Quantifying the Energy-Storage Benefits of Controlled Plug-in Electric Vehicle Charging

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Abstract

Flexibility in plug-in electric vehicle (PEV) charging can reduce PEV charging costs. Moreover, controlled PEV charging can be viewed as a limited form of energy storage, insomuch as charging loads are shifted from high-cost periods to lower-cost ones. Energy storage that is used for generation shifting is used in much the same manner. In this paper, we study these benefits of PEV charging, demonstrating that controlled PEV charging can reduce generation costs. We also determine how much energy storage would be needed to provide the same cost-reduction benefits that the PEV fleet does.

Keywords: Plug-in electric vehicle, controlled charging, energy storage

1. Introduction

Concerns surrounding growing energy demand, climate change, and finite fossil fuel supplies have increased interest in the use of electrified transportation recently. Transportation accounted for close to 20% of total world energy consumption in 2011 [1]. Very little of this transportation energy need was met by electricity, however, meaning that there is potential for greater use of electricity as a transportation fuel. In addition to potentially reducing the environmental and fossil fuel-demand impacts of transportation [2–10], plug-in electric vehicles (PEVs) offer some natural synergies with electric power systems.

Electricity demand and supply must be equal at all times. Thus, generation, transmission, and distribution capacity are built to serve the system's anticipated peak demand. In most systems this peak is rarely achieved. Thus, if PEV charging is properly timed and coordinated, it can be accommodated without any extra capacity needing to be built. For instance, *all* of the driving demand in the United States in 2011 could have been served using electricity without any additional power system capacity needing to be built, so long as PEV charging was properly coordinated with the operation of the electric power system [11].

PEV charging loads can also provide a low-cost source of flexibility to balance electric power system operations. Many power systems currently rely on flexibility from the supply side. Supply-side flexibility is typically provided by natural gas- and oil-fired or hydroelectric generators. Units of these types can typically be switched on and off and can ramp their production up and down relatively quickly. However, with the exception of hydroelectric generators, this flexibility can be quite costly because these types of generators tend to have very high variable operating costs [12–16].

If PEV charging can be coordinated with power system operations, it can provide a source of demand-side flexibility. In this scenario PEVs increase their charging rate when the system is oversupplied and decrease their charging rate when it is undersupplied. A more extreme case of bidirectional vehicle-to-grid services would see PEVs discharge their batteries when the system is extremely undersupplied to help maintain system balance [17]. Bidirectional vehicle-to-grid services are not currently commercially available, however,

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because they raise battery degradation issues that can void vehicle warranties. PEV charging loads also have the benefit of being low-cost sources of flexibility. This is because PEV owners are typically only concerned with having energy charged before the next vehicle departure. Thus, there is potentially a great deal of flexibility in when and the rate at which a PEV is recharged between its arrival to and subsequent departure from a charging station. Properly controlled PEV charging can, therefore, provide demand response to help with integrating renewable energy sources into electric power systems.

Another commonly studied source of power system flexibility is energy storage [18–22]. A number of studies estimate the value of storing energy when the system is oversupplied and discharging later when the system is undersupplied [23–29]. In doing so, storage allows generation and transmission assets to be used more efficiently, reducing system costs. Some of these works examine other potential uses of storage, for instance to provide ancillary services [23, 28, 29]. However, the currently high capital cost of existing storage technologies makes this an uneconomic source of flexibility in most cases today [27, 28, 30].

Although PEVs can provide the same type of flexibility as energy storage, there are some important considerations that must be accounted for in comparing the two flexibility sources. The advantage of PEVs is that they are essentially a free flexibility source. The flexibility comes from controlling PEV charging. The power system operator (SO) does not have to invest in the cost of the storage medium, because the cost of the batteries are incurred by PEV owners. The SO is able to utilize the flexibility in deciding the rate at which to recharge PEVs when the batteries are otherwise idle. Moreover, if PEV owners can be remunerated for making their batteries available for flexible recharging, this can provide an added incentive for PEV adoption and for PEV owners allowing charging rates to be controlled for power system benefits.

On the other hand, PEVs offer limited flexibility in a number of ways. For one, a PEV battery can only be used as a storage medium when the vehicle is parked at a charging station. If PEVs tend to be driven and not grid-connected in the middle of the day, the SO would have limited storage capacity available at that time. Another limitation of PEVs is that the SO only has the flexibility to shift their charging demands around through time. A dedicated storage device that can be charged and discharged offers greater flexibility in terms of substituting high-cost generation during times of scarce system capacity with lower-cost generation.

