EV Specific Time-of-use Rates Analysis for Workplace Charging

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***Abstract*—EV specific time-of-use rate plans have been recently introduced by several utilities to overcome the demand charge issue that is the main barrier impeding EV growth in the commercial and industrial sector. This study analyses two EV specific TOU rates in place from a customer and the grid perspectives. The analysis relies on a developed optimal cost model with coordinated charging strategies that minimizes the total cost of a workplace charging station over its lifetime. From a customer perspective, it is shown that the cost benefits are not always achievable and depends on the rates provided. From the grid perspective, the peak demand is found to be increased. Thus, the EV specific rates may not always provide an efficient use of the grid assets.**

***Index Terms*—Demand charge, EVSE, plug-in electric vehicles, smart charging, time-of-use tariff, workplace charging.**

I. Introduction

The global electric vehicle (EV) market is growing rapidly thanks to the regulatory and incentive instruments for EVs and chargers in leading countries including the U.S. [1]. Calls for a more transition to electrified transportation are being placed by many regulatory authorities. Over 30% EV share is projected in the US by 2030. Global EV electricity demand in the scenario of a 30% EV market share is estimated to reach almost 1,110 TWh in 2030 [1]. While the grid capacity is sufficient for an initial EV uptake, it is estimated to require costly network investments to accommodate higher EV penetrations [2]. Therefore, utilities are looking into new tariff schemes for changing the charging behaviour of EV users in order not only to shift the usage away from the peak hours, but to use EVs in balancing the supply of variable renewable generation [3].

Enabling more charging stations at workplaces can boost up EV adoption. It can mitigate charger access anxiety that will increase the electric driving range for EVs [4]. From the grid perspective, the charging demand can be shifted to off-peak periods in early morning and over solar generation hours [5]. These stations are primarily available for use by employees or commercial EV fleet. It is reasonable that the fleet vehicles can be stored and charged on premises outside of working hours while employees' EVs can occupy the charging points during working hours. However, demand charge is found to be main barrier impeding EV growth at workplaces due to the contribution of total charging loads to peak demand [6]. It was shown that demand charges can be half of the total electricity costs even if charging demand is minimized by controlled charging scenarios [3]. As the peak can be highly sensitive to type of electric vehicle supply equipment (EVSE), the increase in the demand due to EV charging loads can boost up the demand charge significantly [7]. As such, the cost of EV driving might not be competitive as compared to that of driving with conventional fuels. Therefore, several utilities, i.e., Pacific Gas and Electric (PG&E) [8], Southern California Edison (SCE) [9], and San Diego Gas and Electric (SDG&E) [10] have recently introduced new EV specific time-of-use (TOU) tariff schemes to address demand charges. These require a separate meter for EV charging while maintaining the existing workplace energy and demand meters. The idea behind these schemes is to shift the charging demand towards off-peak hours or periods of midday solar over-generation. While these proposals do not include demand charge, a monthly fixed fee is additionally charged.

Minimizing charging costs and demand charge with smart charging control for TOU rates has been overwhelmingly researched [11]. As demand charge is billed over the entire billing period and usually reflected on charging cost component, Lee et al. in [3] proposed a new pricing scheme to distribute demand charge fairly to each charging event while optimizing overall cost. Powell et al. in [5] explored the impact of TOU rates on transformer aging through an optimal model with different objectives. The peak minimization gives closer performance to that of the total cost minimization due to higher demand charge component. Li et al. in [11] maximizes the satisfied charging demand for a given budget constraint in which Level 1 option is found to be the best economics. Muñoz and Jabbari in [4] propose a smart charging control with a prioritizing scheduling to minimize the number of charging units with valley filling performance. Scheduling EVs with respect to their flexibility in terms of charging time gives improved peak reductions and increased savings compared to scheduling with their arrival times. While most of the studies proposes smart charging strategies for both cost and peak minimization with varied pricing, the impact of newly

