the grid price increases, the PEV discharging in scenario 2 is noticeable in comparison to scenario 1, where it even charges at time 7:00. Thus, in scenario 1, PEV is charged with expensive energy from the grid at time 7:00 which increases the EPT_{PEV}. In conclusion, the results indicate that in the first scenario, the PEV has been charged with expensive energy from the grid several times, which is not the most optimum solution in reducing the overall cost of operating the smart home system.

VI. Conclusions

The concept of utilizing EPT in the intelligent energy management of a smart home equipped with PEV, PV array, and battery storage was proposed in this paper. The average cumulative cost of the stored energy was proposed as a tariff that allows a realistic exchange of energy for the PEV especially in a smart home environment. Simulation results for two scenarios were carried out with different objective functions and the results validated the effectiveness of considering EPT for smart home energy management. The results showed that by considering EPT, charging/discharging of the PEV is distributed more effectively resulting in a lower cost of storing energy in the PEV and thus maximizing user benefit in a smart home system.

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