In this paper we use a numerical case study, based on the Electricity Reliability Council of Texas (ERCOT) system, to demonstrate the benefits of using controllable PEV charging as a form of energy storage. Our analysis assumes that PEVs are used solely to provide demand response—the timing of and rate of PEV charging can be adjusted to accommodate system conditions. Our analysis does not allow PEV batteries to be discharged and provide so-called vehicle-to-grid services when grid-connected. Moreover, each PEV must be fully recharged by the time it finishes each stop at the charging station. Thus, the demand response does not allow PEV charging loads to go unserved. The case study assumes about 1.7 million PEVs, which amounts to about 10% of the light-duty vehicle fleet in the test system. Our results show that controlling PEV charging reduces PEV charging costs by approximately 7% compared to a worst-case scenario of uncontrolled charging, in which PEVs charge immediately upon arrival at a charging station. We also examine how much energy storage capacity would have to be added to the system to achieve the same cost reductions that controlled PEV charging delivers. We find that storage devices with capacities between 400 MW and 3.2 GW yield the same cost reductions as controlled PEV charging, with the capacity depending on how many hours of charging capacity the device has. The primary contribution of this paper is to demonstrate, through a detailed numerical case study, that controlled PEV charging could be a viable and effective source of demand response. Moreover, we show that a relatively small number of PEVs could deliver cost savings that are commensurate with a costly dedicated energy-storage system. These benefits of controlled PEV charging have no incremental cost, as they stem from using the flexibility in PEV-charging loads.

The remainder of this paper is organized as follows. Section 2 details the models and methods used to evaluate the benefits of controlled PEV charging. Section 3 summarizes our numerical case study and Section 4 our results. Section 5 concludes.

2. Materials and Methods

Our analysis is based on a combined economic dispatch and PEV charging model [17]. Our analysis assumes perfectly controlled charging, meaning that a single entity co-optimizes PEV charging with generator fleet dispatch. Although our model is agnostic to who this entity is, we refer to it as the SO throughout. Although the SO can control the timing and rate of charging while PEVs are parked, it cannot change PEV driving patterns. Moreover, the SO is required to fully recharge each PEV before it departs its charging station.

The following subsections detail the SO model formulation, the method used to quantify the benefits of controlling PEV charging, and the model used to compare the benefits of controlled PEV charging to dedicated energy storage.

2.1. SO Model Formulation

To reduce notational burden, the model classifies the PEVs into groups. All of the PEVs within a group are assumed to arrive and depart their charging stations at the same times. Moreover, all of the PEVs within a group have the same demand for charging energy upon arrival. Our model can be easily generalized to relax these assumptions, however the notation would be less compact. We also assume that the SO knows future PEV arrival and departure times and charging demands with certainty. This assumption may overstate the value of controlled PEV charging, because the SO is assumed to have information available that may not be the case in practice. If PEV arrival and departure times and charging demands are not known with certainty, this will reduce the SO's ability to use PEV charging demand flexibility. We begin by first defining the following model parameters and sets:

T	hours in optimization horizon
I	conventional generator set
Γ	set of PEV groups
$\mathcal{I}\{\tau, \gamma\}$	indicator that PEVs in group γ are plugged in during hour τ
L_t	hour-t non-PEV energy demand
N_γ	number of PEVs in group γ
X_γ	total energy demand of PEV group γ
R^p	PEV charger power capacity
η^p	PEV charger efficiency
P_i^-	generator i's minimum power capacity
P_i^+	generator i's maximum power capacity
R_i^-	generator i's ramp-down limit
R_i^+	generator i's ramp-up limit
$F_i(\cdot)$	generator i's generation cost function

We also define the following decision variables:

$b_{t,\gamma}$	hour-t energy provided to PEV group γ
$q_{t,i}$	generator i's hour-t dispatch