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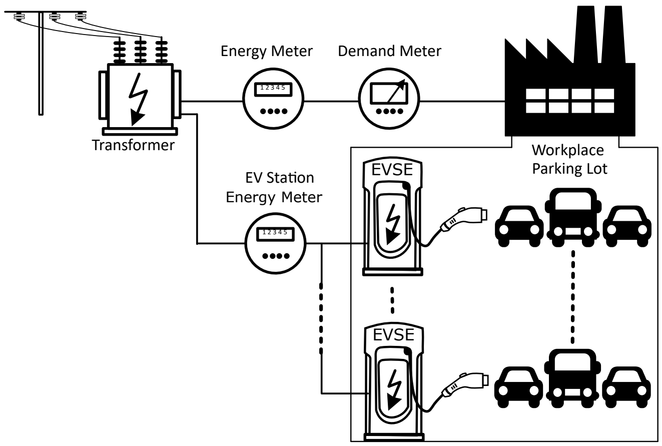

Fig. 1: Workplace electrical layout with general and EV specific meters .

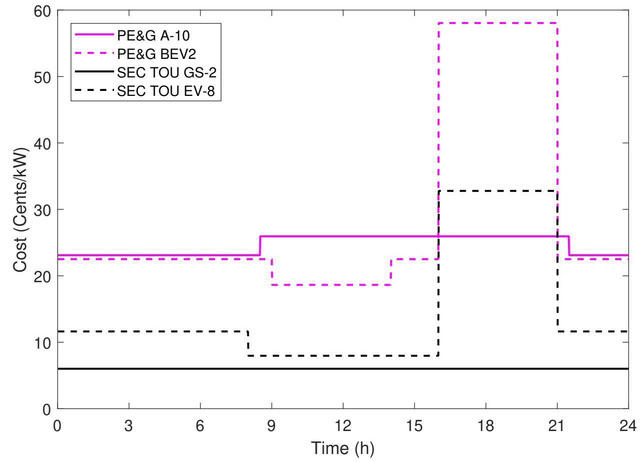

Fig. 2: Time-of-use rates considered.

proposed EV specific TOU rates for various perspectives is largely unexplored. Since demand charge is eliminated in these rates, there is a need to investigate whether EV specific rates capture demand charge effect for an efficient use of the grid assets. Moreover, as workplace charging stations can comprise several EVSE options in terms of charging type and level, the cost and grid behaviors of these rates with respect to EVSE types need to be examined.

This study first proposes a workplace charging cost model that considers all cost components for a given workplace, i.e., energy and demand charges including levelized charging infrastructure costs. Using the proposed model, the behaviour of conventional demand metered TOU rates are then compared with those of corresponding EV specific TOU rates. As such, cost and the grid performances of two EV specific TOU rates are evaluated to promote EV adoption at workplaces. Single and three phase Level 2 (L2-1P and L2-3P) and DC fast charger (DCFC) EVSE types with single and multi port options under proposed coordinated charging strategy are separately considered in the evaluation.

II. Description of EV Specific Tou Rates

Alternative specific rates for EV charging have been designed to encourage the transitioning businesses' vehicles towards an electric fleet. In addition to the service and energy charges, the commercial and industrial customers have to pay for demand charge. It is billed with a specific rate factored with the peak of average power in 15 min per month. The rise in the demand due to EV charging loads can increase the demand charge significantly [3]. This depends on not only the configuration and size of EVSE types but also charging strategy options employed (e.g., coordinated or uncontrolled).

To avoid higher demand charges, some utilities designed several TOU rates for only EV charging at business premises in which the contribution of EV charging loads to peak demand is disregarded. Fig. 1 illustrates the system layout for such a workplace with only EV and general service rates with demand charge in place. Two energy meters, one for EV charging energy and one for workplace energy, including a demand meter for workplace demand measurements are used in this layout. The purpose of the EV specific rates has twofold. The first is to reflect only charging costs to EV user and avoid cross subsidization that could happen as the demand charge are reflected on charging cost evenly without considering each charging service individually. The second is to support grid stability by shifting EV loads toward off-peak hour or over renewable generation periods. However, it is observed that a typical monthly subscription fee is included in these EV specific rates. The amount of this charge varies based on the customer expected charging demand which resulted with several tariff options under EV rates offered by the utilities.

