Title

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Impact of Building Loads on Cost Optimization Strategy for a Plug-in Electric Vehicle Operation

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***Abstract*—Sustainable transportation growth will require wide adoption of electric vehicles in the near future. While the Plug-in Electric Vehicle (PEV) usually shares the same meter in a building, the overall energy cost typically increases due to absence of any optimal strategy. Smart EV charging strategies can help to reduce the energy cost. The amount of cost reduction largely depends on the integrated building load. This paper presents the impact of small and large building loads on an EV charging strategy for different Time of Use (TOU) energy rates of two different utilities. Both grid to vehicle (G2V) and vehicle to grid (V2G) operations have been studied with the goal to reduce the energy cost for a small building with less fluctuating loads and a large building with high fluctuating loads. Real time building loads of two buildings at the University of California Riverside and Nissan Leaf E-Plus EVs actual charging profile have been used in this simulation. Both operations have been examined with two different utilities' energy rates. Bidirectional operation always gives better results in comparison to the unidirectional operation in terms of cost. Large variation in electrical energy rate schedules results in higher percentages of savings for bidirectional operation regardless of the types of building loads.**

Keywords*—*PEV charging, building loads, energy cost reduction, convex optimization, G2V, V2G.

I. INTRODUCTION

Electric vehicles are gaining in popularity around the world as a solution to provide a sustainable transportation system, reducing green-house gas emissions. The sales of EVs are growing rapidly across the world. According to International Energy Agency (IEO) Global EV Outlook 2018 report, more than 1 million electric cars were sold in 2017 and the number of EVs on the road has already crossed the 3 million mark [1]. Due to the rapid growth of EV usage, the impact on the distribution grid as well as overall increase in energy consumption is a major concern. Though EVs ensure energy sustainability and clean energy, it also increases the total energy cost when integrated into a building's energy system. Intelligent strategies of EV charging can minimize these building energy costs.

Clean energy goals of states like California needs mass Electric Vehicle (EV) adoption in the transportation sector by 2045 [2]. Recently, California has set a goal of 5 million Zero Emission Vehicles (ZEVs) on the roads by 2030 and 250 thousand electric vehicle charging stations by 2025 [3-4].To cope with the demand of added energy consumption, optimal charging strategies need to be implemented to minimize both the total energy cost and the adverse impact on the grid. The energy profile of any EV mainly depends on its battery capacity, State of Charge (SOC) and charging rate.

Multiple strategies have been proposed on the optimal way of EV charging in the literature so far. The effectiveness of coordinated EV charging versus uncoordinated EV charging is depicted with the consideration of voltage constraints to reduce the overall grid voltage unbalanced factor [5]. Linear Optimization method and solar potentiality for reducing EV energy consumption cost have been examined. Controlling the apparent power with the consideration of different energy rates for both grid to vehicle (G2V) and vehicle to grid (V2G) operations with a view to minimizing the energy cost has also been studied [6-7]. Shifting PEV loads from on peak to off peak hours is one way to reduce the impact of increasing EV energy use. This also minimizes the battery degradation and electricity cost of PEV charging [8].Optimal charging architecture and partitioning load power into charging and discharging area for reducing the energy cost have also been proposed [9-10].

This paper studies the unidirectional and bidirectional approach of Plug-in Electric Vehicle (PEV) charging and shows the impact of integrated building load on charging strategies for a PEV taking into consideration of various TOU energy rates. The energy cost minimization problem can be solved for different types of building loads such as rapid and slow changing modes. This paper is organized as follows: Section II describes the system, Section III discusses the problem formulation and constraints, Section IV includes the simulation results, Section V shows the cost comparison and Section VI concludes the paper.

II. SYSTEM DESCRIPTION

In this work, each of the buildings is considered to be equipped with an EV charging port and vehicle to grid operation is available for both of these ports. The PEV receives power in grid to vehicle operation and feeds power back to the grid during bidirectional operation. Figure 1 and figure 2 represent the unidirectional and bidirectional operations respectively. For each building-EV pair, the building and the

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EV share the same meter for calculating energy cost. Two building load data are used for simulation purposes. Nissan Leaf E Plus version is used for PEV specifications.