The SO model is formulated as:

$$\min \sum_{t=1}^{T} \sum_{i \in I} F_i(q_{t,i}); \tag{1}$$

$$\text{s.t.} \sum_{i \in I} q_{t,i} = L_t + \sum_{\gamma \in \Gamma} b_{t,\gamma}; \qquad \forall\ t = 1, \ldots, T; \tag{2}$$

$$0 \leq b_{t,\gamma} \leq R^p \cdot N_\gamma \cdot \mathcal{I}\{t, \gamma\}; \qquad \forall\ t = 1, \ldots, T; \tag{3}$$

$$\eta^p \cdot \sum_{t=1}^{T} b_{t,\gamma} = X_\gamma; \qquad \forall\, \gamma \in \Gamma; \tag{4}$$

$$P_i^- \le q_{t,i} \le P_i^+; \qquad \forall\, t = 1, \ldots, T; i \in I; \tag{5}$$

$$R_i^- \le q_{t,i} - q_{t-1,i} \le R_i^+; \qquad \forall\, t = 1, \ldots, T; i \in I. \tag{6}$$

Objective function (1) minimizes total generation costs. Constraint set (2) enforces the load-balance requirement that generation and demand be exactly equal in each hour. Constraint set (3) limits the amount of charging energy scheduled to each PEV in each hour to be less than the capacity of the charger. The $\mathcal{I}\{t,\gamma\}$ term on the right-hand side of each of these constraints only allow PEVs within each class to be recharged when they are not being driven. Constraint set (4) ensures that all of the PEV charging demands are met. Constraint sets (5) and (6) are generator output and ramping limits.

2.2. Measuring Benefits of Controlled PEV Charging

We quantify the benefits of controlled PEV charging based on generation cost reductions compared to having uncontrolled PEV charging. Uncontrolled charging assumes that PEVs charge immediately upon arrival at their destinations and is modeled by fixing:

$$b_{t,\gamma} = \min\left\{ \left(X_\gamma - \eta^p \cdot \sum_{\tau<t} b_{\tau,\gamma} \right)^+, R^p \cdot N_\gamma \right\} \cdot \mathcal{I}\{t,\gamma\}, \tag{7}$$

for all $t = 1, \ldots, T; \gamma \in \Gamma$ in the SO's model. Equation (7) defines the hour-t uncontrolled charging demand of PEV group γ as the minimum between the amount of unserved demand, which is defined as:

$$\left(X_\gamma - \eta^p \cdot \sum_{\tau<t} b_{\tau,\gamma} \right)^+,$$

and the charging station capacity, which is given by:

$$R^p \cdot N_\gamma.$$

2.3. Modeling Equivalent Storage Capacity of a PEV Fleet

We also measure the benefits of the flexibility provided by controlled PEV charging by comparing it to the flexibility offered by energy storage. To do this, we model a case with uncontrolled PEVs and with energy storage added to the system. We study this by augmenting the model developed in Section 2.1 to include a generic storage device [28]. To do so, we first define the following additional model parameters:

R^e	power capacity of energy storage
η^c	charging efficiency of energy storage
η^d	discharging efficiency of energy storage
$\bar{e}$	energy capacity of energy storage

We also define the following decision variables:

c_t	energy stored from grid in hour-t
d_t	energy discharged into grid in hour-t
e_t	ending hour-t energy storage level

The SO's model is then formulated as:

$$\min \sum_{t=1}^{T} \sum_{i \in I} F_i(q_{t,i}); \tag{8}$$

$$\text{s.t.} \sum_{i \in I} q_{t,i} = L_t + \sum_{\gamma \in \Gamma} b_{t,\gamma} + c_t - d_t; \qquad \forall\, t = 1, \ldots, T; \tag{9}$$

$$P_i^- \le q_{t,i} \le P_i^+; \qquad \forall\, t = 1, \ldots, T; i \in I; \tag{10}$$

$$R_i^- \le q_{t,i} - q_{t-1,i} \le R_i^+; \qquad \forall\, t = 1, \ldots, T; i \in I; \tag{11}$$

$$e_t = e_{t-1} + c_t \cdot \eta^c - d_t/\eta^d; \qquad \forall\, t = 1, \ldots, T; \tag{12}$$

$$0 \le e_t \le \bar{e}; \qquad \forall\, t = 1, \ldots, T; \tag{13}$$

$$0 \le c_t, d_t \le R^e; \qquad \forall t = 1, \ldots, T; \tag{14}$$

where the values of $b_{t,\gamma}$ are fixed according to equation (7), since we are modeling a case with uncontrolled PEV charging.

This model has the same objective as in the original model and constraint sets (10) and (11) are the same technical generator limits as before. Load-balance constraint set (9) forces the total generation to equal the sum of non-PEV and PEV load and net energy stored in each hour. Constraint set (12) defines the ending hour-t energy level of storage in terms of its hour-$(t-1)$ storage level and any hour-t charging or discharging. Constraint sets (13) and (14) are storage energy and power limits, respectively.