In this study, two EV specific TOU rates from two utilities with their conventional TOU rates are considered for the workplace charging station cost model. The conventional demand metered TOU rates are PG&E A-10 [12] and SCE TOU-GS-2 [13] while their EV specific TOU rates are PG&E BEV2 [8] and SCE TOU-EV-8 [9], respectively. Fig. 2 compares the TOU rates used for energy charges. It is noticed that the rates of the two utilities are different because of cost variations in their service territories. PG&E A-10 has part and off-peak hours with demand charge of $13.32 per kW while SCE TOU-GS-2 has a flat rate for the entire day with a demand charge of $11.46 per kW. Both the EV specific rates have on, off, and super-off peak hours with either a subscription charge of $95.86 per block of 50kW in PG&E BEV2 or a monthly fixed customer charge of $133.31/Meter in SCE TOU-EV-8 for a demand of between 20 kW and 500 kW. All the rates used in this study are for winter season.

III. Workplace Charging Station Cost Model

The cost model of a workplace charging station is composed of three cost elements. The first term, C_{op} is daily operational charging cost accounting for cost of daily total charging energy at the workplace. The second term, C_{dc} is the contribution of EV charging loads to demand charge that is product of a demand charge rate C_{drate} and peak of the total charging load in 15 min time intervals. The last term, C_{LIC} is daily levelized EVSE infrastructure cost accounting for EVSE unit hardware and installation costs including maintenance cost. C_{LIC} is levelized with an annuity factor, AF to consider the time value of money since the infrastructure cost includes total length of lifetime of EVSE unit [14]. The cost model can be formulated as a linear optimization formulation whose objective is to minimize total cost of a charging station over a life cycle of charging units as follow:

$$\min_{\substack{P_{ch,1}\dots P_{ch,n}\\ S_j}} \Big(C_{op} + C_{dc} + C_{LIC}\Big), \quad (1)$$

with,

$$C_{op} = \sum_{s_j=1}^{s_j}\sum_{i=1}^{n}\sum_{t=1}^{T}\Big(F(t) \times (P_{ch,i,s_j}(t) \cdot \frac{\Delta t}{60})\Big), \quad (2)$$

$$C_{dc} = C_{drate} \cdot (max(\sum_{k=1}^{96}\sum_{t=1}^{15} mean(\sum_{1}^{s_j,n} P_{ch,i,s_j}((k-1)\cdot 15+t)))), \quad (3)$$

$$C_{LIC} = s_j \cdot AF \cdot \Big(C_{unit} + C_{ins}\Big), \quad (4)$$

subject to

$$\sum_{t=1}^{T} P_{ch,i}(t) \cdot \eta_i \cdot \frac{\Delta t}{60} = E_{required,i}, \quad (5)$$

$$\begin{cases} 0 \le P_{ch,i}(t) \le min\Big(\eta_i P_i^{rated}, \eta_J P_J^{rated}\Big), \forall J \in \{1,2,3\} \\ 0 \le P_{ch,i}(t) \le \eta_J \cdot P_J^{rated}, \forall J \in \{4,5\} \end{cases}, \quad (6)$$

$$\sum_{t=1}^{T}\Big(P_{base}(t) + \sum_{s_j=1}^{s_j}\sum_{i=1}^{n} P_{ch,i,s_j}(t)\Big) \le P_{lim}, \quad (7)$$

where, $N = \{1, 2, ...n\}$, $P_{ch,i} = \{Pch,i(1)...Pch,i(T)\}$ are set of EVs and charging rates of the i^{th} EV, respectively. T is number of time slots, $S = \{1, 2, ...s\}$ is number of charging units. J= $\{1, 2, 3, 4, 5\}$ denotes charging levels of the charging units (i.e., L2-1P, single and multi-port L2-3P and DCFC). F = $\{f(1)...f(T)\}$ is the electricity pricing vector. P_i^{rated} and η_i are the on-board charger rated power and its efficiency of i^{th} PEV, respectively. P_J^{rated} and η_J are the rated power and the efficiency of DCFC unit, respectively.