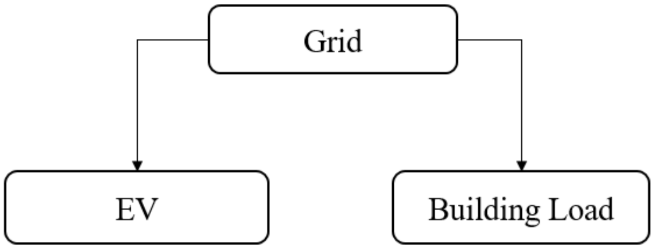

Fig 1: Unidirectional Operation: The PEV Acts as a Load and does not Supply Any Power to The Grid

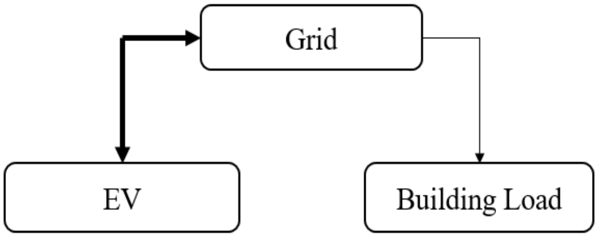

Fig 2: Bidirectional Operation : The PEV can Both Consume and Supply Power Based on Operating Procedure

A. Load Characteristics

The two buildings are located at University of California Riverside campus. The plugged-in time used for simulation is from 5 am to 3 pm to capture a typical working day load profile variation. Figure 3 shows the 15-minute rolling average demand (kW) for both the buildings over this time period. The daily load of building 1 does not fluctuate sharply with time. The maximum load for the first building always stays below 30 kW. On the other hand, the daily load of building 2 fluctuates sharply with time. The maximum load of this building is approximately 785 kW whereas the minimum load is 275 kW. The load of the second building can be categorized into three distinct sections. From 5 am to 7 am it remains below 300 kW, then the demand increases and remains around 500 kW from 8 am to 1.15 pm. Finally, it reaches the peak value of 758 kW at 1.30 pm. The demand fluctuates by 65 percent from low usage period to high usage period.

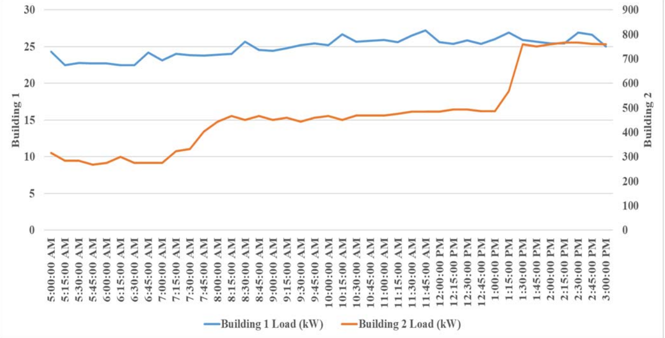

Fig 3: Demand Profile for Building 1 and Building 2.

B. PEV Characteristics

The EV profile used for simulation is from Nissan Leaf E-Plus version whose specifications are given in Table I. The battery capacity is 64 kWh and the rate of charging is between 11kW and 22 kW, depending on user preference [11-12].The maximum charging and discharging rate used in the simulation is 15 kW and the minimum rate is greater than zero. The EV charging starts with a 20% State of Charge (SOC) at 5 am. The SOC characteristics of the EV is assumed linear for the simulation purposes.

TABLE I. PEV SPECIFICATION

Type	Spec
Model	Nissan Leaf E-Plus
Range (miles)	225
Battery (kWh)	64
Maximum Charging Power (kW)	15

C. Energy Price

The energy price used for the cost optimization problem is a Time of Use (TOU) based energy price for a non-commercial building sharing the same meter for EV charging. The energy rates used for simulation are : (1) Southern California Edison (SCE), an Investor Owned Utility (IOU), and (2) Riverside Public Utility (RPU), a Public Municipal Utility. SCE rate is divided into three tiers such as on-peak, mid peak and off-peak. On the other hand, RPU has only two tiers of energy rates such as off-peak and mid peak for the load profile month used in this work. The plugged-in time for EV is selected in such a way so that it can reflect all different energy prices for a day. Table II summarizes the energy rates for a day.

TABLE II. TOU BASED ENERGY CHARGE

Time	SCE Energy Charge ($/kWh)
5 am - 8 am	0.13
8 am - 2 pm	0.16
2 pm - 3 pm	0.25

Time	RPU Energy Charge ($/kWh)
5 am - 6 am	0.1413
6 am -3 pm	0.1696

D. *Notations*

The problem formulation and constraints are represented by various notations as summarized below in table III.