3. Case Study

We study performance of a test system, which is based on the ERCOT system in 2005, over a one-month period. We include all of the thermal and hydroelectric generators that were installed in the ERCOT system in 2005. We combine stepped heat rate data obtained from Ventyx with historical fuel price data from 2005 to estimate piecewise-linear generation costs for each generator modeled. Each piecewise-linear generation cost function is then approximated by a convex quadratic cost function, the parameters of which are fit to minimize the squared error between the piecewise-linear and quadratic cost functions. We also use hourly-ramping-limit data obtained from Ventyx for each generator modeled.

We model the test system as having 5 GW of wind installed. Wind availabilities (which provide the upper generation limits for the wind generators in constraint sets (5) and (10) in the two models) are derived from mesoscale model data produced by AWS Truepower for the Western Wind Resources Dataset (WWRD). The WWRD models wind speeds and translates those into wind availabilities at a variety of locations within the state of Texas that can each accommodate 30 MW of wind capacity. To capture the effects of geographic dispersion, we assume that the 5 GW of wind are spread across the 167 sites in Texas that have the highest average wind availabilities in the WWRD (167 sites are chosen because the assumed 5 GW of wind capacity is divided by the 30 MW of wind that each site can accommodate). We assume that wind availabilities are known with perfect foresight.

The non-PEV loads (*i.e.*, the L_t's) are based on historical data reported by ERCOT between 1 September, 2005 and 30 September, 2005. To capture the relationship between wind speeds and load, the wind availabilities are derived using values reported in the WWRD for the same time period. We assume that there are 1.7 million PEVs, which amounts to about 10% of registered light-duty vehicles in the state of Texas in 2005. Thus, we are modeling a forward-looking case, given the low penetration of PEVs today. The PEVs add 14000 MWh of charging load daily, which is 1.65% of the average daily load. We model PEV charging patterns using a mass simulation model [31]. This model generates vehicle driving profiles using a Monte Carlo-based method and converts the driving profiles into battery energy usage. Each PEV charging station is assumed to have a 4 kW power limit and 90% charging efficiency.

When comparing controlled PEV charging to a dedicated energy storage device, we assume that the storage device has 90% charging and discharging efficiencies. These imply an 81% roundtrip efficiency. This efficiency is comparable to modern battery or pumped hydroelectric storage (PHS) technologies. We examine cases in which the storage device has between half an hour and 20 hours of energy capacity. This means that if fully charged, the device can be discharged at its rated power capacity for between 30 minutes and 20 hours. This range of energy capacities encompasses a number of grid-scale energy storage technologies. Battery and compressed-air energy storage systems can have energy capacities that are less than four hours, whereas PHS systems with 20 hours of energy capacity are currently in operation.

We formulate the SO's models as a non-linear optimization problem using version 12.1.0 of the `AMPL` mathematical programming software package and solve it using `CPLEX` 12.5.1.0.

4. Results and Discussion

Table 1 summarizes average (over the one-month period) daily PEV charging costs. The second column of the table shows total generation costs without PEVs and with controlled and uncontrolled PEVs. The third column shows PEV charging costs in the controlled and uncontrolled cases, which are defined as the increases in generation costs relative to the no-PEV case. The final column normalizes the PEV charging cost to give a cost per kWh of energy recharged into the vehicle batteries. As expected, PEV charging increases generation costs, however controlled PEV charging results in 7% lower charging costs compared to the uncontrolled case.

Table 1: Average Daily Generation and PEV Charging Costs

PEV Case	Generation Cost [$ million]	PEV Charging Cost Total [$ thousand]	¢/kWh
No PEVs	66.564		
Controlled	66.722	158	1.13
Uncontrolled	66.735	170	1.22

The results in Table 1 also show that controlled PEV charging adds flexibility to a power system, reducing generation costs. This is because the SO can exploit the inherent flexibility of PEV charging to have the load follow generation costs and supply availability more closely. This reduces the need to use expensive generation to balance supply and demand.

As noted above, controlled PEV charging can also be viewed as a limited form of energy storage. Energy storage reduces system generation costs by storing energy during low-cost periods and discharging it later when generations cost are higher. Controlled PEV charging has a similar effect, since the SO is able to shift PEV demand from high- to lower-cost periods. If PEV owners suffer no disutility or cost from delaying vehicle charging, controlled PEV charging is a more efficient cost-reduction scheme than energy storage. This is because there are energy losses when energy is stored in and discharged from a storage system. These losses are not incurred from controlling PEV charging. On the other hand, controlled PEV charging is a limited form of energy storage, since only a small portion of the system load can be shifted from high- to low-cost periods.