Equation (5) guarantees the charging energy desired for each EV by its departure time while (6) imposes charging power rates that are between 0 and maximum power ratings of either on-board or EVSE depending on the EVSE type selected. As there is usually a limit on the demand for each rate plan imposed by the utility, (7) is to limit total power drawn from the distribution transformer. P_{lim} is set to 600kW in this study.

Two coordinated charging strategies with scheduling EVs with respect to their arrival times are proposed to solve (1). The first strategy employs an uninterrupted charging profile between the plug-in and off times [15] that represents typical present charging practice with the current EVSE technology at the workplace charging stations. The charging power can be either fixed or varied rates. The second strategy on the other hand, applies an interrupted charging profile that can give idle times between plug-in and off times [16]. This charging strategy requires that EVSE can have multiple ports which EVs are plugged-in even though only one EV can be charged at a time. The principle of both strategy is based on maximizing the use of charging units, s. For this, a heuristic algorithm is developed that places EVs into a charging unit sequentially until an incoming EV does not fit in the current unit. Charging units are added sequentially only if any incoming EV cannot be placed on existing charging units. It is controlled by checking available time slots and energy for every existing units sequentially. The available energy is calculated based on arrival and departure times of the incoming EV and the charging powers of previous EVs. The implementation of both strategies assumed that a charging station operator collects the data, i.e, arrival and departure times including the desired state-of-charge by the departure time as EVs arrive. Then, optimal charging rates are calculated using (1) for each arriving EV only once when it is plugged-in.

IV. Comparative Analysis

A typical workplace power demand based on collected data from a research institution is used for comparative analysis. A set of 5 different PEV types in the market are selected as possible cars at the workplace. The set of PEVs is composed of (13.8 kWh, 3.7kW), (24kWh, 6.6kW), (30kWh, 6.6kW), (50kWh, 11kW), and (64kWh, 7.2kW) and equally distributed among a group of 100 EVs. The plug-in, plug-off times and the required charging energy are assumed to be Gaussian. The vehicles arrive in workplace at 8:40 A.M. with a standard deviation of 1h 05, and they leave workplace at 4:10 P.M. with a standard deviation of 2h 28. The efficiency of the on board chargers and DCFC EVSE are considered as 90% and 97%, respectively. The required SoC is assumed to be Gaussian with a mean of 0.45 and a standard deviation of 0.18. The EVSE types considered are L2-1P type rated at 7.36 kW (single phase), L2-3P type rated at 22kW (3 phase, 32 A), and DCFC at 50 kW. For L2-3P and DCFC, single and two-port options (L2 MP and DCFC MP) are considered separately.

The model is developed and run using Matlab optimization toolbox [17] with 1 min time interval for 100 times to consider different randomly generated mobility scenarios. Results presented are the mean values of 100 trails. A group of 100 EVs at a workplace are considered to charge with first-come first-served charging schedule.

Fig. 3 and Fig. 4 present the behaviors of uninterrupted and interrupted EV charging unit costs for each EVSE type for PG&E and SCE rates, respectively. The unit cost is calculated as the cost per kWh energy required to charge all EVs considered. Since there is a significant difference in the TOU rates considered as in Fig. 2 , PG&E and SCE are not compared in the analysis. Instead, their conventional TOU rates with demand charge have been compared with corresponding EV specific rates. As shown, the unit cost with the PGE EV specific rate reduces for all EVSE types