TABLE III. SUMMARY OF NOTATIONS

Notation	Notation Description
i	index of a time slot in the billing cycle
e_i	energy cost in slot i
n	total number of slots
P_i	energy price for billing cycle in slot i
$G2V_i$	total power drawn from grid to vehicle in slot i
L_i	total building load in slot i
SOC_i	State of charge of PEV battery in slot i
$V2G_i$	total power delivered from vehicle to grid in slot i
$\eta_{charging}$	PEV battery's charging efficiency
$\eta_{discharging}$	PEV battery's discharging efficiency
SOC_{max}	PEV battery's maximum SOC
SOC_{min}	PEV battery's minimum SOC
$G2V_{max}$	maximum power drawn from grid to vehicle
$V2G_{max}$	maximum power delivered from vehicle to grid
$L_{maxallowed}$	maximum possible load
μ	time interval for each energy cycle

III. PROBLEM FORMULATION AND CONSTRAINTS

The problem to minimize the electricity cost is an optimization problem with required total power, PEV and building load constraints.

A. *Objective Function*

The objective of our problem is to minimize the energy cost of PEV charging associated with any building. In order to minimize the energy cost, we need to solve the following equation.

$$\text{minimize} \sum_{i=1}^{n} e_i$$

B. *Constraints*

The constraints for this optimization problem can be classified according to the direction of power transfer. As the power transfer can be both unidirectional and bidirectional, the total load equation and SOC constraints will vary accordingly. The constraints for the vehicle to grid power transfer will also be added for bidirectional operation. The first to fifth constraints stand for unidirectional power transfer, while the rest are used for bidirectional power transfer.

$$1.\ \mathrm{e}_i = P_i \times (G2V_i + L_i) \times \mu$$

$$2.\ \mathrm{SOC}_i = \begin{cases} \mathrm{SOC}_{\mathrm{Primary}} & \mathrm{i=1} \\ \mathrm{SOC}_{\mathrm{i\text{-}1}} + \eta_{charging} \times \mathrm{G2V}_i \times \mu & 2 \le \mathrm{i} \le \mathrm{n} \end{cases}$$

$$3.\ 0 < \mathrm{G2V}_i \le \mathrm{G2V}_{\mathrm{max}}$$

$$4.\ \mathrm{G2V}_i + \mathrm{L}_i < \mathrm{L}_{\mathrm{max}\,allowed}$$

$$5.\ \mathrm{SOC}_{\mathrm{min}} \le \mathrm{SOC}_i \le \mathrm{SOC}_{\mathrm{max}}$$

$$6.\ \mathrm{e}_i = P_i \times (G2V_i - \mathrm{V2G}_i + L_i) \times \mu$$

$$7.\ \mathrm{SOC}_i = \begin{cases} \mathrm{SOC}_{\mathrm{Primary}} & \mathrm{i=1} \\ \mathrm{SOC}_{\mathrm{i\text{-}1}} + \eta_{charging} \times \mathrm{G2V}_i \times \mu - \eta_{discharging} \times \mathrm{V2G}_i \times \mu & 2 \le \mathrm{i} \le \mathrm{n} \end{cases}$$

$$8.\ 0 < \mathrm{V2G}_i \le \mathrm{V2G}_{\mathrm{max}}$$

$$9.\ \mathrm{G2V}_i + \mathrm{L}_i - \mathrm{V2G}_i < \mathrm{L}_{\mathrm{max}\,allowed}$$

The first constraint denotes that the total energy cost at any time will be equal to the summation of the building energy consumption and EV energy consumption cost. The second constraint calculates the SOC of EV battery at any time instant. Here the SOC indicates the stored energy in the battery. At any instant the stored energy in the battery must be equal to the energy stored at the previous time slot plus the energy supplied from grid to the vehicle. We assume that initially the SOC is 20% which is 12.8 kWh for Nissan Leaf E-Plus version. The third constraint states that the power supplied from grid to vehicle must be greater than zero and will be less than or equal to the maximum charging power; whereas the fourth constraint denotes that the sum of charging power supplied from the grid, and building load will be less than the maximum possible load for that building. The fifth constraint shows that SOC should be within the allowable limit. The constraints from 6-9 are the additional constraints for bidirectional operation. The sixth constraint shows that the energy transferred from vehicle to grid needs to be subtracted to find the net energy charge. The seventh constraint denotes that the discharging energy is subtracted to find the SOC of the battery. Finally, the eighth constraint determines the limit for vehicle to grid power transfer and the ninth constraint describes that the net power must be less than the maximum demand for the building.

C. *Convex Optimization*

The formulated objective function is linear which is convex. Similarly, the constraints used here are also linear and convex. Therefore, the optimization problem itself is convex. MATLAB CVX tool [13] has been used to solve this convex optimization problem.

IV. SIMULATION RESULTS

Both unidirectional and bidirectional operations are studied for both of the buildings and the energy rate profiles. The detailed results are discussed below.