To quantify these benefits of controlled PEV charging more rigorously, we estimate how much energy storage added to the system gives the same generation cost reductions that controlled PEV charging gives relative to uncontrolled charging. Table 1 shows that average daily generation costs with uncontrolled PEV charging is about $66.735 million. Introducing PEV charging control reduces these generation costs to $66.722 million. Thus, we determine the equivalent storage capacity of controlled PEV charging as the amount of storage capacity that must be added to the system to reduce average daily generation costs with uncontrolled charging to $66.722 million.

Figure 1 shows average daily generation costs with uncontrolled PEV charging, as a function of the power capacity of the added storage. As expected, energy storage reduces generation costs, since low-cost energy is stored and used to displace high-cost generation later. The figure also shows generation costs with controlled PEV charging. The intersection point between each of the energy storage and the controlled PEV charging cost curve gives the amount of storage capacity that yields the same cost savings as controlling

PEV charging. Table 2 summarizes the amount of storage capacity that yields the same cost reductions as controlled PEV charging. The results in Figure 1 and Table 2 show that controlling PEV charging yields cost reductions that are commensurate with what can be achieved with significant investments in energy storage. It should be noted that there is no incremental cost in using this demand flexibility, whereas dedicated storage can have costs in excess of $2000/kW [27].

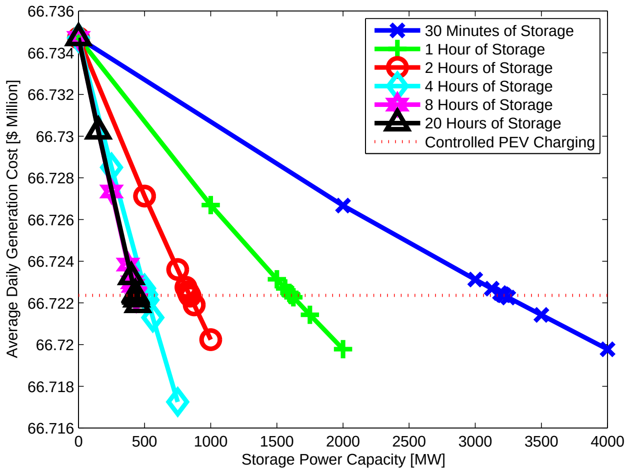

Figure 1: Average Daily Generation Cost with Uncontrolled PEV Charging as a Function of Storage Power Capacity

Table 2: Storage Capacity That Yields the Same Cost Reductions as Controlled PEV Charging

Hours of Storage	Storage Capacity [MW]	[MWh]
0.5	3206	1603
1	1605	1605
2	838	1676
4	514	2056
8	428	3424
20	432	8640

5. Conclusions

We quantify the flexibility benefits that controlled PEV charging can provide a power system. We demonstrate that controlled PEV charging reduces the charging costs compared to an uncontrolled case. This is because the SO can exploit the inherent flexibility in PEV charging to have the load follow generation costs and availability. We demonstrate that controlled charging of a relatively small PEV fleet, that only constitutes 1.65% of the average daily system load, can reduce the incremental cost of PEV charging by close to 7% relative to the uncontrolled case. These cost reductions benefit PEV and non-PEV drivers directly, since generation costs and retail prices are reduced, as indicated in Table 1. We also compare the benefits of controlled PEV charging to energy storage, showing that a relatively small PEV fleet can deliver the same cost savings as a large storage device.

Overall, our work shows that PEVs can be a significant source of demand-side flexibility. Although a large body of work studies the benefits of demand response, few examine the details of what sources of demand flexibility could be effectively leveraged. Our results suggest that small PEV fleets can offer great cost-reduction benefits.

Future work could expand upon our findings and analysis here. One direction of study is to examine the benefits of controlled PEV charging to provide other services, such as frequency regulation. This would require a model with a finer temporal resolution (*e.g.*, at one-minute intervals), to capture the temporal granularity of the frequency regulation signal. Another area of research would be to study the benefits of controlled PEV charging in reducing the cost of integrating the uncertain and variable output of wind generators into electric power systems. Recent works show the wind-integration benefits of demand response [32]. Controlled PEV charging is a viable and cost-effective source of such demand response.

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