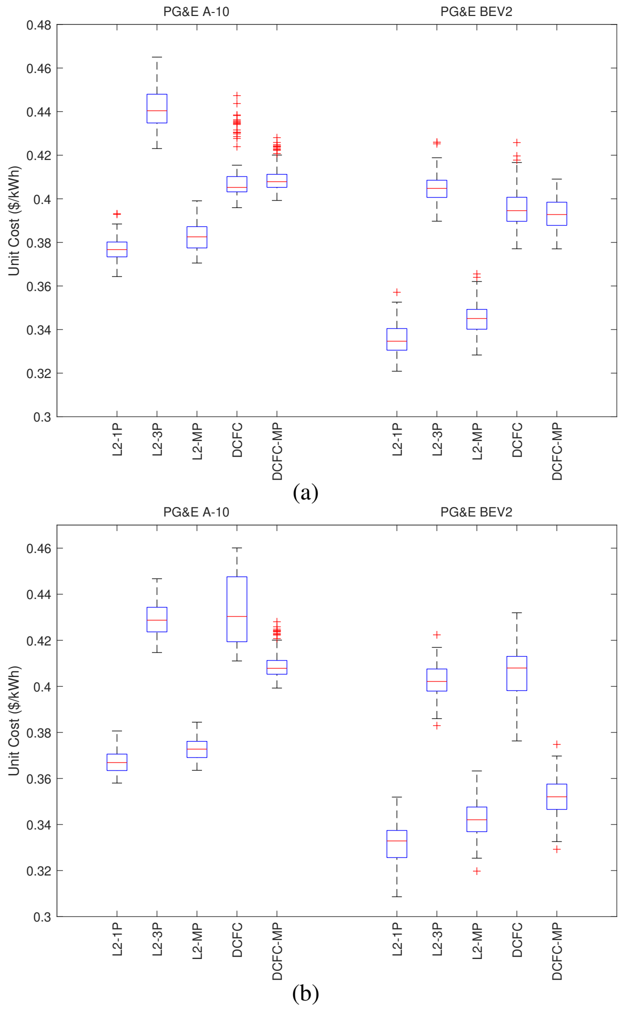

Fig. 3: Total unit costs for EVSE types with PG&E rates, a) uninterrupted charging profile, b) interrupted charging profile.

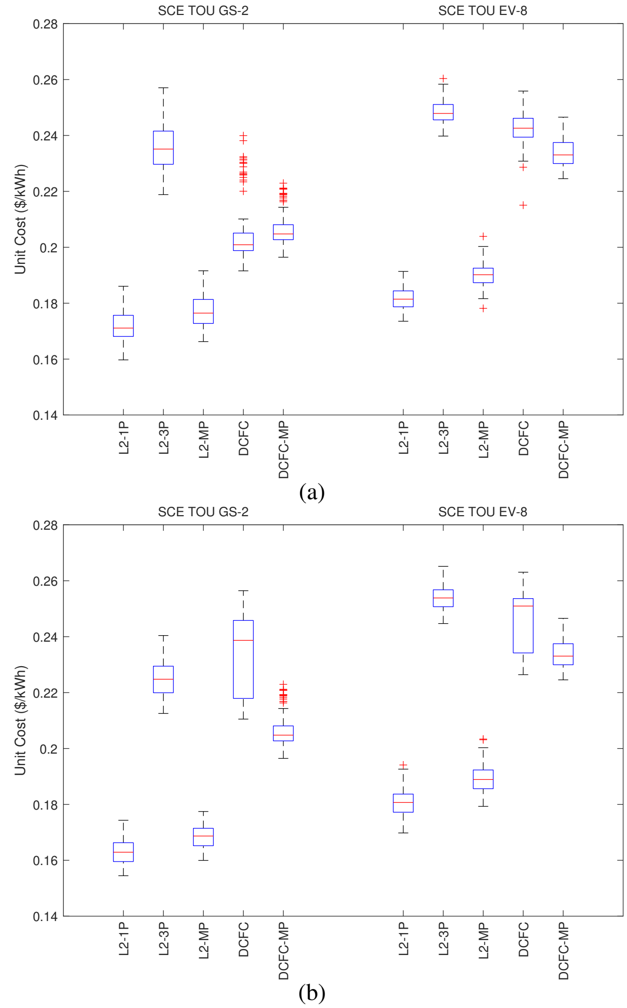

Fig. 4: Total unit costs for EVSE types with SCE rates, a) uninterrupted charging profile, b) interrupted charging profile.

considered while the SCE TOU EV-8 increases the unit cost slightly for all EVSE types.