A. *Unidirectional Operation*

The grid to vehicle charging profile is shown in figure 4 for all possible cases in unidirectional operation. For small and less fluctuating building load (building 1), the optimization scheme requires charging power consumption to be higher for SCE energy rate at the earlier hours as SCE energy rate is less than

RPU rate at that time. But with time, the EV consumes more power from the grid for RPU rates in comparison to SCE rates. For large and high fluctuating building load (building 2), the difference between energy rates is not creating significant impact on charging profile for EV. This is due to relatively small size of 15 kW EV charging rate compared to minimum building load of 275 kW along with building's inherent large load variation.

Fig 4: Unidirectional Operation : Charging Profile for EV

Figure 5 shows the impact of various charging scenarios on battery SOC. As EV battery starts charging at 5 am in this scenario, SOC keeps on increasing steadily for all possible cases considered here and reaches up to 87% at the end of the charging period.

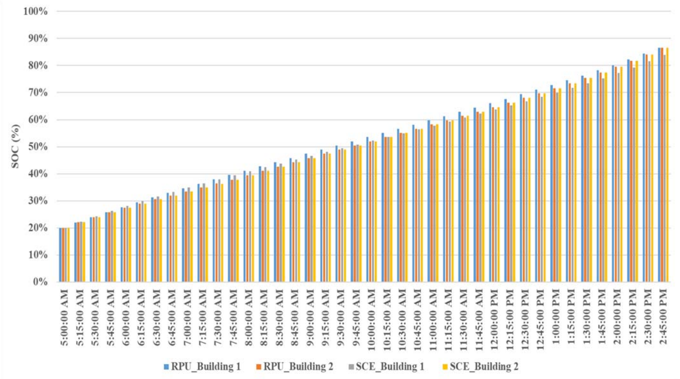

Fig 5: Unidirectional Operation : SOC Profile for EV

B. *Bidirectional Operation*

The bidirectional charging profile is shown in figure 6 for all possible cases. For small and less fluctuating building load (building 1), the EV feeds more power back to the grid for SCE rates as compared to RPU rates. The EV acts in a similar way for the second building too. As RPU energy rate increases after 6 am, EV operates in V2G mode after this period to facilitate the maximum reduction in energy cost. On the other hand, SCE rate increases after 8 am, making the PEV to begin V2G operation later for this energy rate as compared to RPU's rate. Figure 6 also shows another drop in power consumption after 2 pm for SCE energy rate, as the energy rate increases again after 2 pm. For building 2, the PEV starts discharging later while RPU rate is activated. In case of SCE rates, at first the PEV feeds more power back to the grid for the first building, later on, it does the opposite.

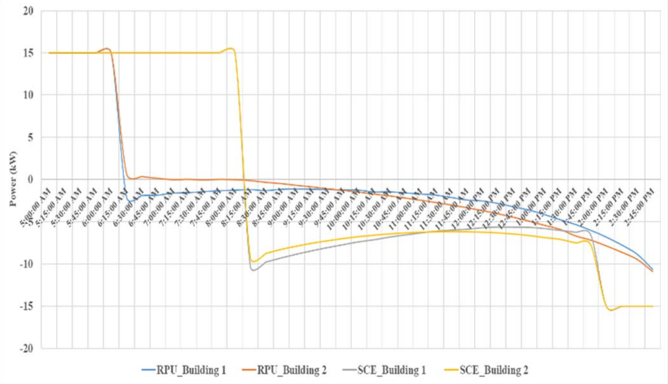

Fig 6: Bidirectional Operation : Charging Profile for EV

Figure 7 shows the impact of bidirectional charging on battery SOC. The SOC increases up to 93% for SCE energy rate for both buildings whereas the SOC does not reach more than 49% for RPU energy rate. As the goal is to minimize the energy cost, the SOC starts decreasing to provide the maximum power to the grid and hence reduces the energy cost. Large building loads result in better SOC in comparison to small building loads which means the EV feeds less power back to the grid for large building loads. For complete recovery of SOC, EV should be charged during low cost off-peak hours.

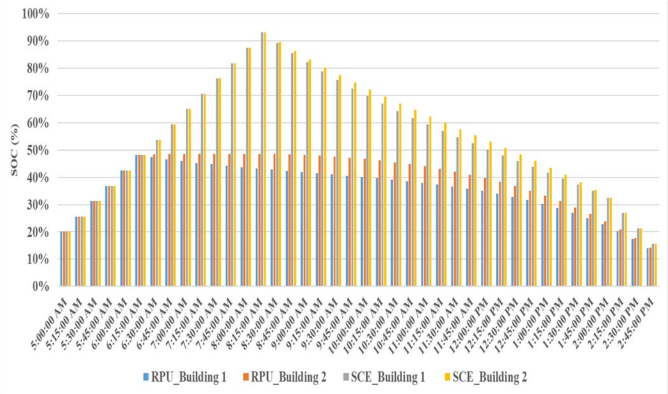

Fig 7: Bidirectional Operation : SOC Profile for EV

V. COST ANALYSIS

The simulation results show more reduction in energy cost for bidirectional operation. Though the percentage of cost reduction in bidirectional operation is large for the building with smaller average loads, the cost minimization is small for the building with larger average loads due to the EV charging power being very small compared to the building load itself. The cost reduction also depends on energy rates. RPU energy rate is both low and difference between on-peak and off-peak is smaller compared to SCE energy rates. When the building load is small, the total cost is lower for SCE rates in both operation. On the other hand, the total cost is lower for RPU rates in case of a large integrated building load. Figure 8 and 9 shows the total cost for all scenarios.

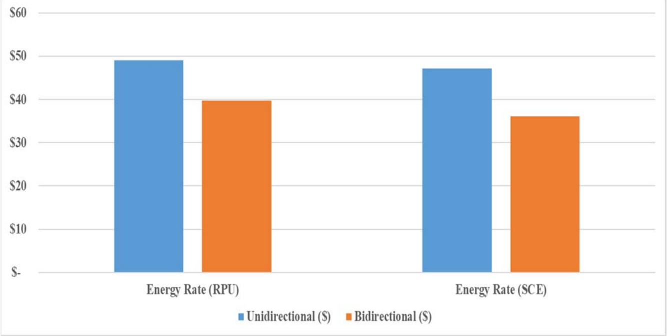

Fig 8: Cost Comparison: Small Building Load (Building 1)

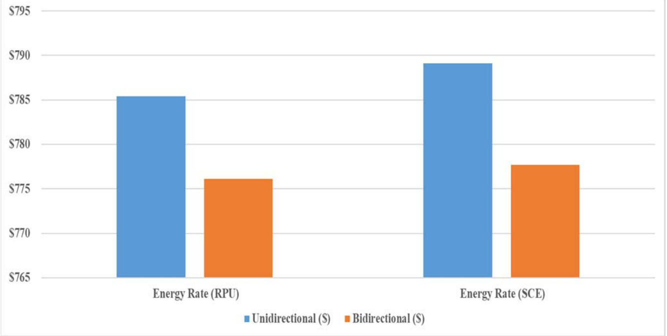

Fig 9: Cost Comparison: Large Building Load (Building 2)

This study shows that 18.9-23.5% cost reduction is possible for small building loads whereas 1.2-1.4% cost reduction is possible for large building load when using a single level 2 EV charger. Table IV shows the estimated daily savings in bidirectional operation for all possible cases.

TABLE IV. COST SAVINGS IN BIDIRECTIONAL OPERATION

Building Type	Rate and Load	Savings in Bidirectional Operation (%)
Building 1 (Small Average Load)	Energy Rate (RPU)	18.9%
	Energy Rate (SCE)	23.5%
Building 2 (Large Average Load)	Energy Rate (RPU)	1.2%
	Energy Rate (SCE)	1.4%

Any similar EV with equal or less charging power capability will act in similar manner for the given building loads and energy rates. Another verification was done by applying this methodology to a Nissan Leaf 2nd Generation EV with maximum charging power of 6 kW, where it showed similar results except one scenario. This EV model can not optimize the cost for large building loads in bidirectional mode due to its lower charging rate being dominated by inherent large building load variations.

VI. CONCLUSION

In residential and commercial buildings, EV chargers may be sharing the same electric meter of the building or have their own separate meter. Loads of the households can vary depending on their energy usage. Sharing the same meter with an EV can increase the overall energy cost if the charging does not follow any optimal strategy. Smart EV charging strategy is needed to ensure overall electrical energy cost reduction. This also depends on other connected loads of the building. In this paper, the impacts of different building loads on optimal EV charging for both unidirectional and bidirectional operation have been examined, taking different electrical utility energy rates into consideration.

This study has shown that low price differential between on-peak and off-peak electrical energy rates result in lower EV charging cost for large building loads whereas high differential electrical energy rate does the same for smaller building loads. Bidirectional operation can save up to 23.5% energy cost in comparison to unidirectional operation despite having lower SOC for EV. Bidirectional operation always gives higher percentage of savings for higher differential energy rates. As electric rates are rapidly increasing throughout the country, energy cost optimization will become more important in the future.

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