A. Coordinated Charging with Uninterrupted Charging Profile

As shown in Fig. 3a, each EVSE type displays cost reductions with the PG&E EV specific rate. In this respect, the mean unit cost values vary from 33 Cents/kWh to 44 Cents/kW for PG&E BEV2 and PG&E A-10, respectively. L2-1P always shows the lowest cost figure while L2-3P gives the highest with each rate. The breakdown of the total costs for each EVSE type considered are shown in Fig 5a. It is observed that the major difference in cost elements is due to demand charge. It is also noticed that the optimal solution returns the same EVSE cost figures for both rates. Even though the charging cost element slightly increases in the EV specific rate, a cost saving ranging from 3.5% to 10.9% depending on EVSE types occurs in the EV related cost (i.e., sum of charging cost, demand/customer charge, and EVSE cost) as compared to the demand metered TOU rate. The most cost saving is achieved with L2-1P while DCFC type gives the least cost reduction. The demand charge is eliminated as intended and replaced with a monthly fixed fee that is much less than the demand charge. It is observed that the conventional demand charge approach is highly sensitive to EVSE type while EV specific rate shows similar customer charge figures irrespective of EVSE type.

Fig. 4a shows the unit cost behaviours of EVSEs with the SCE rates. Unlike PG&E BEV2, SCE TOU EV-8 increases the unit costs. The increase in the EV related cost happens the most at DCFC with 17.9% while L2-3P displays the lowest increase of 5.25%. The lowest unit cost is still achieved by L2-1P EVSE with SCE TOU GS-2 as 17 Cents/kWh while SCE TOU EV-8 for L2-3P returns to the highest as 25 Cents/kWh. The cost breakdown in Fig. 6a demonstrates that the charging costs with SCE TOU EV-8 increase significantly. This is due to the fact that the EV specific TOU rates in Fig. 2 are always higher than its general demand TOU rate throughout the day. The change of charging costs contributes to the increase in the total unit cost. The optimal model gives similar EVSE cost

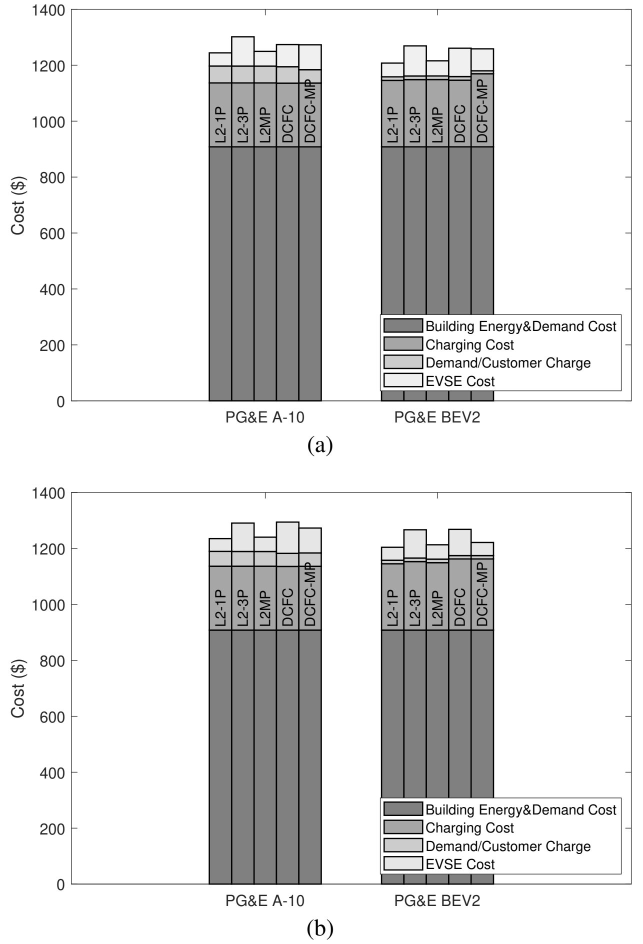

Fig. 5: Cost breakdown for EVSE types with PG&E rates, a) uninterrupted charging profile, b) interrupted charging profile.

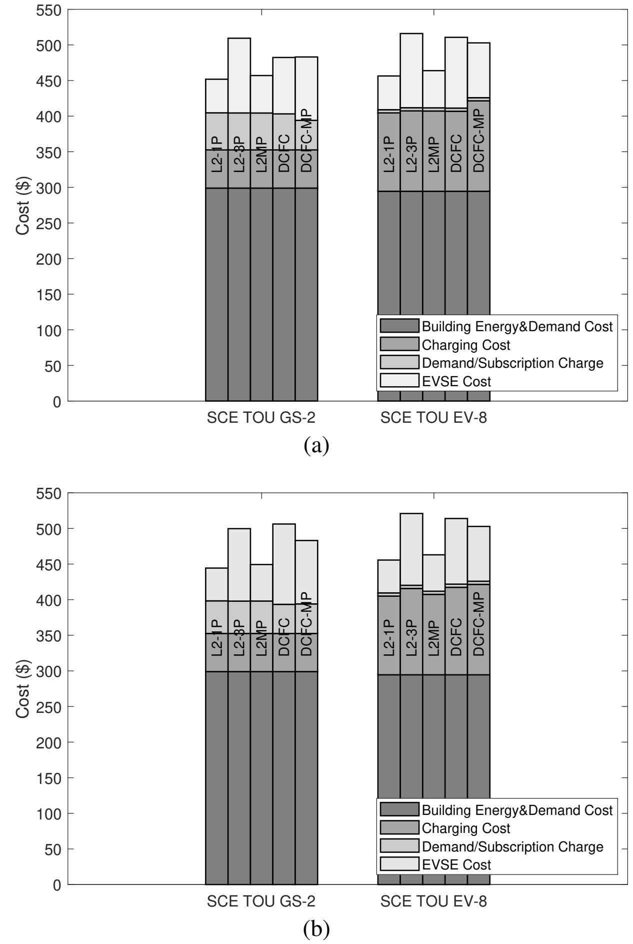

Fig. 6: Cost breakdown for EVSE types with SCE rates, a) uninterrupted charging profile, b) interrupted charging profile.

figures for both general service and EV specific rates. The figure also shows that the demand charge is replaced with a significantly lower subscription charge in the EV specific rate. Both PG&E and SCE rates analysis recommends that the cost behavior of EV specific rates differ from utility and EVSE type.

B. Coordinated Charging with Interrupted Charging Profile

The unit costs of each EVSE types with interrupted charging for PG&E A-10 is given in Fig. 3b. The total unit costs for each EVSE type are slightly reduced as compared to the uninterrupted charging. The lowest unit cost is achieved with L2-1P as 33.2 Cents/kWh while the highest is with DCFC as 43.2 Cents/kWh. Cost breakdown given in Fig. 5b shows that the EV specific rate provides a cost saving between 6.3% and 14% in the EV related cost depending on EVSE type.

A cost increase in the SCE EV specific rate compared to its conventional counterpart is also observed in the interrupted charging as given in Fig. 4b. However, the rate of increase becomes slightly lower as compared to the uninterrupted charging case. The lowest mean unit cost of 16.3 Cents/kWh is achieved by L2-1P with SCE TOU GS-2 rate while SCE EV-8 rate performs the highest unit cost of 25.4 Cents/kWh. Similar cost breakdown is observed as shown in Fig. 6b. The optimal model results confirm that this EV specific rate does not provide cost saving from a station owner's perspective even though smart charging strategies are employed.

C. Impact on the Grid

The impact of the EV charging loads on the grid is analysed through peak of 15 min intervals and variance of the charging load profile reported in Table I. The variance of charging profile is a measure to evaluate load fluctuation that increases power systems operational cost and transmission level operation [18]. For both utilities, the same base load profile was used. Among the peak demands with the PG&E rates, the highest peak of 192.41 kW is observed for DCFC with the uninterrupted charging for PG&E BEV2 while the lowest peak of 129.33 kW is obtained with PG&E A-10 rate for the multi-port DCFC. In terms of EVSE type, similar grid behavior is observed for the SCE rates with the highest of 175.96 kW for DCFC with the uninterrupted charging and the lowest

TABLE I: Impact of EVSE Types on the Grid with general and EV specific rates.

Charging Strategy	Scheduling Type	**L2-1P**		**L2-3P**		**L2 MP**		**DCFC**		**DCFC MP**	
		Peak [kW]	Variance $[kW]^2$	Peak [kW]	Variance $[kW]^2$	Peak [kW]	Variance $[kW]^2$	Peak [kw]	Variance $[kW]^2$	Peak [kw]	Variance $[kW]^2$
Uninterrupted	**PGE Demand**	148.99	3,581.5	146.37	3,501.5	145.93	3,498.3	143.00	2,815.6	129.33	3,101.1
	PGE BEV	173.36	4,711.8	172.63	4,549.5	172.88	4,564.4	192.41	4,196.4	149.53	3,457.2
	SCE Demand	149.27	3,583.7	146.38	3,508.5	146.32	3,507.9	143.00	2,814.7	131.30	3,174.5
	SCE EV8	165.86	4,624.2	162.85	4,482.7	163.16	4,503.3	175.96	4,137.5	145.65	3,445.5
Interrupted	**PGE Demand**	137.42	3,544.8	136.62	3,495.7	136.69	3,503.2	131.68	3,206.9	129.33	3,101.1
	PGE BEV	160.22	4,069.3	157.08	3,855.1	158.41	3,946.3	165.84	3,674.1	165.84	3,674.1
	SCE Demand	137.94	3,573.5	136.84	3,521.1	137.13	3,527.8	131.80	3,276.5	131.30	3,174.5
	SCE EV8	157.59	4,082.5	155.62	3,879.1	156.71	3,968.0	155.92	3,660.7	145.65	3,445.5

of 131.30 kW for multi-port DCFC interrupted charging. It is observed that the peak demands in conventional rates are always lower than those in EV specific rates for all EVSE types. The peak increase is mainly due to the elimination of demand charge in the objective function which considers only charging and EVSE costs. This results in a new peak at the lowest rate periods. It can then be concluded that EV specific rates may increase the peak power and may not become grid friendly.

V. Conclusions

This study analyses the performance of EV specific rates in terms of cost and grid behaviour at a workplace. The analysis relies on a developed optimal model with two different coordinated charging strategies. The objective is set to minimize total cost of a workplace charging station over its lifetime. Two EV specific rates from different utilities have been considered.

In terms of station owner perspective, it has been found that the cost behavior of EV specific rates differ from utility and EVSE type. As compared to general demand metered TOU rates, the PG&E BEV 2 achieves a cost saving of between 3.5% and 10.9% in the total unit cost figure depending on charging strategy and EVSE type. In this case, the charging cost can increase, but total cost reduces thanks to elimination of demand charge. On the other hand, it has been observed that the total unit cost increases with the SCE EV-8 rate since the EV specific TOU rate in this case is always higher than the general demand metered TOU rate. That leads to increased charging costs.

In terms of the grid perspective, it has been shown that both the EV specific rates do not reduce the peak demand due to the elimination of demand charge. This results in scheduling charging requests at the lowest TOU rate periods in order to minimize charging cost only. Thus, new peak occurs at the off-peak hours. This analysis shows that EV specific rates may not provide always an efficient use of the grid assets. It can also be concluded that the benefits from the station owner or EV user perspective are not guaranteed as the benefit depends on EV specific TOU rates provided.

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